enough to use Coulomb's development for active pressure, but for passive pressure the combination log spiral-plane shearing surface should be assumed."

PROF. G. P. TSCHEBOTARIOFF, *Princeton University:* My general impression is favorable, although similarly to Professor Kimball, I feel that this "Summary" appears to have gone far beyond the scope of stress distribution studies. In fact, the majority of phases of applied soil mechanics have been touched upon. The question arises whether it is advisable in a necessarily abbreviated form. In the affirmative, a very careful study of all details would have to be undertaken.

RESEARCH ON SOIL STABILIZATION

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SYNOPSIS

On most of the highways in China which were designed and built for the light traffic before the war and on those which have been hastily built during the war to keep pace with the needs of military operations, the road surfaces have proven to be inadequate to carry the continuously increasing, heavily-loaded truck traffic. On some stretches of the highways which are of considerable military importance the maximum daily traffic is over 1,000 vehicles, of which 85 to 90 per cent are trucks.

It is apparent that, by improvement of the existing road surfaces of the 10,000 miles of trunk military highways, millions of dollars could be saved annually by reduction of gasoline consumption, tire wear, replacement of spare parts, depreciation, and other factors pertaining to the cost of vehicle operation and road maintenance Owing to the necessity of improving the highways, the National Tsing Hua University has been co-operating since December 1939, with the Bureau of Highways of the Ministry of Communications in carrying out an extensive highway research project in which soil stabilization is one of the most important problems.

In dealing with the specific problems in accordance with the prevailing local conditions there are some differences which must be borne in mind, but the underlying principles of soil stabilization are the same One of the main differences is to obtain immediately a serviceable surface course, while the prevailing practice in the United States is to use a stabilized base course which, sooner or later, will be surfaced. Economic conditions in China will prevent improvement to a higher type of surface in the near future. In addition to the use of soil stabilization in its strictest sense, the soil binder of clay-bound macadam surfaces, which are the typical type of road surface in China, must also be stabilized Although the clay-bound macadam is an all-weather surface, it tends to become dusty in dry weather and muddy in rainy seasons

Another difference is that use must be made of cheap, local stabilizing agents, such as burnt-clay, quick lime, cinders, tung-oil, etc., instead of cement, asphalt emulsion or oil, tar, calcium chloride, sodium chloride, etc , which are commonly used in the United States Research work on soil stabilization has been carried on under adverse conditions and must be strictly limited to local materials. The application of the science of soil stabilization will mark a new era in road-building in China.

NECESSITY OF SOIL STABILIZATION

Roads in China fall, generally, into five types: earth, sand-clay, gravel, untreated macadam and bituminous surface treatment, with the earth and untreated macadam predominating. When both the soil and climatic conditions are excellent, an earth road under constant maintenance may serve light traffic during most of the year; otherwise it will be exceedingly rough and dusty in dry weather and almost impassable during the rainy weather.

