PAPER No. 383

Experimental Use of Hydrated Lime in Road Construction

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The vast alluvium of West Pakistan which has been classified as recent and sub-recent deposits in the regional geology, normally provides the predominant soils for road construction. The engineering properties of these soils can be improved by stabilization with hydrated-lime for sub-base and in some rare cases, surface courses. For primary roads, lime stabilization is generally carried out in sub-grades and sub-bases whereas for secondary roads it may be used for base courses as well. Since the use of lime is restricted to warm or moderate climates, as the lime-stabilized soils are susceptible to breakup under freezing and thawing, the process can be used profitably in temperate zones of West Pakistan.

The quality of lime as stabilizer has been determined by means of laboratory tests on molded, soaked and cured samples which simulate field conditions of weathering and other durability processes. The representative soil sample was used for the soil-lime admixtures wherein the lime was used up to 10 *percent. These soil admixtures were tested for plasticity, density, volume changes, compressive strength and C.B.R. values. An analysis of the test results shows that* 5 *percent hydrated lime is the optimum value for soil stabilization in road construction. These results clearly indicate that the engineering properties of these alluvial soils undergo a transitional change at* 5 *percent hydrated lime for the soil under test.*

The results of these investigations were applied for the construction of base courses in various experimental roads which have stood well under heavy vehicular traffic.

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1. GENERAL

The vast alluvium of West Pakistan which has been classified as recent and subrecent deposits in the regional geology normally provides the predominant soils for roads construction. The engineering properties of these soils can be improved by stabilization with hydrated lime for sub-base, base and in some rare cases, surface course. For primary roads, lime stabilization is generally carried out in sub-grades and sub-bases whereas for secondary roads it may be used for base courses as well. Since the use of lime is restricted to warm or modrate climates, as lime stabilized soils are susceptible to breakup under freezing and thawing, the process can be used profitably in temperate zones of West Pakistan.

The soil stabilization, in general, implies improvement in both strength and durability. In its earlier stages, the terms stabilization signifies improvement in a qualitative sense only but more recently it has become associated with quantitative values of strength and durability which are related to performance. These quantitative values are exposed in terms of compressive strength, shear strength, volume changes, load-bearing qualities, absorption, softening and resistance to wetting and drying to indicate the durability of the stabilized construction. The soils may be improved by mechanical, chemical, portland cement, bituminous and electrical stabilization. The chemical stabilization includes (*a*) lime and lime with other puzzolana additions, such as lime-flyash, lime-cement and lime-bitumen, (*b*) calcium chloride, (*c*) sodium chloride (*d*) resins, (*e*) lignin, (*f*) sodium silicate and (*g*) molasses.

2. TYPE OF LIME

Lime, when strictly defined, is calcium oxide (CaO) but as commonly used, the term indicates forms of quicklime and hydrated lime, which are oxides and hydroxides of calcium or calcium-magnesium.

(*a*) Quick lime, Calcium Oxide (CaO).

Commercial lime is manufactured by heating a crushed carbonate rock such as limestone ($CaCO_3$) to above 1000°C or 2000°F, causing release of carbon dioxide CO_2, and leaving the high-calcium *i.e.*, lime or CaO

$$CaCO_3 = CaO + CO_2$$

a second type of carbonate rock termed dolomite is often used for lime manufacture. Dolomite consists of equal molar parts of $CaCO_3$ and $MgCO_3$. The resulting lime called dolomitic lime, is a mixture of CaO and MgO.

Two types of kilns are used (*i*) the older type which is intermittent in operation and is rather wasteful in fuel though very cheap to instal, (*ii*) the modern or shaft kiln which is continuous in operation. The crushed limestone gradually works its way down the kiln, which is heated by producer gas and is converted to lime which is removed at the bottom.

(*b*) Hydrated lime (slaked lime), Calcium Hydroxide. Ca $(OH)_2$

Quicklime has a great affinity for water. It reacts with water at ordinary temperature. Thus when quicklime (CaO) is moistened with water as

$$CaO + H_2O = Ca(OH)_2$$

a hissing sound is produced, much heat is generated, a portion of water escapes as steam and after addition of the requisite quantity of water, quicklime swells up, cracks and falls to dry white powder. The powder is called hydrated or slaked lime, when left exposed to the atmosphere, it absorbs CO_2 and is converted into calcium carbonate.

The ASTM, specifies the classification of lime and direction for slaking of quicklime. To quote it adverbatum, it runs as follows:—

Classification of Limes

In a bucket, put two or three lumps of lime about the size of one's fist, or, in the case of granular lime, an equivalent amount. Add sufficient water to just barely cover the lime, and note how long it takes for slaking to begin. Slaking has begun when pieces split off from the lumps or when the lumps crumble. Water of the same temperature should be used for test and field practice.

If slaking begins in less than 5 min., the lime is quick slaking; from 5 to 30 min., medium slaking; over 30 min, slow slaking.

Directions for Slaking

For quick slaking lime, always add the lime to the water not the water to the lime. Have sufficient water at first to cover all the lime completely. Have a plentiful supply of water available for immediate use a hose throwing a good stream, if possible. Watch the lime constantly. At the slightest appearance of escaping steam, hoe thoroughly and quickly, and add enough water to stop the steaming. Do not be afraid of using too much water with this kind of lime.

For medium slaking lime, add the water to the lime. Add enough water so that the lime is about half submerged. Hoe occasionally if steam starts to escape. Add a little water and then if necessary to prevent the putty from becoming dry and crumbly. Be careful not to add any more water than required, and not too much at a time.

For slow slaking lime, add enough water to the lime to moisten it thoroughly. Let it stand until the reaction has started. Cautiously add more water, a little at a time, taking care that the mass is not cooled by the fresh water. Do not hoe until the slaking is practically complete. If the weather is very cold, it is preferable to use hot water but if this is not available, the mortar box may be covered in some way to retain the heat.

The AASHO specified that the hydrated lime shall conform to the requirements of ASTM C 207, type N. The type N has been defined as normal hydrated lime for necessary purposes. The chemical composition of hydrated lime shall conform to the following:—

Calcium and Magnesium oxides	.. 95 percent Min.
Carbondioxide:—	
If sample is taken at the place of manufacture	.. 5 percent Max.
If sample is taken at any other place	.. 7 percent Max.
Unhydrated oxides	.. 8 percent Max.

