

# IMMEDIATE AMELIORATION OF WET COHESIVE SOILS BY QUICKLIME

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Immediate amelioration of wet cohesive soils by lime, a current practice in earthwork operations for highway construction in Belgium, is performed with 1 to 1.5 percent quicklime. Such small doses are effective because they agglomerate the soil into crumbs that are stable in free water and retain their individuality after kneading and compaction. Procedures for evaluating the crumb stability and the amount of lime needed for adequate CBR value have been developed. Additions of 1 percent quicklime produce not only the immediate amelioration effects but long-term strength gains as well. Strontium and barium hydroxides produce the same immediate effects as equivalent amounts of lime but far lower long-term strength gains. Lime percentage has far less incidence on immediate amelioration than on long-term strength gains.

• IN BELGIUM, and in neighboring parts of France and Germany, large areas are covered with loess soils, which are moderately plastic clayey silts. Summer in northwestern Europe is rather wet and cool, and the moisture content of the loess at depths of 2 ft or more under the natural surface remains close to the plasticity limit the year round. This limit is about 20, about 8 percent higher than the optimum water content for compaction. When these soils are excavated from hills, they are too wet for appropriate compaction; therefore they were discarded in the past and replaced by borrowed materials for the construction of highway fills and embankments.

Improvement of loess by a lime additive has become a current process of earthwork operations, resulting in appreciable cost and time savings in highway construction.

Research findings of the Centre de Recherches Routières on the lime treatment of loess soils are discussed in this paper. The investigation, initiated in 1970, deals primarily with the short-term ameliorating effects of the lime; more research devoted to the long-term effects is still in progress.

## LIME TREATMENT OF SOILS IN BELGIUM

Since 1960, much research has been devoted to the effects of lime treatment of cohesive soils. However, as pointed out by Neubauer and Thompson (1), most of that research has considered the long-term effects, or cured strength, of the lime. Fewer findings are available on the immediate effects that result in an amelioration of the geotechnical properties of uncured lime-soil mixtures as compared to the natural soil.

In Belgium, improvement of wet cohesive soils by quicklime has been used for earthwork operations in highway construction since 1968.

Powdered quicklime is generally used in Belgium for the treatment of soils because it is cheaper than slaked lime. Hazards of using quicklime are largely assuaged by pneumatic handling, and use of protective clothing and spectacles is recommended (4, 5). The grade of quicklime currently available is approximately 100 percent passing No. 10 (2 mm) sieve and 40 to 50 percent passing No. 200 (75  $\mu$ m) sieve. The free

CaO content of the lime, measured by the "rapid sugar method" (ASTM C 25-67), is 90 to 95 percent. Slaking in water (ASTM C 110-67) is rapid (less than 10 min).

When mixed with a wet soil, the calcium oxide in the powdered quicklime is readily converted into calcium hydroxide, which dissolves in the soil water in exactly the same way (about 1.4 grams/litre) as if slaked lime had been added. From then on, the effects of the addition of 1 part quicklime of the grade described are identical to those brought about by 1.3 parts slaked lime of the same degree of purity.

#### DRYING EFFECTS OF QUICKLIME AND EXPOSURE

Use of quicklime, which is an advantage when wet soil is treated, results in a decrease in the water content of the mixture. This drying effect is brought about by the chemical fixation of the hydration water, by evaporation of some water by a part of the heat of hydration, and by the increase in weight of the solids caused by the lime addition (2). The drying effect was shown by Van Ganse (3, 4, 5), by laboratory and field experiments, to be about 0.65 percent loss in moisture content per gram of commercial quicklime added to 100 grams of dry soil. Field experiments have shown (4, 5) that exposure of the fresh, loose lime-soil mixture to sunshine and wind can result in a much larger loss of moisture, up to 2.5 percent, than can be obtained by the action of the usual small dose of quicklime.

#### IMMEDIATE EFFECTS OF SMALL DOSES OF QUICKLIME

Immediate effects of additions of quicklime to Belgian loess soils have been reported (4, 5, 6, 7) and are comparable to the findings of other authors (1, 8, 9, 10, 11). The following have been observed on many types of loess and other clayey soils: (a) an increase of the plastic limit; (b) improvement of trafficability of the soil; (c) a shift of the moisture-density relationship toward a lower maximum dry density and a higher optimum water content, allowing a higher relative dry density to be obtained by compaction; and (d) a substantial increase in the CBR value of the compacted lime-soil mixtures.

Evidence was obtained, however, that the instant improvements of the soils do not increase proportionally with the amount of lime. In fact, about two-thirds of the effects produced by 3 percent quicklime are obtained with an addition of 1 percent, at the same water content.