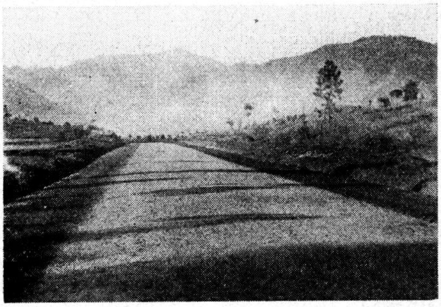

Figure 1. Typical Clay-Bound Macadam Surface, 20 Feet Wide with 5-foot Shoulders

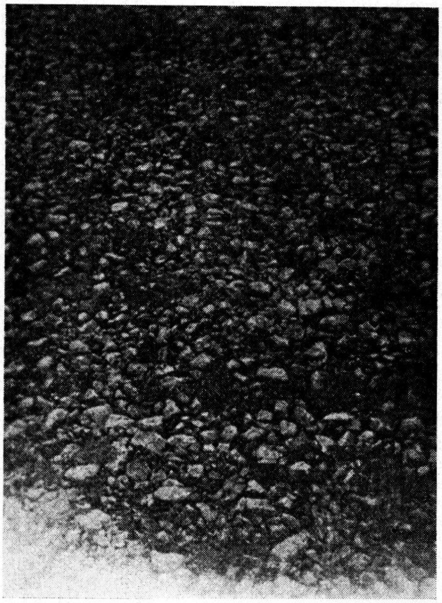

Figure 2. Typical Clay-Bound Macadam Surface: Close View

The untreated macadam is a clay-bound macadam. Since clay borrow-pits are usually available, clay is naturally the cheapest binder material in general use. Heavy roller equipment is limited, and as a result most of the road surfaces have never been thoroughly rolled and are later compacted by traffic. It is apparent that in the early stage there is a high percentage of voids, which must be filled with an excessive amount of clay binder. When it rains the clay is squeezed out to the top of the surface and forms a layer of mud. Although it is passable to traffic, it is quite slippery and the tractive resistance is greatly increased. In dry weather when the binder dries out, the surface becomes dusty. Figure 1 shows a typical clay-bound macadam surface under proper maintenance and Figure 2 shows a close view of the same type of surface.

Since most of the roads have been constructed before and during the war to meet the needs of a national defense plan, economic conditions will prevent change to a higher type of surface for the duration. In a few instances where the road is of strategic importance, it has been or will be paved regardless of cost. Until the time when those road surfaces can be built up to a higher type, they can be most economically improved by soil stabilization.

STABILIZATION OF CLAY BINDER

A good binder of untreated macadam surface must have a high binding strength to cement the interlocking broken stone into a solid mass and must not be affected by changes in moisture content as produced by the cycles of the climate. Clay usually possesses sufficient binding strength when it contains a proper amount of moisture. The stabilizing property of clay depends on its chemical and mineralogical composition, and on the grading and the orientation of its particles. The worst condition is that in which the clay slakes in water and loses completely its cementing property.

If the clay binder could be stabilized so that it would not slake in water and would retain its original binding power, the surface would approach a permanent state. The following test program was worked out to study these characteristics of a good binder.

Test Program

One of the important tests was a study of the cementing property of binder. It was found that the standard cementing value test (1, 2)[1] was particularly useful in this investiga-

[1] Numbers in parentheses refer to the list of references at the end of the paper.

tion although it has become obsolete in the United States. A ball grinding mill is used to pulverize the soil, and a briquette-making machine is used to mold the specimen from the soil fraction passing No. 40 sieve into a cylinder 2½ centimeters high and 2½ centimeters in diameter under a pressure of 132 kilograms per square centimeter. Figure 3 shows the details of a cementation testing machine which registers the number of blows of a 1-kg. hammer under a constant fall of 1-cm. necessary to crack the specimen.

Test specimens for both the wetting and drying test and the optimum moisture content test were made in exactly the same manner as those for the cementing value test. The wetting and drying test was made in four cycles to determine the durability of the binder. The wetting was done by immersing the specimen in water at room temperature for 18 hr. and the drying was done in a constant temperature of 300 deg. F. for 8 hr. (3). The use of small-size specimens for the optimum moisture content test greatly expedited the work and gave an approximate result which was considered close enough in this study. Molding the specimen under a pressure of 132 kg. per sq. cm. might duplicate more closely the partially-compacted surfaces by flat rollers while the tamping compaction of the Proctor Method (4) was aimed to duplicate the effect of sheep foot rollers.

Other important tests of physical constants of soil, such as liquid limit, plastic limit, mechanical analysis, etc., were also used in connection with this investigation (5). Figures 4, 5 and 6 show how the standard soil tests were made in China.

Stabilized Lime and Burnt-Clay Binder

Burnt-clay was used in the United States to stabilize earth roads as early as 1890 in Philadelphia (6) and research was later done in 1904 by the U. S. Office of Public Roads (7). Burnt-clay for soil stabilization has also been used in Australia, India and other countries. Experience in the use of burnt-clay on roads in Australia has shown that heat treatment is suitable for soils of a high clay content, provided the clay has suitable refractory values (8).

The theory of burnt-clay stabilization is that the clay fraction of soil undergoes both physical and chemical changes during the heat treatment. Its well-known sticky or plastic quality is destroyed, so that even in the wettest weather it will bear traffic. Soil is a complex mixture of silica, alumino-silicates, hydrated oxides, salts, organic matter and water. It consists of variable fractions of