The standard hydrated lime has 99 percent passing No. 30 sieve and 90 percent passing No. 200 sieve (ASTM).

3. MECHANICS OF LIME STABILIZATION

When hydrated lime is mixed with moist soil, the following reactions take place.

Aggregation or Flocculation

Lime affects the water film surrounding the soil particles and reduces the plasticity index and linear shrinkage of cohesive soils so that they become more friable and more easily worked. This mechanism is either a cations exchange or a crowding of additional cations on to the clay both processes acting to change the electric charge density around the clay particles. The clay particles then become electrically attached to one another, causing flocculations or aggregation. The clay, now occurring as aggregate, behaves like silt which has a low plasticity or cohesion. Aggregation takes place rather quickly and is caused by addition of only 1 or 2 percent lime. Aggregation lowers the maximum density obtainable with a given compactive effort and increases the optimum moisture content for compaction. The change of plasticity in the soil-lime system is an important phenomenon. It has been observed that for soils having a plasticity index of less than 15, lime increases both the liquid and plastic limit values, which in turn brings about an increase in plasticity index. For the more plastic soils, lime generally decreases the liquid limit and increases the plastic limit which in turn brings about a decrease in plasticity index. But exceptions to this generalization are not rare. Admixtures of lime makes a soil more friable and granular generally.

Soil-lime mixtures have lower compacted densities than those of the natural soil. The decrease in density may be up to 5 percent but there is no decrease in soil strength against the expectations of a casual observer; the specimens kept for a period of time brings about further increase in strength.

(*b*) **Puzzolanic Reactions**

These reactions result in a lower, long-term cementation of compacted soil lime mixtures. These reactions possibly involve interaction between hydrated lime and available silica and calcium (colloidal) to form complicated compounds of calcium silicates and aluminates. This is a form of slow setting cement which continues to gain strength over long periods of time and is commonly referred to as a puzzolanic reaction. The rate of this cementation varies a great deal with the type of soil and climatic conditions. Puzzolanic reactions are greatly accelerated by heat or by the addition of certain chemicals.

(*c*) **Carbonation**

This slow process involves the absorption of atmospheric carbon dioxide so as to react with the calcium hydroxide (hydrated lime) to form calcium carbonate on limestone. The reaction can be represented as

$$Ca(OH)_2+CO_2=CaCO_3+H_2O$$

calcium magnesium carbonates are weak cements and carbonation must be prevented to attain the maximum strength and stability in a road construction job. The hydrated lime should not be exposed unnecessarily to the atmospheric carbon dioxide before its use, undue delay during construction should be avoided and the soil-lime mixtures in the road sub-grade, sub-base and base should be protected against infiltrating carbon dioxide in rain water or surface sprinkling used as a cure. Carbonation danger is most pronounced in industrial areas where CO_2 content of the air may be twice than in the rural areas and the CO_2 content of rain water is sometimes increased several hundred percent.

4. SUITABILITY OF SOIL-LIME SYSTEM

The reaction and suitability of the various types of soil-lime mixtures have been studied in many research organizations and the results obtained therefrom can be quoted as follows:—

(*a*) The lime stabilization is most effective with clay-gravel or gravel-binder mixes. In such mixtures, the plasticity index is considerably reduced with a substantial increase in the compressive strength. This increase is due to the satisfactory gradation of gravel or coarse material with such soils, about 3 percent hydrated lime by weight is required for best results.

(*b*) Lime is also effective with fine-grained and cohesive soils. The over-puzzolanic reaction takes place and the strength of such soils is very much increased. The strength of treated soil keeps on increasing for a period of several months depending on the type of soil and concentration of lime. More lime is required than with gravel-clay binder mixes. The addition of lime makes the clayey soils friable and makes it easier to handle them in the field.

(*c*) Lime is not effective with fine-grained silty and loamy soils as with clays as most silts do not exhibit as much puzzolanic activity with lime as with clayey soils.

(*d*) Lime is not recommended for sandy soil. Although it has some value as a binding agent for sandy soils, it alone is not satisfactory for this purpose as other additions. Moreover there is little or no puzzolanic reaction; however, the addition of clay-lime slurry might stabilize roads satisfactorily.

4. HAZARDS OF QUICKLIME

Although theoretically the use of quicklime is economical on basis of its active ingredient since it contains no water, but quicklime cannot be spread dry because the dust is highly caustic and dangerous to workers. Quicklime when coming in contact with perspiring workers' skin, can cause burns. On a hot windy day pulverised quicklime would be particularly dangerous to apply to a road unless workers are properly protected. On account of these hazards, quicklime is, therefore, hydrated in a tank and sprayed as a slurry. Hydrated lime (in powder form) can be directly purchased in bulks and spread with mechanical spreaders or otherwise purchased in bags and spread by hand or applied in a slurry. As limestone is abundant in West Pakistan, it can be hauled up directly to the site of road project and burnt there in kilns to produce quicklime which can, in turn, be slaked to hydrated lime for use in the soil stabilization.

It may be mentioned here that while slaking the quicklime, the amount of water in a slurry is adjusted to give the optimum moisture content for compaction except that the slurry must be at lowest one-half to two-third free water if it is more easily sprayed. About 70 percent water may be required for sprayable slurries of high-calcium quicklime.

As already mentioned, under carbonation both quicklime and hydrated lime tend to re-carbonate readily by absorbing CO^2 from air and therefore their storage must be in tight containers and under dry conditions. Quicklime ordinarily should not be stored for more than 3 to 6 months, whereas hydrated lime should not be stored longer than about one year. The maximum CO^2

contents specified for quicklime and hydrated lime are 10 to 7 percent respectively.—(A.S.T.M.)

6. LABORATORY TESTING OF SOIL-LIME MIXTURES

The effect of hydrated lime on the engineering properties of soil has been studied by conducting the various laboratory tests including Atterberg Limits, moisture-density relationship, C.B.R. values, volume change and unconfined compressive strength. The laboratory compound soil was selected for this purpose and the tests were performed in the laboratory to determine the extent of improvement in the engineering properties of the representative soil with the addition of hydrated lime in fine state. The soil sample belongs to A-4(8) group as specified by AASHO soil classification system. The results of the laboratory investigations are given as follows:—

(*a*) Effect of Lime on Soil Consistency

The index properties of the soil passing No. 40 sieve were determined by performing the liquid limit and plastic limit tests and the plasticity index of soil was obtained from the values of these tests. The six samples of soil-lime mixtures were prepared by dry mixing of 2, 4, 5, 6, 8 and 10 percent hydrated lime (by weight) and the values of plasticity index for each were determined after conducting the liquid limit and plastic limit tests respectively. From the comparison of soil and soil-lime mixtures it was found that the plasticity index of the soil increases gradually with the addition of lime and attains its maximum value at 6 percent lime and then decreases subsequently. The test results are given in Table I.