The actual decrease in water content, initiated by the slaking of the quicklime and by exposure of the mixture before compaction, enhances the immediate effects of the lime. However, a very high initial water content of the soil, even when not impeding long-term strength gain by a large lime dose, may prevent sufficient improvement to expedite the earthwork.

#### PROCEDURE FOR EVALUATING MINIMUM LIME DOSE

A standard procedure has been developed (12) to evaluate the amount of quicklime needed to ameliorate a given soil (with its natural water content) to obtain a sufficient CBR value after compaction. CBR values considered suitable in Belgium are 10 percent for the bulk of highway embankments and 15 percent for 30-cm-thick ameliorated subgrades. The procedure plots moisture content against CBR values (immediately after compaction) for 2-hour-old mixtures of soil and arbitrary (e.g., 3 percent) doses of quicklime. If allowance is made for the loss of moisture that occurs on the construction site during the 2-hour exposure of the loose mix before compaction, the probable CBR strength can thus be evaluated. If the predictable CBR strength is higher than the required value, the test is resumed with a smaller amount of lime.

This laboratory procedure, which has been checked by field trials, has shown that in the majority of cases adequate amelioration of Belgian loess soils with their natural water content is obtained with 1 to 1.5 percent quicklime. In favorable cases where the soils were somewhat drier than usual, quicklime doses as low as 0.5 percent have been effective.

In fact, from 1968 to 1971, over 12 million cubic meters of soil were treated in Belgium with an average dose of 1.65 percent commercial quicklime, with excellent results (5). The actual average quicklime percentage used has decreased from 3 percent in 1968 to about 1 percent today.

#### EFFECT OF LIME ON SOIL STRUCTURE

The effectiveness of small doses of lime in the instant amelioration of cohesive soils is explained by the primary instant effect of the lime as a modification of the soil structure.

Unsaturated cohesive soils in a loose condition do not fall apart into elementary particles like sand does. They form aggregates, called clods, lumps, or crumbs, according to size. The soil particles may be glued together by substances such as humus or cemented by calcium carbonate, for example. Physicochemical forces in the ionic layer surrounding the soil particles may also act. The main binding force, however, is the traction exerted by menisci of capillary water on adjoining particles. Most soil aggregates disintegrate when immersed in water because capillary forces disappear when saturation arises.

Therefore, the structure or aggregate division of a soil mainly depends on the moisture content. Structure is promoted by drying and shearing and deteriorated by moisture and compression. (Soil structure is important in agriculture because permeability for air and water, which is vital for the root functions in plant life, depends on the voids between aggregates. Tilling the soil is aimed mainly at restoring deteriorated soil structure.)

When a small amount of lime is mixed into a moist, though unsaturated, fine-grained cohesive soil, striking changes appear almost instantaneously. The color of the soil becomes lighter, its gloss duller, and its consistency pulverulent. These changes are brought about by the formation of soil crumbs (granules), into which the mixture readily divides. The size of the crumbs ranges from 0.20 to 0.5 cm (Fig. 1).

Mixing under standard conditions has shown that the mean diameter of the lime-soil granules increases with the water content for a given soil and with the plasticity index for different soils. Freshly prepared lime-soil granules are soft and can be crushed easily between the fingers; however, they do not quite disintegrate when immersed in water.

#### MEASUREMENT OF CRUMB STABILITY

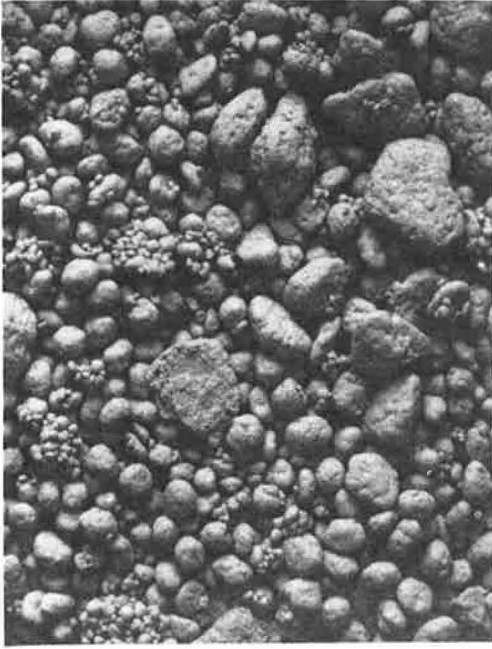
Crumb stability in the presence of free water can be measured by the percentage of dry weight of crumbs retained on a suitable sieve after repeated immersion (13). The size of the crumbs and their stability depend on soil type and moisture content. The stability of lime-soil crumbs depends also on the dose of lime and increases with time because of pozzolanic reactions. A standard procedure for measuring the crumb stability (fixing all the variables) and a suitable automatic sieve apparatus have been developed by the Centre de Recherches Routières (14).