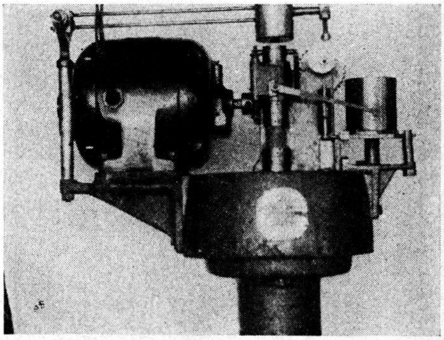

Figure 3. Cementation Testing Machine

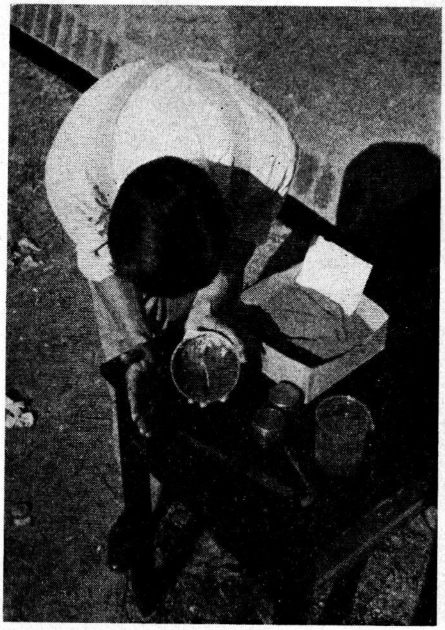

Figure 4. Liquid Limit Test (Hand Method)

sand, silt and clay. In the ordinary range of heat treatment from 400 to 700 deg. C., the sand fraction is not affected.

The first result of heat on the clay fraction is the loss of water. Water mechanically held in voids of the soil is first driven off below 100 deg. C. and adsorbed water which is held by forces at the surfaces of the soil grains is removed between 100 and 400 deg. C. Between 400 and 700 deg. C. the crystal lattice structure of the clay minerals is broken down, the OH ions in the empirical formulae of clay minerals, $Al_2O_3 \cdot ySiO_2 \cdot xH_2O$, interact to form water, and

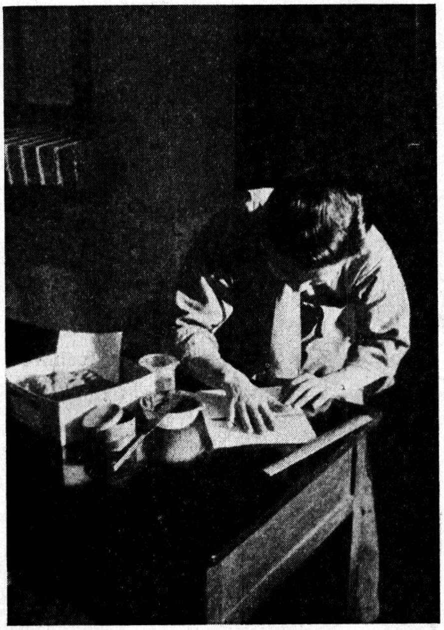

Figure 5. Plastic Limit Test

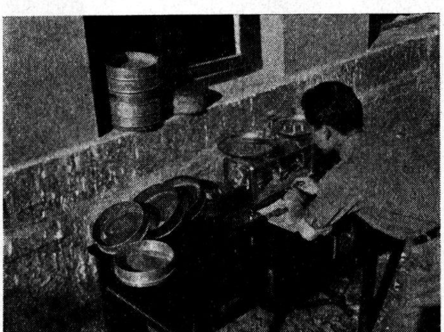

Figure 6. Mechanical Analysis

heat is absorbed. After the loss of OH ions at this dehydration temperature, free alumina and silica are probably formed. At temperatures above the dehydration point alumino-silicates will be formed. The binding strength and water resistance of the final burnt-clay product will depend on the time and temperature of heating. The longer the time and the higher the temperature of heating, the better will be the product. In practice, the highest temperature and longest time of heating should be used in conformity with the furnace capacity and fuel cost (9).

In the study of the use of burnt-clay and lime as a binder (10), both materials were obtained from local kilns in the vicinity of Kunming. The burnt-clay was a typical, local red clay, burned in a kiln at an approximate temperature of 300 deg. C. and had the characteristics according to the chemical and physical analysis shown in Table 1. The lime is in lump form and contains a relatively high percentage of underburnt matter. Table 2 shows the properties of the lime.

Table 3 gives the results of mixing burnt clay with various proportions of lime. It seems that lime has a tendency to increase the cementing value and to decrease the loss by the wetting and drying test. The cementing value of more than 25 for stone dust in water-bound macadam was considered fair in the early days when water-bound macadam surfaces were popular in the United States (12), but a higher cementing value should be required for the soil binder of clay-bound macadam to counteract the effect of less compaction of this type of surface. An arbitrary value of more than 75 would be logical.