TABLE I—*Showing the Results of Atterberg Limits.*

S. No.	Description	Liquid Limit.	Plastic Limit.	Plasticity Index.
1.	Lab. Compound Soil only ..	24.4	17.4	8.0
2.	,, ,, ,, + 2% lime ..	31.7	20.5	11.2
3.	,, ,, ,, + 4% lime ..	33.1	20.9	12.2
4.	,, ,, ,, + 5% lime ..	30.7	18.9	11.8
5.	,, ,, ,, + 6% lime ..	31.6	16.9	14.7
6.	,, ,, ,, + 8% lime ..	30.8	23.3	7.5
7.	,, ,, ,, +10% lime ..	31.1	24.2	6.9

The "flow curves" for Liquid Limit tests are given in Appendix A.

(*b*) Moisture-Density Relationship

Subgrade soil encountered in the laboratory compound, at a depth of 1—2 ft. below the natural surface level, has been selected as a representative subgrade soil sample for the study of hydrated lime treatment and its effect upon the moisture-density relationship. Upon receipt of the subgrade soil sample it was dried in oven for about 24 hours at 140°F, then pulverized to pass No. 4 sieve. A representative sample was taken from this material and routine soil tests, including moisture-density determination, were performed on the subgrade soil sample as prepared in the laboratory.

The subgrade soil sample was compacted in the standard mold to determine the optimum moisture-maximum density relationship according to standard AASHO compaction test. After conducting the tests upon the subgrade soil sample, the value obtained was made as a standard value and the test of the values obtained from the soil-lime mixtures of different percentage were to be compared with it. Upon completion of the test on soil, six soil-lime mixtures were prepared by dry mixing of 2,4,5,6,8 and 10 percent hydrated lime (by weight) with six soil samples previously prepared to pass No. 4 sieve. The standard AASHO compaction tests were then performed on each of the six portions of the soil-lime mixtures to determine the optimum miosture—maximum density relationship as in case of untreated soil sample. The values obtained after conducting the tests upon the soil-lime mixtures, were compared to the values obtained, from the untreated soil sample, previously. From the comparison of these results it has been noted that as greater percentage of hydrated lime is added, the maximum density decreases and the optimum moisture increases.

However, certain variations are also observed as the optimum moisture of soil-lime mixture of 6% lime has abruptly increased while the rest of the numbers have been increasing gradually. Again in case of maximum density it has been observed that the maximum density of the soil-lime mixtures gradually decreases almost up to 8% lime but the addition of 10% lime in the representative sample of soil, the maximum density has been shown to increase instead of decreasing accordingly. The results of all the tests are represented in Table II.

TABLE II—*Showing the Results of Moisture-Density Relationship (Standard AASHO Test).*

S. No.	Description	Maximum dry density in lbs/cft.	Optimum Moisture Content %
1.	Lab. Compound Soil only ..	112.6	15.2
2.	,, ,, ,, + 2% lime ..	109.0	15.3
3.	,, ,, ,, + 4% lime ..	107.3	16.0
4.	,, ,, ,, + 5% lime ..	106.4	17.0
5.	,, ,, ,, + 6% lime ..	104.0	18.5
6.	,, ,, ,, + 8% lime ..	102.0	17.2
7.	,, ,, ,, +10% lime ..	105.4	17.8

The moisture-density curves for standard AASHO are given in Appendix B.

(c) California Bearing Ratio (C.B.R.)

The selected soil sample from the laboratory compound was oven-dried and pulversied to pass No. 4 sieve. A representative soil sample was taken from this material and the proper amount of water, determined from the moisture-density relationship was mixed to obtain the condition of optimum moisture content for maximum density. Immediately after mixing, the moist soil was used for moulding the specimen of 6 inch in diameter and 6 inch in height *i.e.*, in C.B.R. mold. The soil was compacted in C.B.R. mold in five equal layers with a rammer of 10 lbs. weight having a fall of 18". and 55 blows on each layer. The compacted specimen was then subjected to C.B.R. test on a testing machine capable of applying the load at a rate of 0.05 inch per minute through penetration of a circular plunger having an area of 3 square inches. The load applied by the C.B.R. machine was noted for every 0.05 inch penetration and the C.B.R. curve was drawn from the values of loads against penetration. From this curve the C.B.R. value of the representative soil sample has been calculated against 0.1" penetration and the value was recorded as a standard to compare with the values to be obtained from the various soil-lime mixture specimens. On completion of the test on untreated soil sample, six soil-lime mixtures were prepared by dry mixing of 2, 4, 5, 6, 8 and 10 percent hydrated lime (by weight). The predetermined amount of water was then mixed in each of the six soil-lime mixtures, to obtain their respective optimum moisture condition for maximum density. Immediately after mixing, the moist soil-lime mixtures were used for molding the specimens as described above.

Each compacted specimen was then subjected to C.B.R. tests in the same manner as described for untreated soil sample. The C.B.R. curves were drawn for all the specimens from their respective values of load against penetration. The C. B. R. values against 0.1″ penetration for each were obtained. From the study of these results it is obvious that after the treatment of soil with hydrated lime the soil becomes stiffer and consequently yields higher values of C. B. R. A considerable increase of C. B. R. values was obtained by the addition of different percentages of lime. It has been noted that the C. B. R. value after curing at 5 percent lime is quite high. The highest value of C. B. R. at optimum moisture condition, was obtained at 8 percent addition of lime.