Crumbs of an untreated soil do not, as a rule, disintegrate completely when soaked in water for a rather short time. In the test procedure, a soaking time of only 20 min is usually sufficient to show the stabilizing effect of lime, without unduly increasing the time required for the test.

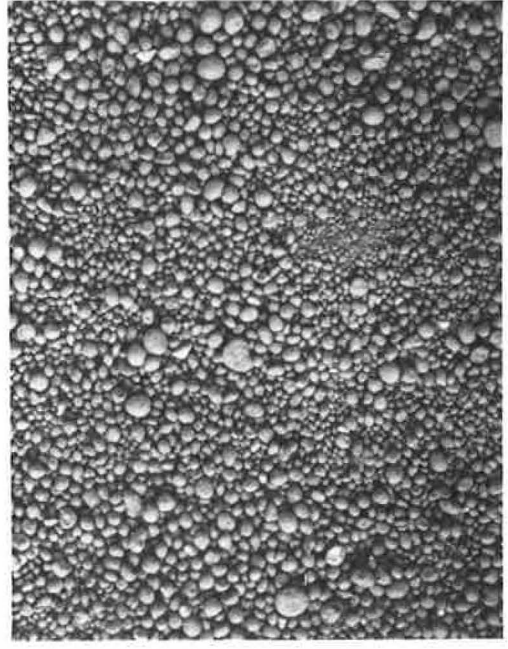
Comparison of crumb stabilities measured on an untreated soil 2 hours after addition of 32.8 meq of CaO per 100 grams of dry soil (1 percent quicklime of 92 percent grade) is an adequate, simple, and rapid method for evaluating the fitness of that soil for instant amelioration. On 84 Belgian soils that have actually been treated successfully with lime, crumb stability increases of 30 percent or more were found, except in a few cases where high stability of the natural soil crumbs precluded detection of such a large increase.

In many cases, the crumb stability test gives a univocal answer, its main advantages being that only a 1-kg soil sample and 1 hour of an operator's time are needed.

Figure 1. Structure of Belgian loess soil: (a)  $w_p = 19$ ,  $I_p = 8$ , loosened with  $w = 16$  percent; and (b) after mixing with 1 percent quicklime.



a.



b.

Figure 2. Rupture faces of (a) untreated loess soil, (b) loess soil with 1.5 percent quicklime in the laboratory, and (c) loess soil with 1.5 percent quicklime on a construction site.



a.



b.



c.

## EFFECTS OF LIME-INDUCED CRUMB STABILITY

The instant improvements of geotechnical properties of cohesive soils by addition of lime have been explained in relation to an increase of the plastic limit by Hilt and Davidson (15). A more general explanation, however, is suggested because the water-stable crumbs of a lime-treated soil retain their individuality to a large extent when the lime-soil mixture is subjected to kneading and rolling (as in the plastic limit test) or to compaction.

Figure 2 shows rupture faces of broken compacted specimens, which had been prepared from an untreated soil and from the same soil treated with 1.5 percent quicklime. Almost no structure is visible in the specimen of untreated compacted soil, but the treated specimens clearly show the granulated structure of the compacted lime-treated soil with a visible macroporosity along the edges of the crumbs. This macroporosity is thought to be the primary cause of the increase of the plastic limit and of the shift of the Proctor curve toward a lower dry density and a higher optimum moisture content. On the other hand, the increase in CBR strength at the wet side of optimum is also because of the stability of the crumbs, which opposes parallel orientation of clay mineral particles.

### NATURE OF IMMEDIATE REACTION

The nature of the immediate reaction of calcium hydroxide dissolved in soil pore water with the clay minerals has been the object of many speculations. Diamond and Kinter (11) reviewed several hypotheses and concluded that cation exchange, flocculation, and carbonation cannot be retained as essential factors of instant modification of soil. They believe that the primary phenomenon is a very rapid physical adsorption of both calcium and hydroxyl ions on the clay surfaces, even when these are already calcium-saturated. They suggest that an immediate reaction occurs between the alumina-bearing edges of clay particles and the lime adsorbed on the faces of adjacent particles. This results in the formation of bonds of tetracalcium alumina hydrate and, possibly, calcium silicate hydrate, which link the clay particles together.

The appearance of water-stable soil crumbs is entirely consistent with the hypothesis of such a linking process. To date, however, evidence of the instant formation of calcium aluminate or calcium silicate hydrate or both does not seem to have been demonstrated. Another type of link, made up by the bivalent calcium ion itself, has been suggested by Grossmann (16).