It is apparent that by comparison of burnt-clay with and without lime, burnt-clay itself had sufficient binding strength as well as non-slaking stability. It would not be necessary to incorporate any lime with burnt-clay as a stabilizing binder. Furthermore, since burnt-clay could be made cheaper than lime, it would not be economically justifiable to add any lime.

Stabilized Lime and Raw Clay Binder

The raw clay used in this experiment was the same typical red clay prevailing in the vicinity of Kunming. Table 4 gives the summary of the test results of the stabilized lime and raw clay binder (13).

Raw clay is a very unstable material and slakes almost instantaneously when it is immersed in water. In spite of the fact that raw clay had a higher cementing value than burnt-clay, it should be stabilized before its use as a road binder. By increasing the amount of incorporation of lime with raw clay, the stability was not reached until 7½ per cent of lime was added. In other words, with this particular clay, the proportion of the mixture would be one part of lump lime to

TABLE 1
CHEMICAL AND PHYSICAL ANALYSIS OF BURNT CLAY

Chemical Analysis	Per cent	Physical Analysis	Per cent
SiO_2	55	Liquid Limit (Hand Method)	62
FeO	12	Plastic Limit	58
Al_2O_3	23	Plasticity Index	4
MgO etc.	10	Optimum Moisture Content	48 1
		Wetting and Drying	2.5
		Cementing Value	90

TABLE 2
LIME ANALYSIS

Specific Gravity	2 50	Liquid Limit (Hand Method)	60
Voids, per cent	18	Plastic Limit	41
Surface Moisture, per cent	7	Plasticity Index	19
Absorption (46 days) per cent	32	Field Moisture Equivalent	65
Slaking Value	Over 1 month	Shrinkage Limit	54
Wetting and Drying		Shrinkage Ratio	1
Four Cycles, per cent	2 6	Apparent Specific Gravity	2.14
Fifteen Cycles, per cent	3 4	Volumetric Change	7
Cementing Value	17	Lineal Change	3

This cementing value was tested by a special portable impact machine designed by the author, with a hammer weighing 1 kilogram under a constant fall of 2½ cm. The height of fall can be set up to 50 cm The equivalent value on the standard cementation testing machine would be up in thousands (11).

TABLE 3
TEST RESULTS OF LIME AND BURNT-CLAY

Type of Binder	Liquid Limit (Hand Method)	Plastic Limit	Plasticity Index	Optimum Moisture Content (per cent)	Cementing Value	Wetting and Drying (per cent)
Burnt Clay	62	58	4	48 1	90	2 5
With 2 per cent Lime	64	45	19	48 5	110	2 1
With 4 per cent Lime	68	47	21	48 0	110	2 0
With 6 per cent Lime	70	49	21	51 0	220	1 9
With 8 per cent Lime	75	51	24	50.9	290	1.7
With 10 per cent Lime .	77	54	23	52 2	400	1 1

TABLE 4
TEST RESULTS OF LIME AND RAW CLAY

Type of Binder	Liquid Limit (Hand Method)	Plastic Limit	Plasticity Index	Optimum Moisture Content (per cent)	Cementing Value	Wetting and Drying (per cent)
Raw Red Clay	60	34	26	27 3	490	100
With 2½ per cent Lime	61	35	26	28 5	680	100
With 5 per cent Lime	61	37	24	27 7	1150	100
With 7½ per cent Lime	61	37	24	31 5	5050	6 6
With 10 per cent Lime	62	38	24	30 7	over 6000	6 1

nine parts of raw clay by weight to ensure the stability of the binder. By stabilizing clay with lime, it would be still cheaper than to use burnt-clay alone. Stabilization of raw clay by burnt-clay would be another solution.

Consistency of Lime-Clay Grout

The lime-clay grout used on lime-clay-bound macadam should have a proper consistency to ensure the proper penetration. The flow cone used by the Portland Cement Association for testing the consistency of cement grout in cement-bound macadam was found adaptable in this experiment (14) The details of the flow cone and the method of test are well understood and need no further explanation. The lime-clay grout was made by mixing 2970 g. of clay with 330 g. of lump lime, and water was added in increments as shown in Table 5 (15).