Again, these tests were conducted to the soil and soil-lime mixture specimens after curing for seven days by wet-sand. At first the results obtained from untreated soil and soil-lime mixtures were compared. From the comparison, it was indicated that the C. B. R. values obtained from soil-lime mixtures were much greater than that of the untreated soil. It increased successively by the addition of 2, 4 & 5 percent lime in the representative soil sample but reduced abruptly at 6 percent lime addition and then again started to increase yielding maximum value at 10 percent lime. All these values obtained from cured specimens of soil and soil-lime mixtures were then compared to those obtained at optimum moisture condition. It was found that better results were achieved in case of seven days' curing of the specimens, of soil-lime mixtures except that of 8 percent lime. Also the untreated soil specimen after curing gave a better value than that given at optimum moisture condition.

After conducting the tests on optimum moisture and seven days' curing, the specimens of soil and soil-lime mixtures were again prepared under similar conditions. These were placed in a trough of water for soaking. After four days soaking the specimens were taken out from the water and finally subjected to C. B. R. tests, as done before. The values of C. B. R. obtained from soil-lime mixtures, after four days soaking, were compared with the values obtained from that of untreated soil. Also in this case, the soil-lime mixtures yielded higher values than that of the soil specimen. The successive addition of lime gave increasing values except at 5 and 6 percent lime where the values were reduced gradually and then again started to increase so as to reach maximum value at 10 percent addition of lime. It was noted that all these values were individually less than compared to those obtained at optimum moisture and cured for seven days respectively. All the values are given in a table where from the idea of improvement of the soil by stabilizing it with hydrated lime may be obtained. The test results are given in Table III.

(*d*) Volume Changes

Volume changes in the specimens were also noted during the soaking procedure. For this purpose a perforated plate with a handle was placed on the surface of each specimen along with the two slotted weights of 5 lbs. each. The gauges of the order of 0.001″ reading were set upon the arrangement and the initial readings of each were noted down. The swelling action of the soil and soil-lime mixture specimens was carefully noted. The action stopped itself after three days. However, the final readings were noted down after four days just to ensure complete swelling of the specimens, immersed in water. It was observed that the maximum swelling of the specimens was shown at 2 and further at 4 percent lime, with a subsequent increase as obvious from the table. The tesult reslts are given in Table III.

TABLE III—*Showing the Results of C.B.R. Values (at 0.1″) and Volume Changes.*

S. No.	Description	Swelling after 4 days soaking.	CBR values at optimum moisture.	CBR values after 7 days' curing.	CBR values after 4 days' soaking
1.	Lab. Compound soil	0.063″	3.7%	1.3%	1.3%
2.	,, ,, ,, +2% lime ..	0.012″	15.3%	28.7%	10.0%
3.	,, ,, ,, +4% lime ..	0.011″	28.8%	38.7%	15.0%
4.	,, ,, ,, +5% lime ..	0.015″	22.0%	46.3%	10.3%
5.	,, ,, ,, +6% lime ..	0.014″	12.0%	25.3%	8.7%
6.	,, ,, ,, +8% lime ..	0.042″	54.3%	35.3%	20.8%
7.	,, ,, ,, +10% lime ..	0.032″	42.0%	50.0%	21.3%

The test curves are given in Appendix C.

(*e*) Unconfined Compressive Strength

To find the compressive strength of the soil as selected from the Laboratory compound, it was oven-dried and pulverised to pass No. 4 sieve. A representative soil sample was taken and the calculated amount of water, predetermined from the moisture-density relationship, was mixed to obtain the condition of optimum moisture for compacting to maximum density. After mixing, the moist soil was used for molding the specimen according to standard AASHO Compaction test. In the remolded state of soil specimen a number of sampling tubes of 1.5″ dia and having a length of 6″, were inserted in the compacted soil. This was done by applying a uniform load so as to get undisturbed specimen from the mold. The specimens were taken out of the tubes by the help of twister and the plug. The specimen were made to 3″ in length and subjected to the unconfined compression strength tests by using a spring capable of compressing the sample in a longitudinal state at a stretch of 33 lbs. per inch. The samples were tested on an autographic machine meant for unconfined compression tests. After conducting tests the graphs were obtained for each specimen The elongation was measured vertically between the starting and failure points from the graph and then the compressive strength was calculated. On completion of the test of untreated soil, six soil-lime mixtures were prepared by dry mixing of 2, 4, 5, 6, 8 and 10 percent lime respectively with six portions of the soil previously prepared to pass the No. 4 sieve. The predetermined amount of water was then mixed in each of the six lime mixtures to obtain their respective optimum moisture condition for compacting at the maximum density. Immediately after mixing, the moist soil-lime mixtures were used for molding the specimens as described before. Each of the compacted specimen was then subject to unconfined compression tests in the same manner as already stated for untreated soil sample. The compressive strength obtained from soil-lime mixtures were compared to that of the value obtained from untreated soil. All these values were tabulated and from the study of this table, it is obvious that the effect of lime on the compressive strength of soil is not prominent. However, a little increase is indicated at 10 percent addition of lime.

Again, these tests were conducted on the soil and soil-lime mixture specimens after curing for seven days wet sand in similar way as that of optimum moisture condition. Here in this case the unconfined compressive strength attained its maximum value at 5 percent addition of lime with a subsequent decrease. From the individual comparison of the values obtained at optimum moisture condition and then after curing the specimens for seven days, it is obvious that in each case the compressive strength has been decreased by curing the specimens except at 5 percent lime. The test results are given in Table IV.

TABLE IV—*Showing the Results of Unconfined Compressive Strength.*

S. No.	Description	Compressive strength in tons/Sq. ft.							
		Remoulded State				After 7 days' curing			
		1	2	3	Mean	1	2	3	Mean
1.	Lab. Compound Soil	1.57	1.51	1.39	1.49	1.35	1.11	0.84	1.10
2.	,, ,, ,, + 2% lime	1.37	1.33	1.03	1.24	1.10	0.97	..	1.07
3.	,, ,, ,, + 4% lime	1.53	1.45	1.45	1.44	0.76	1.10	0.90	0.92
4.	,, ,, ,, + 5% lime	1.15	1.03	0.80	1.00	1.57	1.20	..	1.38
5.	,, ,, ,, + 6% lime	1.66	1.39	1.20	1.42	1.17	1.29	..	1.23
6.	,, ,, ,, + 8% lime	1.57	1.51	..	1.54	1.20	0.84	0.72	0.92
7.	,, ,, ,, +10% lime	1.81	1.63	..	1.72	0.78	0.72	0.54	0.68