An essential requirement of the instant reaction is alkalinity of the medium. A neutral calcium salt like  $\text{CaCl}_2$  exerts, notwithstanding its potent flocculation action, no instant amelioration effects on clayey soils. It is sufficient however to add, with the  $\text{CaCl}_2$ , an equivalent amount of  $\text{NaOH}$  to obtain the same effects as those produced by lime. The high pH value of a  $\text{Ca}(\text{OH})_2$  solution obviously implicates increased solubility and reactivity of silica and alumina at the faces and edges of clay mineral particles.

Some experimental work has been performed by Van den Bergh (17) in connection with instant reactions. These experiments involved (a) substitution of  $\text{Ca}^+$  ions by  $\text{Sr}^{++}$  and  $\text{Ba}^{++}$  ions, (b) measuring the amounts of hydroxide consumed in early and in later stages, and (c) measuring the respective unconfined compression strengths.

The experiments were performed on five typical Belgian loess soils. Table 1 gives their main characteristics. The main differences between these soils are the calcium carbonate content, which is high in soil 361, and the percentage of particles less than  $2 \mu\text{m}$  in size, which is determined by ASTM D 422-63.

### Crumb Stability

Crumb stability was measured (14) on the untreated soils and 2 hours after adding a mixture of 1 percent quicklime containing 92 percent free  $\text{CaO}$  or equivalent quantities of strontium hydroxide and barium hydroxide. The dose in each case was 32.8 meq per 100 grams of dry soil (Table 2). The coefficient of variation (standard deviation divided by mean) of the measured crumb stabilities is about 0.05.

No significant difference appears between the crumb stabilities induced in a given soil by the three hydroxides. The increase in crumb stability in all cases is in the range 30

**Table 1. Characteristics of five typical Belgian loess soils.**

Soil No.	Origin	Horizon	Specific Gravity (g/cm <sup>3</sup> )	CaCO <sub>2</sub> (percent)	Organic Matter (percent)	Liquid Limit	Plastic Limit	Plasticity Index	Percent Passing	
									No. 200	No. 10
361	Sterrebeek	B	2.706	12.1	0.05	27	20	7	98	13
362	Hingeon	B	2.702	2.4	0.04	31	20	11	98	25
363	Orbais	B	2.705	1.8	0.01	28	20	8	98	25
364	Lavoir	B	2.685	1.7	0.25	26	19	7	97	18
365	Tihange	Mixture	2.730	2.6	0.21	32	21	11	93	30

Note: The Belgian loess soils are predominantly illitic and contain chlorite.

**Table 2. Crumb stability of loess soils, untreated and treated with hydroxides of Ca, Sr, and Ba.**

Soil No.	Crumb Stability (percentage of dry weight)			
	Untreated	Ca	Sr	Ba
361	11	49	55	51
362	51	84	92	92
363	3	66	—	—
364	8	54	63	56
365	57	96	—	—

**Table 3. Fixation, in meq, of hydroxides in soil-hydroxide mixtures.**

Soil No.	Cation	Hydroxide Fixation (meq/100 g)			
		2 Hours, 20 C	24 Hours, 20 C	28 Days, 20 C	28 Days, 40 C
361	Ca	8	9	13	27
	Sr	5	11	16	18
	Ba	5	12	14	17
362	Ca	10	15	20	26
	Sr	10	10	19	24
	Ba	10	17	18	24
363	Ca	15	—	19	24
	Sr	—	—	—	—
	Ba	—	—	—	—
364	Ca	9	13	17	28
	Sr	8	10	19	23
	Ba	7	10	23	24
365	Ca	9	—	25	25
	Sr	—	—	—	—
	Ba	—	—	—	—

**Table 4. Unconfined compressive strength of untreated soils and hydroxide-soil mixtures.**

Soil No.	Cation	Compressive Strength (bars) for Curing at			
		2 Hours, 20 C	24 Hours, 20 C	28 Days, 20 C	28 Days, 40 C
361	Untreated	1.1	1.2	1.5	1.5
	Ca	2.1	2.8	7.1	17.2
	Sr	1.7	1.7	1.4	1.7
	Ba	1.7	1.6	1.3	1.4
362	Untreated	1.7	1.8	2.3	2.3
	Ca	3.7	5.7	6.5	12.5
	Sr	3.2	2.0	3.4	4.7
	Ba	3.1	2.7	4.9	6.4
363	Untreated	2.3	2.3	2.3	2.3
	Ca	3.6	—	5.1	10.8
	Sr	—	—	—	—
	Ba	—	—	—	—
364	Untreated	1.2	1.2	1.3	1.3
	Ca	2.2	2.5	2.9	5.8
	Sr	2.0	2.1	1.8	2.7
	Ba	1.9	1.7	2.9	3.8
365	Untreated	1.9	1.9	2.0	2.0
	Ca	5.9	5.9	5.9	9.9
	Sr	—	—	—	—
	Ba	—	—	—	—

**Table 5. Development of unconfined compressive strength in lime-soil mixtures, with 5 percent quicklime.**

Soil No.	Compressive Strength (bars) for Curing at			
	2 Hours, 20 C	24 Hours, 20 C	28 Days, 20 C	28 Days, 40 C
361	2.4	3.8	11.0	41.5
362	5.5	7.9	11.3	57.1
363	4.2	7.8	9.8	52.3
364	4.3	5.3	6.4	32.9
365	12.0	14.8	17.7	26.1

to 60, indicating a strong instant reaction. This suggests that the three hydroxides react in the same way, in spite of the large differences in size between Ca, Sr, and Ba ions. This in turn suggests that the instant reaction occurs outside the clay mineral particles.