A consistency of between 21 and 23 and between 23 and 25 was usually specified for the cement grout for 1½ inch–2½ inch and 2 inch–3 inch aggregates respectively (16). If the consistency were to hold true in both cases, the lime-clay grout would require approximately 74½ per cent of water by weight The exact amount of water to be added should be determined in the field

SOIL STABILIZATION BY LIME

In 1924 the U. S Bureau of Public Roads in conjunction with the State Highway Departments of Iowa and South Dakota, and the National Lime Association cooperating with the University of Missouri, undertook investigations of the effect of lime in earth roads Tests were made in the field and in the laboratory over a period of two years. The results of this study showed that lime had a tendency to reduce the formation of mud and ruts and to prevent the surface stickiness under wheels Maintenance could be more easily accomplished because there was no formation of the hard crust on the surface before the road was sufficiently dry for dragging It seemed that the dust nuisance was not by any means reduced; in some cases it might be increased. Field practice indicated that between 2½ per cent and 4 per cent of hydrated lime would be enough in most cases. A treated depth of 6 in was recommended although no marked difference appeared in the results brought about by the various depths of incorporation (17, 18).

TABLE 5
CONSISTENCY OF LIME-CLAY GROUT

Percentage of Water By Weight	Fluidity of Grout (Seconds)
70	41 3
71	35 6
72	33 6
73	32 0
74	29 0
75	19 4
76	19 2
80	18 9
90	16 0
100	15 3
110	14 9

A more recent laboratory study on soil stabilization by lime was made and published by the National Lime Association in 1940. Much higher stability was obtained by incorporation of 5 per cent of hydrated lime with clay. From this investigation of the use of hydrated lime in stabilizing clay for roadbeds, the following procedure is indicated. first, the clay should be mixed intimately with about 2 to 10 per cent of hydrated lime (dry-weight basis) and, with the optimum percentage of moisture present, the roadbed should be thoroughly rolled; second, the roadbed should be covered with the asphaltic topping as soon as possible to prevent evaporation of the water and thus stop the exchange adsorption between the lime and the clay. The topping will retain permanently the moisture in the lime-treated, clay roadbed (19).

In India and Burma where molasses has been used as a soil stabilizing agent it has been claimed that the incorporation of lime would prevent the washing off of molasses during the rains. Molasses has a great hygroscopic property to keep moist and an adhesive quality to act as a good binder, while the chemical action of lime with molasses produces tricalcium sucrate which is insoluble in water (20, 21)

Investigation on stabilization by lime in the National Tsing Hua University was made on silty soils prevailing in the northwestern part of China Artificial silty soils were prepared from two different local soils in the vicinity of Kunming. Table 6 gives the results of mechanical analysis by the combined sieve and hydrometer method and also the physical constants of these soils (22).

The mechanical analyses of soils, divided into six groups according to the size of the particles as shown in Table 6, are based on the standard classification by the Bureau of Public Roads (23). According to the recently proposed classification of materials for subgrades and granular type roads by Hogentogler and Barber, these soils will probably fall within the limits of the new A-4-7 Group which is a moderately plastic, silt and clay-soil mixture They may be susceptible to frost and softening due to moisture penetration, and sub-bases are needed for prevention of loss of stability during thaws The maximum liquid limit is 40 and the plasticity index is less than 0.4 of the liquid limit with 0 2 of the liquid limit as the minimum (24).

Table 7 gives a summary of the results of the wetting and drying test (8 cycles) of the effect of incorporation of various proportions of lime and cement with these soils under consideration. Cement was used as a standard for the purpose of comparison. It can be shown that cement was a better stabilizing agent than lime, particularly in small proportions of incorporation. The amount of incorporation of lump lime with silty soils should be well over 10 per cent.

In order to get some idea of the abrasive value of these treated silty soils which might be used as a temporary surface course for light traffic, the old standard Dorry Hardness Machine (Fig 7) (25) was utilized to make a comparative study. As shown in Table 8, with the incorporation of up to 15 per cent of either lime or cement, the coefficient of hardness was a negative value; that is, the average loss of the specimens was more than 60 grams.