(*f*) The representative sub-grade soil samples for Daska-Pasrur Road (mile 10) are tested in the laboratory and the results obtained therefrom are given as follows:—

TABLE V—*Showing the Soil Classification and Compaction Characteristics*

Station (Mile etc.)	Sieve Analysis percent passing			Plasticity Tests			AASHO soil classification.	Compaction Test Standard AASHO	
	No. 10	No. 40	No. 200	L. L.	P. L.	P. I.		Max. density in Lbs/Cft.	Opt. M.C. %
9/2 ..	100.0	99.68	92.0	26.7	15.0	12.0	A-6(9)	123.8	12.0
9/3 ..	99.9	99.77	92.2	27.8	16.1	12.7	A-6(9)	124.0	12.0
9/4 ..	100.0	99.79	90.49	29.0	14.7	14.3	A-6(10)	123.5	12.0
9/5 ..	100.0	99.78	90.91	29.0	15.6	13.7	F-6(9)	123.4	12.0
9/6 ..	99.99	99.75	96.54	26.9	14.1	12.8	A-6(9)	123.5	12.0
9/7 ..	100.0	99.77	79.43	26.1	13.2	12.9	A-6(9)	124.3	12.0
10/0 ..	100.0	99.79	78.06	27.0	15.9	11.1	A-6(8)	124.5	12.0

The test results of Table V, as given above, clearly show that the percentage passing through No. 200 sieve varies from 78 to 96.54, the plasticity index varies from 11 to 14.3 and the plastic limit varies 13.2 to 16.1 percent. The subgrade soil, in general, falls under the A-6 (9) group of the AASHO soil classification system, which corresponds to the CL group of the Unified Soil Classification (originally developed by Casagrade).

As for the compaction characteristics of the soil, the maximum dry density varies from 123.4 to 124.5 pcf on the standard AASHO basis at an optimum moisture content of 12 percent. The materials of this group have usually high volume changes between wet and dry states.

The material can be profitably compacted with the pneumatic-tyred and sheep foot rollers. The recommended height of the lift (loose) is 9 in. which is normally compacted to 6 in. at or near the optimum moisture content (± 2 percent).

(*g*) An analysis of the laboratory investigations shows that 5 percent of hydrated lime is the optimum value of the soil stabilizer for clayey soil generally encountered in the alluvium of West Pakistan.

7. CONSTRUCTION PROCEDURES FOR LIME STABILIZATION

The construction procedure for soil-lime systems involves preparation of the road sub-grade, addition of water and lime stabilizer and the soil, mixing, spreading, compaction and curing. Some operation as are sometimes combined in practice for convenience. There are various methods of construction but here in West Pakistan, Mixin-Place method is quite suitable for our conditions. The requirements of various construction steps are given as follows:—

(*a*) Scarifying and Pulverization of Soil

The subgrade soil on the project site is scarified to the desired depth by the use of a ripper or a scarifier attachment or a motor grader. The soil is then pulverised by the method of offset disc harvester, gang ploughs, or rotary speed mixers. It is generally required that the soil with the exception of gravel or stone be pulverized until at the time of compaction 100 percent of the soil lime mix will pass 1-inch sieve and at least 80 percent will pass a No. 4 (ASTM) sieve. Aeration of a wet soil or the addition of water to a dry soil may be necessary in some cases.

(*b*) Application of Hydrated Lime

The calculated amount of hydrated lime is spread on the soil surface either by hand or by mechanical means. On small jobs, bags of lime are spotted by hand along the surface in rows. The bags are then opened and the lime spread in uniform transverse rows. Spreading is completed by the use of a spike-toothed harrow. If bulk lime is used, a mechanical spreader may be employed on to the soil from pressure distributors or their equivalent.

(*c*) Mixing

The mixing or blending of soil and lime is achieved by the use of gang ploughs, disc harrows, spring-tooth cultivators and rotary tillers. Dry mixing is normally followed by wet mixing where no machinery is available, dry mixing and wet mixing may be done manually. It is essential that the materials be blended to a high degree of uniformity if the best results are to be achieved. The proper amount of water is added by means of pressure distributors to the soil-lime and water is thoroughly mixed to a uniform mixture. A complete train of equipment will include spring-tooth cultivator, gang ploughs, motor grader, rotary mixer, water distributor and spike-tooth harrow. The amount of water added is generally enough to increase the moisture content to 1-2% more than the optimum desired for compaction. This is done because of the loss of water which may occur during mixing operation as compared with laboratory mixing. The water used for this purpose should conform to the AASHO requirements as for its pH. value, total solids and inorganic matter.

(*d*) Compaction and Finishing

Initial compaction is generally achieved by the use of sheep-foot roller. A typical compacted thickness of a layer is about 3 inches. After the sub-base or base has been compacted to within 2 or 3 inches of the surface, the layer is brought to shape with a motor grader. Rolling is continued until satisfactory density has been achieved. In very sandy soils, compaction may not be possible with sheep-foot roller and compaction may be completed by the use of pneumatic-tyred roller. Steel wheel rollers have been used with granular soils and types of compaction plants such as vibratory compactors, grid and segmented rollers are finding increasing use. After the compaction, rollers are taken off, and then surface brought to the final shape. The final shaping by using spike-toothed harrow nail drags or weeder to remove the compaction planes left in the surface by the rollers followed by a broom drag. A rubber-tyred roller may be used again, the surface shaped by a motor grader and compaction planes finally removed by the nail drags. Final compaction is then secured by rolling with pneumatic-tyred rollers alone or in combination with steel rollers weighing from 3 to 12 tons.

(*e*) Protection and Curing

The water contained in the soil-lime mixture is necessary for various chemical reactions occurring within the soil-lime mass as already explained in this paper and therefore steps must be taken to prevent losses of moisture for the compacted subgrades, sub-base or base by evaporation. A protective casing of 2 to 4 inches of soil may be placed over the soil stabilized layer or hay or straw may be used. Another method is to keep the surface moist by periodic spraying from a water tank. Where rains are expected and would be harmful, a sealed cover is recommended.

Bituminous materials commonly used for curing are RC-2 or MC-3 or RT-5 and asphaltic emulsions the exact type depending on the climate and road conditions. Rate of application is 0.15—0.30 gallons per sq. yd. or 1.65—3.3 gallons per 100 sq. feet.