#### Rate of Hydroxide Consumption

The quantity of hydroxide remaining that was available was determined by ASTM C 25-67. By subtracting from the amount added, the amount of hydroxide consumed could be calculated. These figures, reproducible within about  $\pm 2$ -meq limits, are given in Table 3.

Although the rate of fixation of hydroxide in the first 2 hours depends on the soil, no important differences between the fixation rates of the three hydroxides are evident. The only possible exception is soil 361, which has a fairly high calcium carbonate content, in spite of which it consumes more calcium hydroxide than strontium or barium hydroxide in the ultimate stage of curing. Curing for 28 days at 40 C is roughly equivalent to about 1 year at 20 C.

Experiments not given in Table 3 have shown that the lime fixation within the first 10 min after mixing is almost as much as within the first 2 hours. Therefore, in well-mixed laboratory samples, the immediate reaction is almost completed within a few minutes and from then on the pozzolanic reactions are much slower.

Note that the data in Table 2 were obtained with additions of hydroxides equivalent to 1 percent commercial quicklime. Larger additions of lime produce higher rates of fixation in the early stage as well as later on. More detailed observations of fixation rates will be available after completion of research on the long-term effects of lime.

#### Unconfined Compressive Strength

Cylindrical specimens, 5 cm in diameter and 10 cm high, were molded from the untreated soils and from mixtures with three hydroxides with water contents at the wet side of optimum so that in each case 95 percent of the maximum dry density of the modified Proctor USCE test could be obtained.

After various periods of curing in sealed wrappings at 20 C and 40 C, the unconfined compressive strength of the specimens was measured, with a rate of strain of 0.127 cm/min. The remains were used to determine the available free hydroxide.

Table 4 gives the mean results of a series of five identical specimens. The coefficient of variation of the results of individual specimens is about 10 percent. It is apparent from these results that breaking strengths of the specimens of 2-hour-old hydroxide-soil mixtures are roughly twice those of the untreated soils and that the effects of strontium and barium hydroxides are practically the same as those of lime in this early stage.

After curing, large gains in strength appear in the lime-treated specimens. However, strontium and barium hydroxides produce insignificant gains in strength, in spite of the fact that consumption of strontium and barium hydroxides progresses, during curing, at rates comparable to those of lime consumption. This suggests that similar low-speed reactions may occur, but that the reaction products are different, perhaps for steric reasons.

For accelerated curing, 40 C rather than 48.9 C has been chosen to obtain strength-time curve shapes and chemical compositions of the reaction products that more closely approximate the behavior of the lime-treated soils at 20 C.

### LONG-TERM REACTION OF SMALL AMOUNTS OF LIME

It may seem surprising that an addition as small as 1 percent of 92 percent grade quicklime produces not only instant ameliorations of geotechnical properties but also a relatively high long-term gain in strength. This evidence was obtained even though the lime dose added was much smaller than the "lime fixation (or retention) point" [i.e., the amount of calcium hydroxide beyond which the plastic limit is not increased by a larger dose of lime (15, 18, 19)]. This critical amount of lime, the modification

optimum (20), "contributes to the soil workability but not to increases in strength, while amounts of lime beyond this dose cause the formation of cementing materials" (15). The fact that even a small amount of lime does evolve both these results is not consistent with this theory.

### PRACTICAL CONSIDERATIONS

Long-term effects of an admixture of 1 percent quicklime are far inferior to those brought about by larger amounts of lime. Table 5 gives unconfined compressive strengths of specimens of mixtures of five Belgian soils of Table 1 with 5 percent quicklime. This is not the "optimal" dose for long-term stabilization of these soils; optimal doses may be larger.

Comparison of Tables 4 and 5 shows that, as far as immediate effects are considered, the strength after 2 hours at 20 C obtained with 5 percent quicklime is by no means five times but at most two times as large as the strength brought about by 1 percent. Only after a rather long curing time will the ratio of 5 percent to 1 percent strength become really large, justifying the use of relatively high and expensive amounts of lime in long-term stabilization for structural purposes (21).