TABLE 6
MECHANICAL ANALYSIS AND PHYSICAL CONSTANTS

	Grain Size (mm)	Mechanical Analysis						
		X	Y	A	B	C	D	E
		Fractions						
		Soil	Soil	90%X 10%Y	80%X 20%Y	70%X 30%Y	60%X 40%Y	50%X 50%Y
Coarse Material, per cent	above 2	0	0	0	0	0	0	0
Coarse Sand, per cent	0 42 -2 0	5 7	0	5 1	4 6	4 0	3 4	2 8
Fine Sand, per cent	0 05 -0 42	38 3	6.0	35 1	31 8	28 6	25 4	22 2
Silt, per cent	0 005-0 05	56 0	70 0	57 4	58 8	60 2	61 6	63 0
Clay, per cent	below 0 005	0	24 0	2 4	4 8	7 2	9 6	12 0
Colloidal Clay, per cent	below 0 001	0	0	0	0	0	0	0
Physical Constants								
Specific Gravity		2 33	2 39					
Liquid Limit (Mechanical Method)		28	55	32	33	36	39	41
Plastic Limit		23	31	25	25	26	27	27
Plasticity Index		5	24	7	8	10	12	14
Optimum Moisture Content, per cent		16 0		16 7	17 2	17 9	19 7	20 6
Maximum Density (lb per cu ft)		115 6		116 9	120 9	121 5	117 3	114 7

TABLE 7
DURABILITY TEST OF LIME AND CEMENT STABILIZATION

Percentage of Incorporation	A 90%X 10%Y		B 80%X 20%Y		C 70%X 30%Y		D 60%X 40%Y		E 50%X 50%Y	
	Lime	Cement	Lime	Cement	Lime	Cement	Lime	Cement	Lime	Cement
3	100	29 4	60	9 3	4 5	3 1	9 9	1 2	100	4 2
6	40	25 8	19 4	7 5	2 8	2 2	1 4	0 5	4 6	1 6
9	13 5	17 7	5 7	6 3	1 0	1 7	0 8	0 4	0 3	0 4
12	4 4	14.0	3 1	4 1	1 0	1 3	0 7	0.3	0 2	0 3
15	0 5	5 0	0 2	0 8	0 6	0 9	0.2	0.2	0 2	0 1

SUMMARY

No attempt has been made to draw any definite conclusions from this laboratory study on soil stabilization by either burnt-clay or lime at the present time. There is much need for further laboratory investigation, as well as experimental road study, before this work could be applied in the field on a large scale. There is, however, every reason to believe from this study, as well as from experiences at other places where such treatments have proven successful to some extent, as mentioned herein, that both burnt clay and lime have stabilizing effects as water-repellents in some types of the soils

From this study it has been found that by incorporation of lime with clay binder, clay-bound macadam surfaces could be most economically stabilized It might not be necessary to treat the entire thickness of an 8-in clay-bound macadam surface, and this would mean that the cost could be further reduced The amount of incorporation of lime with clay and the thickness of treatment required would vary with various types of soils, climatic conditions and densities and classes of traffic, and should be determined in each case.

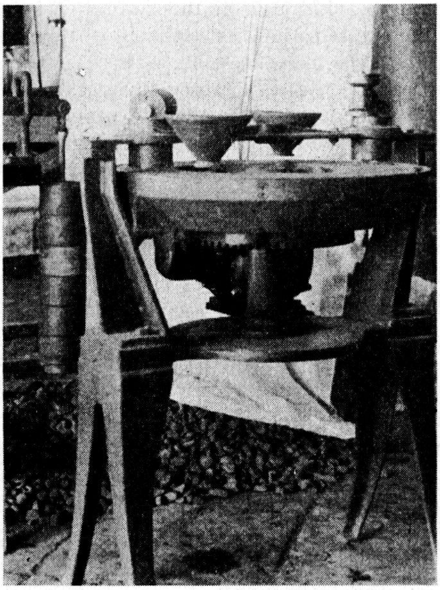

Figure 7. Dorry Hardness Machine

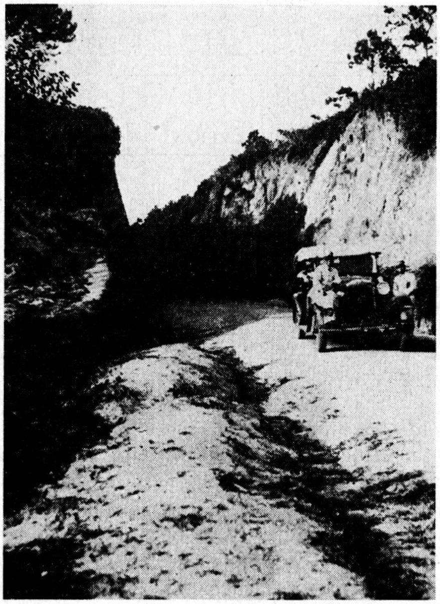

Figure 8. A Typical Open-Cut Earth (Loess)-Section in China

Stabilization of earth roads by lime treatment seemed promising on certain types of soils, such as the silty soils used in this experiment. The general practice of 6-in. treatment in soil stabilization would seem to be necessary, and the amount of lime required would depend upon the actual field conditions. Further study of this subject should be made to determine the feasibility of lime stabilization on other types of soils.