Excessive penetration of sprayed bituminous material into stabilized granular soil, resulting in weakening of the upper layer, is prevented by preliminary light sprinkling with water. After application, the bituminous coat is sealed prior to use by traffic. The curing seal coat gives a worthwhile resistance to abrasion and forms part of the subsequent later surfacing. Generally, 7 days of favourable weather will yield satisfactory curing of the soil-lime construction and during this period traffic should be kept off.

(*f*) Surfacing

The lime stabilized soil layers are generally meant to serve as sub-base and base course under a bituminous surfacing. The common bituminous wearing course for light traffic roads is a double surface treatment about 3/4 inch thick. Higher traffic volumes require a thicker and higher type of surfacing such as $1\frac{1}{2}$ to 3 in of asphaltic concrete.

8. STRUCTURAL DESIGN OF EXPERIMENTAL ROAD PAVEMENT AND THEIR PERFORMANCE

These results obtained from the laboratory testing of soil-lime mixtures, were applied in the field for a number of experimental roads comparing the lime stabilized sub bases and base courses were constructed in West Pakistan and their performance observed over a fairly long period. The details of the design of the lime stabilized soil are given as follows:—

(1) Daska-Pasrur Road, Mile 10

The design of the experimental road in this portion of the roads is given as follows:—

(*a*)	Lime-stabilized sub-base with 3% lime	= 6″
	Crushed brick base course	= 6″
	Crushed stone wearing course	= $4\frac{1}{2}$″
	Rituminous surfacing	= $\frac{1}{2}$″ (3 coats of spray B & R specifications).

(*b*) Lime-stabilized sub-base with 3% lime = 6″
Lime stabilized base course with 5% lime = 6″
Crushed stone wearing course = 3″
Bituminous surfacing = ½″ (3 coats of spray grout B & R specifications).

(*c*) Lime stabilized sub-base with 3% lime = 6″
Brick on edge (base course) = 4½″
Crushed stone wearing course = 3″
Bituminous surfacing = ½″ (3 coats of spray grout B & R specifications).

The cross-sections of these experimental road pavements are given in Appendix "C".

2. Lahore-Sheikhupura-Lyallpur Road, Mile 54.

(Sheikhupura-Shahkot Section)
Lime stabilized sub-base with 3% lime = 5″
Lime stabilized base-course with 5% lime = 5″
Brick on edge = 4½″
Crushed stone = 4½″
Bituminous surfacing = ½″ (3 coats of spray grout B & R specifications).

The cross-sections of these experimental pavements are given in Appendix D.

3. Recommended Sections of Road Pavement

These sections are given as a guide under average field conditions in the alluvial plains of West Pakistan where crushed stone is comparatively expensive. The actual design, however, will depend upon the nature of the subgrade and specific field conditions:—

(*a*) **Recommended Pavement Section for Light Traffic (up to 50 Commercial Vehicles per day).**

Lime stabilized sub-base with 5% hydrated lime in two layers of 4½″ each. = 9″ (compacted).
Crushed stone base course = 4″ (compacted).

Bituminous Surfacing	= 3 coats of spray grout.
Total thickness of construction	= 13″ (compacted)+Bit. surfacing.

(*b*) **Recommended Pavement Section for Medium Traffic (50-300 Commercial vehicles per day)**

Lime stabilized sub-base with 5% hydrated lime in two layers of 4½″ each.	= 9″ (Compacted).
Crushed stone base course	= 6″ (Compacted).
Bituminous surfacing	= 2″ Asphaltic Concrete.
Total thickness of construction	= 17″ (Compacted).

If required, three coats of bituminous surface treatment may be given for the present but subsequently, 2″ asphaltic concrete is necessary.

(*c*) **Recommended Pavement Section for Heavy Traffic (More than 300 commercial vehicles per day).**

Lime stabilized sub-base with 5% Hydrated lime in two layers of 4½″ each.	= 9″ (Compacted).
Crushed stone base course	= 8″ (Compacted).
Bituminous surfacing	= 3″ Asphaltic Concrete.
Total thickness of construction	= 20″ (Compacted).

(If required, 3 coats of bituminous surface treatment may be given for the present but subsequently, 3″ of asphaltic concrete is necessary. In case the asphaltic concrete cannot be managed for, 3″ penetration macadam plus bituminous suracing may be provided as an alternative.

The recommended pavement sections have been shown in Appendix "D".

4. Performance of Experimental Road Pavements

The performance of existing experimental road pavements on Daska-Pasrur road has been excellent and it has stood well under very heavy traffic. The performance of existing pavement on the Lahore-Sheikhupura-Lyallpur Road is also satisfactory.

5. The extent of economy that can be effected by providing lime-stabilized sub-base in the areas where pit-run gravel has to be imported from long distances, may be worked out from a comparative study of the thickness design of the flexible pavement given as follows:—

The pavement design has been worked out on the assumption that the lower limits of the C. B. R. values of pitrun gravel and lime-stabilized soil are 20% and 10% respectively for sub-base purpose.

(*a*) Thickness design of flexible pavement for 18,000 lbs. axle load for a sub-grade with 3% C. B. R value using pit-run gravel or soil-aggregate mix sub-base.

Granular sub-base	=12″ (compacted)
Base course (crushed stone)	= 5″ ,,
Bituminous surfacing (asphaltic concrete)	= 3″ ,,
Total thickness	=20″ (compacted)

(*b*) Thickness design of flexible pavement for similar conditions but using lime-stabilized sub-base.

Lime stabilized sub-base (with 5% hydrated lime)	= 9″ (compacted)
Base course (crushed stone)	= 8″ ,,
Bituminous surfacing	= 3″ ,,
Total thickness	=20″ (compacted)

6. A comparative study of the cost analysis for flexible pavement using pit-run gravel and lime-stabilised soil sub-base.

Lime Stabilized Sub-base

Quantity:

Taking a length of one mile a 12′ wide road

(*i*) Total cubic contents of soil	= 13×9—12×5280=51480 cft.
(*ii*) Weight of soil	= 51480×120 lbs.
(*iii*) Weight of lime	= (5% of wt. of soil)
	= 51480×120×0.05 lbs.
	= 308880 lbs.
	= 3749 Maunds
Add 5% for wastage	= 188 ,,
Total	... 3937 Say 3950 Maunds

Cost:

(*i*) 3950 Maunds cost of lime including slaking and screening (89% passing 200 sieve) and spreading at 7/50 per md.	= 29,625.00
(*ii*) 64 hours of Tractor with disc harrow for mixing lime with soil (8 hrs./furlong in two layers) at Rs. 20 per hour	= 1,280.00
(*iii*) 51480 cft. Earthwork at Rs. 90%	= 4,635.00

Cost of Additional 3″ compacted stone base-loose $3\frac{1}{2}$″

Stone metal = 5280×12×7—24+18480 cft.