In earthwork operations, however, the only purpose of the lime treatment is immediate amelioration of the soil (1). Long-term gain in strength may then supply a factor of safety, but it can also become a nuisance when trenching work is to be performed in a lime-treated embankment, for example.

The Belgian practice in highway construction is to treat wet clayey fine-grained soils with the lowest dose of quicklime, ensuring adequate workability and a sufficient bearing value after compaction 2 hours after mixing. This practice appears to be justified from the technical as well as from the economical viewpoint. Extensive descriptions of the actual earthwork procedures involved, of the equipment used, and of quality control test results have been published elsewhere (4, 7, 22).

### CONCLUSIONS

The following describe the usefulness of quicklime when mixed with loess soils.

1. Instant improvement of wet loess soils by an admixture of 1 to 1.5 percent quicklime proved to be sufficient, not only in expediting earthwork operations, but also in allowing loess soils to be used, instead of discarded, in the construction of highway embankments.
2. A decrease in moisture content of about 0.65 percent per 1 percent quicklime is evolved, but drying of the loose mixture by exposure on the site is often more important.
3. A procedure has been developed for evaluating the amount of lime necessary to ameliorate a given soil just enough to obtain a suitable CBR value after compaction.
4. Structuring the soil into water-stable crumbs is the basic instant effect of lime. A simple and rapid procedure for measuring the increase of crumb stability, which indicates the fitness of the soil for instant amelioration, has been developed.
5. The instant ameliorations of geotechnical properties by lime treatment are caused by the experimental fact that lime-soil crumbs retain their individuality to a large extent when a lime-soil mixture is kneaded and compacted.
6. Hydroxides of strontium and barium produce the same immediate effects as an equivalent amount of lime. In later stages also, the rates of consumption of the three hydroxides remain nearly equal; however, long-term strength gain is far higher with calcium hydroxide than with strontium hydroxide or barium hydroxide.
7. Both immediate and long-term effects are brought about by small amounts of lime. This fact is not consistent with the lime retention point theory.
8. Lime percentage has less incidence on immediate effects than on long-term strength gains.

### ACKNOWLEDGMENT

Permission for publication of the present paper was granted by J. Reichert and J. Verstraeten, Centre de Recherches Routières. Financial support from l'Institut pour la Recherche Scientifique dans l'Industrie et l'Agriculture is gratefully acknowledged.



## REFERENCES

1. Neubauer, C. H., and Thompson, M. R. Stability Properties of Uncured Lime-Treated Fine-Graded Soils. Highway Research Record 381, 1972, pp. 20-26.
2. Schaeffner, M., and Philippe, A. Abaissement de la teneur en eau des sols par addition de chaux vive. Bull. de Liaison des Lab. Routiers des Ponts et Chaussées 49, 1970, pp. 13-18.
3. Van Ganse, R. L'assèchement des limons par la chaux. Bull. de Liaison des Lab. Routiers des Ponts et Chaussées 53, 1971, pp. 126-127.
4. Van Ganse, R. Quelques aspects théoriques et pratiques de la stabilisation des sols à la chaux. La Technique Routière 16-3, 1971, pp. 1-36.
5. Van Ganse, R., et al. Stabilisation des sols à la chaux. 13e Congrès belge de la Route, Rapport A 1, 1973, pp. 55-72.
6. Van Ganse, R. Efectos Inmediatos de la Cal en la Estabilizacion de Suelos. Boletín de Información del L.T.M.S. (Madrid) 93, 1972, pp. 38-70.
7. Doyen, A. Objectifs et mécanismes de la stabilisation des limons à la chaux vive. La Technique Routière 14-1, 1969, pp. 9-15.
8. Brand, W. Der Einfluss von Kalziumhydroxyd auf die Eigenschaften schluffiger Böden im Strassenbau. Dissertation Technische Univ., Aachen, 1960.
9. Relotius, F., et al. Les limons traités dans le Nord de la France. Revue Générale des Routes et des Aérodrômes 455, 1970, pp. 87-110.
10. Le Roux, A. Traitements des sols argileux par la chaux. Bull. de Liaison des Lab. Routiers des Ponts et Chaussées 40, 1969, pp. 59-96.
11. Diamond, S., and Kinter, E. B. Mechanisms of Soil-Lime Stabilization. Highway Research Record 92, 1965, pp. 83-102.
12. Mode opératoire des essais en laboratoire pour l'évaluation de l'aptitude d'un sol à la stabilisation immédiate à la chaux vive. Centre de Recherches Routières, Brussels, Méthode de Mesure C. R. R., MF 33/72, 1972.
13. Verhasselt, A. La stabilité des grumeaux de sols traités à la chaux. La Technique Routière 18-1, 1973, pp. 25-36.
14. Mode opératoire pour la détermination de la stabilité des grumeaux de limons traités à la chaux. Centre de Recherches Routières, Brussels, Méthode de Mesure C.R.R., MF 34/73, 1973.
15. Hilt, G. H., and Davidson, D. T. Lime Fixation in Clayey Soils. HRB Bull. 262, 1960, pp. 20-32.
16. Grossman, W. Die Kalkstabilisierung bindiger Erdstoffe. Erdstabilisierung in Theorie und Praxis, Dtsch., 1966, pp. 99-125. (French translation 68-T-140, DIRR 54869, L.C.P.C., Paris, 1971.)
17. Van den Bergh, H. Fisicochemische Aspecten van Bodemstabilisering met Kalk. Proefschrift. Centre de Recherches Routières, Brussels, 1972.
18. Eades, J. L., and Grim, R. E. Reaction of Hydrated Lime With Pure Clay Minerals in Soil Stabilization. HRB Bull. 262, 1960, pp. 51-63.
19. Eades, J. L., and Grim, R. E. A Quick Test to Determine Lime Requirements for Lime Stabilization. Highway Research Record 139, 1966, pp. 61-72.
20. Marks, B. D., and Haliburton, T. A. Effects of Sodium Chloride and Sodium Chloride-Lime Admixtures on Cohesive Oklahoma Soils. Highway Research Record 315, 1970, pp. 102-111.
21. Thompson, M. R. Engineering Properties of Lime-Soil Mixtures. Proc., 17th Annual Meeting, American Society for Testing and Materials, Proc. Paper 78, 1967.
22. Van Ganse, R., et al. La stabilisation à la chaux pour la construction des autoroutes. Excavator, Brussels, Dec. 1972, pp. 1-61.