Figure 9. A Typical Rock-Cut Section of the Burma Road

TABLE 8
HARDNESS TEST OF LIME AND CEMENT STABILIZATION

Per cent of Incorporation	Coefficient of Hardness	
	Lime	Cement
3	0	0
6	0	0
9	0	0
12	0	0
15	0.4	3.4

BIBLIOGRAPHY

1. Devised and Perfected by Logan Waller Page.
2. A. Black: "The Laboratory for the Testing of Road Materials at Columbia University with Observations on Current Prac-

tice," School of Mines Quarterly, Vol. 26, No. 2, Jan. 1905.
3. W. H Mills, Jr: "Stabilizing Soils with Portland Cement, Experiments by South Carolina Highway Department," *Proceedings*, Highway Research Board, Vol. 16, 1936, pp. 322–349.
4. R. R Proctor: "Fundamental Principles of Soil Compaction," *Engineering News-Record*, Vol. 111, Nos. 9, 10, 12, 13, Aug. 31, Sept. 7, 21, 28, 1933.
5. A.A S.H.O.: Standard Specifications for Highway Materials and Methods of Sampling and Testing, 1938 and 1941.
6. "A Move for Better Roads": Essay on Roadmaking and Maintenance, Henry Carey Baird & Co., Philadelphia, 1891, p. 166
7. William L Spoon: "The Construction of Sand-Clay and Burnt-Clay Roads," Office of Public Roads Bulletin No. 27, 1906
8. Garland, Gawith, Loxton & Paterson: "Road Construction by the Heat Treatment of Surface Soils," Permanent International Association of Road Congress No 80, 1938
9. G. W. Eckert· "Soil Stabilization by Heat Treatment," *Chemistry and Industry*, Vol 58, No. 37, Sept 16, 1939, pp. 846–851
10. M. C. Li: "Stabilized Lime and Burnt-Clay Binder," Highway Engineering Experiment Station Report, National Tsing Hua University, Vol. 1, No. 1, Feb. 1940.
11. M. C Li: "A Simple Portable Impact Machine for Testing Roughness of Stone and Cementing Value of Binder" Highway Engineering Experiment Station, National Tsing Hua University, 1940.
12. E. E. Bauer: Highway Materials, 1932, pp. 149–152
13. M. C. Li: "Clay Binder Stabilized by Lime," Highway Engineering Experiment Station Report, National Tsing Hua University, Vol. 1, No. 2, March 1940.
14. Portland Cement Association: Cement-Bound Macadam.
15. M. C. Li: "Consistency of Lime-Clay Grout in Lime-Clay-Bound Macadam Surfaces," Highway Engineering Experiment Station Report, National Tsing Hua University, Vol. 1, No. 3, April 1940.
16. A. G. Bruce· Highway Design and Construction, 1937, pp. 370–375.
17. E. J McCaustland: "Lime in Dirt Roads," *Rock Products*, Vol. 28, No. 18, Sept. 5, 1925, pp 63–4, *Pit and Quarry*, Vol 10, No 5, June 1, 1925, pp. 93–5.
18 Out of the Mud with Lime, National Lime Association, Bulletin No 317, 1926
19 Sherman D Lesesne: "Stabilization of Clay Roadbeds with Lime," National Lime Association, Bulletin No. 325, 1940.
20. Diwan Bahadur, N. N. Ayyangar and J. Bakshi: "Examination of the Subsoil of Roads," Permanent International Association of Road Congress No 87, 1938.
21. Sugar Coated Roads in British India, *Contractors and Engineers Monthly*, May 1936, p. 29
22 P. T. Chen: "Soil Stabilization by Lime and Cement," Highway Engineering Experiment Station Report, National Tsing Hua University, Vol. 2, No. 3, August 1940
23. C. A. Hogentogler: Engineering Properties of Soil, 1937, pp 20–21.
24. Thickness of Flexible Pavements for Highway Loads, Wartime Road Problems No. 8, Highway Research Board, 1943.
25 Developed in the French School of Bridges and Roads and Later Modified.