(*i*) 18480 cft. stone metal at Rs. 130% cft.	=	24,024.00
(*ii*) 18480 cft. compaction of stone base 100% Modified A.A.S.H.O. at Rs. 45% cft.	=	8,316.00
Total cost Rs.	=	67,880.00
Say Rs,	=	68,000.00

12″ compacted sub-base of pit-run gravel-loose 15″

Quantity:

Pit-run gravel = 5280×13×15—12
= 85800 cft.

Cost:

(*i*) 85800 cft. cost of pit-run gravel at Rs. 100% cft.	=	85,800.00
(*ii*) Compaction of $3\frac{1}{2}$″ loose pit-run gravel (compacted thickness 3″) in lieu of 3″ stone base 5280×13×7—24=20020 cft. at Rs. 45% cft.	=	9,000.00
Total Rs.	=	94,800.00
Say Rs.	=	95,000.00

SAVING by use of lime stabilized base instead of pitrun gravel per mile for a 12′ wide road=27,000.

It may be noted that the above calculations have been given just as a guide to indicate the extent of saving that can be expected by use of lime stabilized sub-base in place of pitrun gravel in areas in the vicinity of Lahore where such a material has to be brought from long distances. Therefore, the economics will have to be calculated for the particular project depending upon the availability of granular sub-bases and their comparative costs.

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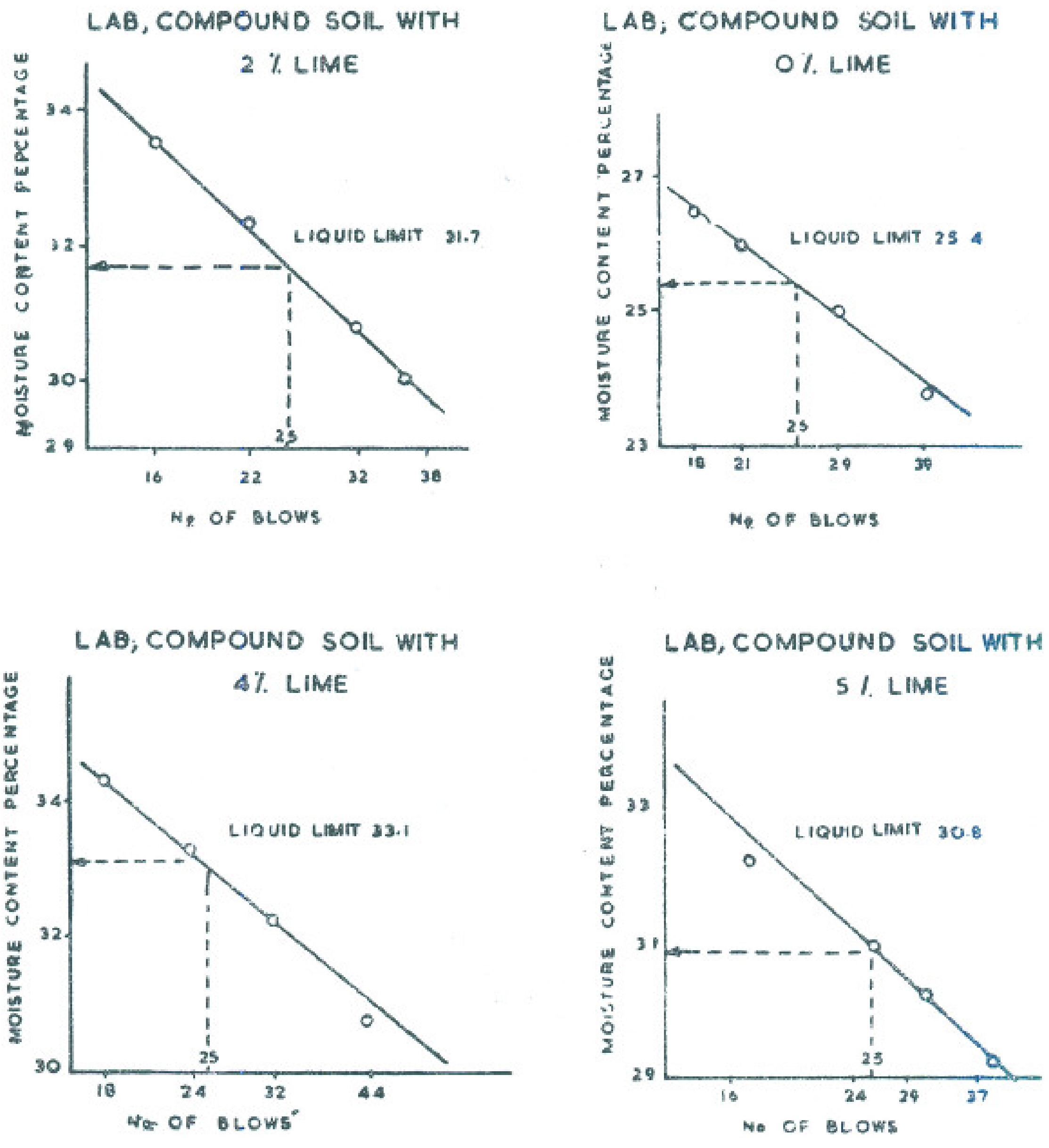
APPENDIX A