## DISCUSSION

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The experiences reported by Van Ganse in his paper indicate that the application of Verhasselt's technique (23) for measuring crumb stability may help in easily determining the minimum lime content required for immediate and economical amelioration of loessial soils containing illite. Unconfined compressive strength data generally confirmed crumb stabilities measured on 1 percent lime-treated soil after a 2-hour period at 20 C; no crumb stability data were given on cured specimens.

Analysis of unconfined compressive strength data in relation to  $-2\mu$  clay content (13 to 30 percent) and organic matter content (0.01 to 0.25 percent) indicates the following:

1. Total ineffectiveness of a higher percentage of lime (>1 percent) on the lowest clay-content (13 percent) specimen. Strength gains at higher clay contents are a function of increasing clay content.

2. A marked decrease in effectiveness of a given lime percentage on higher clay-content specimens containing organic matter (0.21 and 0.25 percent).

3. For the higher organic content specimens, total ineffectiveness of 20 C curing for more than 1 day, with lime treatment of 1 percent. Unconfined compressive strength data for 5 percent lime-treated specimens after the longest (28-day), higher temperature (40 C) curing period reveal that specimens containing more than 20 percent clay have only one-fourth the strength because of a fourfold increase in the organic content.

4.  $\text{Ca}(\text{OH})_2$  consumption levels at 1 percent lime treatment of specimens, uncured and cured at 20 C, generally increasing with increases in clay content. However, data on specimens of intermediate clay content, cured at 40 C, indicate greatest consumption occurs for the one containing the highest organic matter. Although all specimens examined had approximately equal lime concentrations (grams of lime/litre of water), higher quantities of lime are used by those with higher organic matter content. Furthermore, strength gains normally associated with increased clay content are reduced.

Data collected by this discussor and other investigators of soil materials containing various amounts of montmorillonite relate to these findings.

Immediate ameliorative effects of hydrated lime treatment on materials tested at 20 C for cohesion and unconfined compressive strength are reported by Neubauer and Thompson (1). Materials contained approximately the same range of  $-2\mu$  clay percentages (13 to 46 percent) and were molded at water contents (w) near the plastic limit (PL), as Van Ganse had done. Those data indicate the maximum rate of cohesion improvement occurred for the lowest level of treatment used, 2 percent, and there were decreasing benefits at higher treatment levels.

Direct tensile strength data by Glenn (24) indicate that immediate amelioration occurs on 90 percent bentonite clay ( $\text{Na}^+$ ) with greatest strength gains from about 1 percent treatment with hydrated calcitic lime. Lower strengths are obtained with higher levels of treatment (3, 6, and 9 percent) on specimens molded near optimum moisture content for the untreated material. The necessary sensitivity to measure effects of minute changes in specimen constituents is available in newly developed apparatus (25). Tensile strengths are also greatest for 1 percent lime treatment at w greater than 40 percent, exceeding that for the untreated specimen at 40 percent w by 100 percent.

Indirect tensile strength data by Kennedy and Moore (26) were taken on a marl clay containing illite, montmorillonite, and kaolinite (in proportions of 5:3:1). Although the data for specimens cured for 3 weeks at 5 C are not strictly comparable, they are the only other published work available. Analysis of w versus tensile strength for the 50 percent clay-content specimens, molded at w near 18 percent PL, provided conclusions comparable to those of Verhasselt (23). In proportion to higher clay-content percentages, strengths increased with increasing lime treatment level but at a de-

creasing rate of gain. Indirect tensile testing method is not easy to use with  $w$  much above PL; therefore, no higher  $w$  data are reported. Extrapolation of the curves plotted from the tabulated data indicates that higher strengths would occur with higher  $w$ .

Higher temperature data from the curing of treated specimens (24, 26) show similar tensile strength response to the 1 percent lime treatment. Optimum lime percentages, giving maximum cured strengths, are 5 percent or more. The trend is toward lower strengths for treatments above the optimum amount of lime.

One may then correctly conclude that commonly found constituents in expansive and nonexpansive clayey soils are amenable to immediate amelioration by relatively low lime percentages. However, in design, one should consider the longer term effects of the variables involved: the immediate effects of clay and organic matter content percentages and their bearing on cured strengths.

Higher strengths for 1 percent lime treatment may be accounted for by the additional strength of lime-flocculated structures as compared to the dispersed structures for untreated clay. This is indicated also at higher water contents by the higher strengths that occur at still higher void ratios, suggesting the fuller development of edge-to-face bonds with increased  $w$ .

The concept that increased macroporosity in clayey soils occurs with increased lime follows directly from the flocculating effect of lime on loess soils and the consequent increase of void ratio. Higher flocculated structure strengths, indicated by increased tensile strength, are also associated with higher PL, increased CBR, and cohesiometer measurements; higher interparticle bond strengths are developed. The influence on the PL may be noted by considering those physicochemical phenomena that operate in the system with decreasing  $w$  as the specimen is remolded to smaller diameters. Decrease in  $w$  alone leads to a decrease in soil-water tension, associated with decreased numbers of interparticle menisci, which may lead to a decrease in strength.

On the other hand, there is the concomitant increase in cation concentration with reduction in  $w$ . The resulting reduced interparticle repulsion that leads to the flocculated structure may compensate for the loss in menisci with increased strength. This, of course, leads to crumb development, which is seen in the breakup of the  $\frac{1}{8}$ -in. -diameter bead in the rolling- and drying-out process at the PL. This clearly demonstrates the greater strength of the flocculated structure in the crumbs or clods that form in the bead as compared to that of the soil-water continuum that preserves the stable cylindrical specimen geometry at  $w > PL$ .

#### REFERENCES

23. Verhasselt, A. La stabilité des grumeaux de sols traités à la chaux. La Technique Routière, Vol. 18-1, 1973, pp. 25-36.
24. Glenn, G. R. Physicochemical Factors Related to Design of Lime-Treated Soil. Presented to HRB Committee on Lime and Lime-Fly Ash Stabilization, HRB 50th Annual Meeting, 1971.
25. Glenn, G. R. Direct Tensile Strength Measurements of the Physicochemical Effects of Stabilizers on Clayey Soils. In preparation for publication.
26. Kennedy, T. W., and Moore, R. K. Estimation of Indirect Tensile Strengths for Lime-Treated Materials. Highway Research Record 351, 1971, pp. 66-77.

#### AUTHOR'S CLOSURE

The influence of  $-2\mu$  clay content and organic matter content on unconfined compressive strength and that of lime consumption on mixtures of illite-containing loess soils with lime are, as Glenn states, very important. Development of cured strength is retarded, not prevented, by organic matter. The delay during which unconfined com-

pressive strength does not progress much may amount to several months at 20 C. This delay may lead to consideration of some soils that respond normally to lime in immediate amelioration as unfit for long-term stabilization. This conclusion may be sound from a practical viewpoint when a fairly rapid increase in strength is desired; however, after the delay period, during which harmful organic constituents are destroyed, strength increase is resumed, provided enough lime is still available.

An important feature of the retarding action of organic matter is the content in "blocked" nitrogen compounds (compounds, not immediately attacked by lime, with no ammonia being given off by fresh lime-soil mixture). However, these compounds become unblocked during the curing period, and while unconfined compressive strength gain is retarded, ammonia is emitted by the cured specimens. The blocked nitrogen compounds are not eliminated by hydrogen peroxide, and as a consequence partly escape the organic matter determination with  $H_2O_2$ . However, the  $H_2O_2$  treatment does unblock these compounds, that is when the  $H_2O_2$ -treated soil is mixed with lime, it immediately emits ammonia. A 0.1 percent nitrogen soil content (determined by Kjeldahl attack) has been found to be effective in producing the described phenomena.