ROAD RESEARCH INSTITUTE, LAHORE



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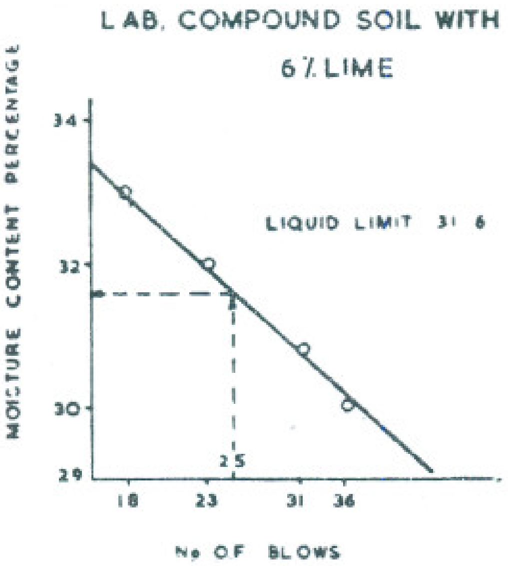
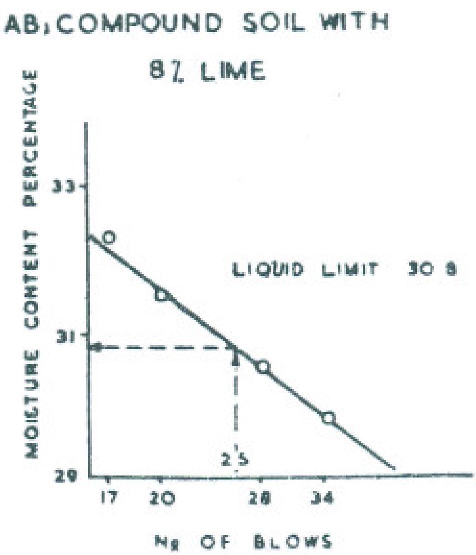
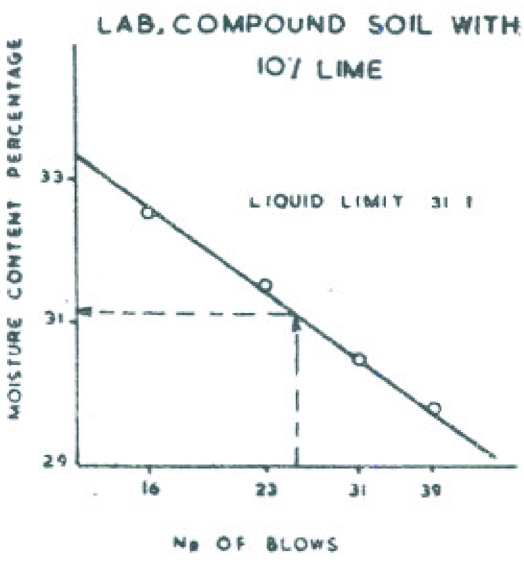




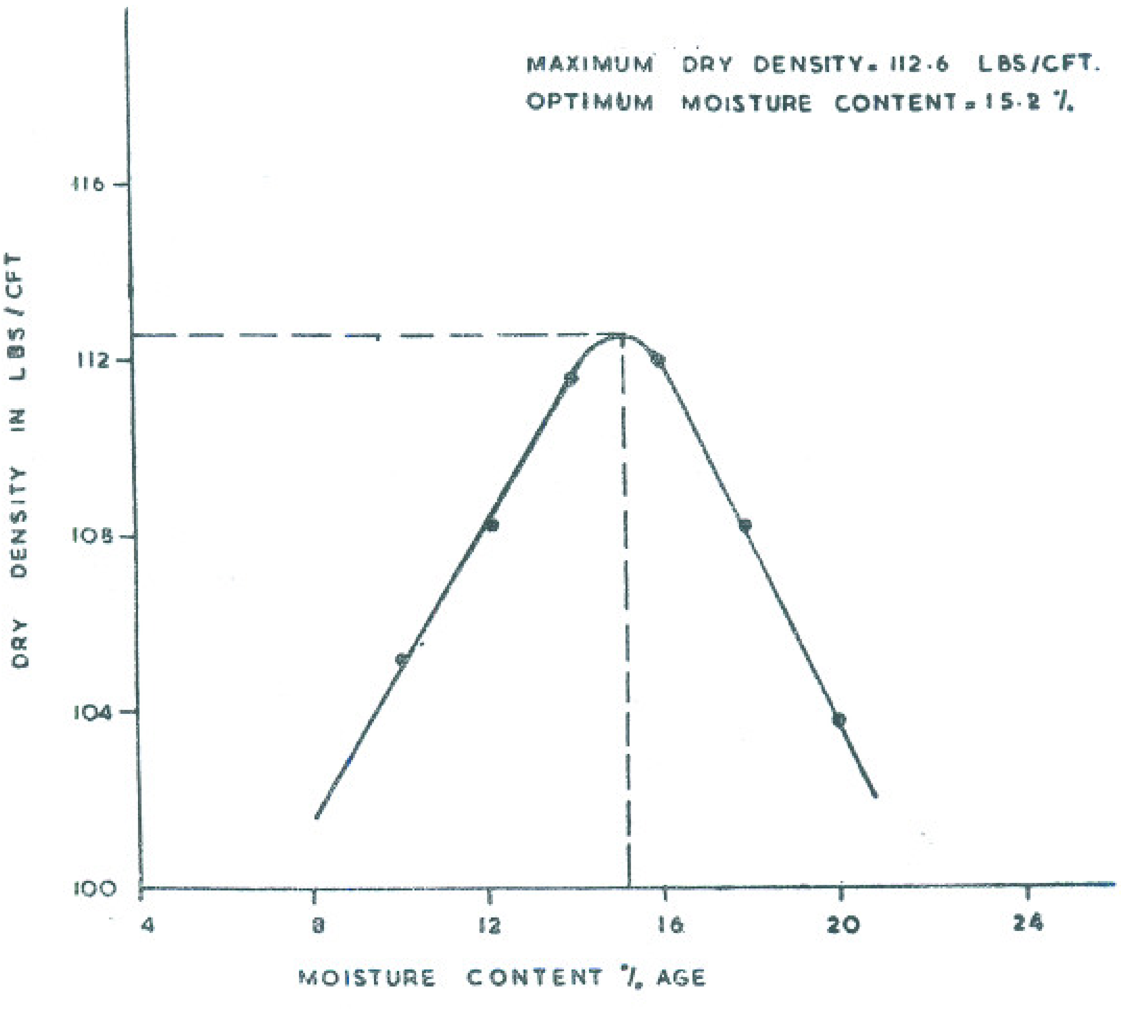


APPENDIX B

ROAD RESEARCH INSTITUTE, LAHORE

STANDARD A.A.S.H.O.

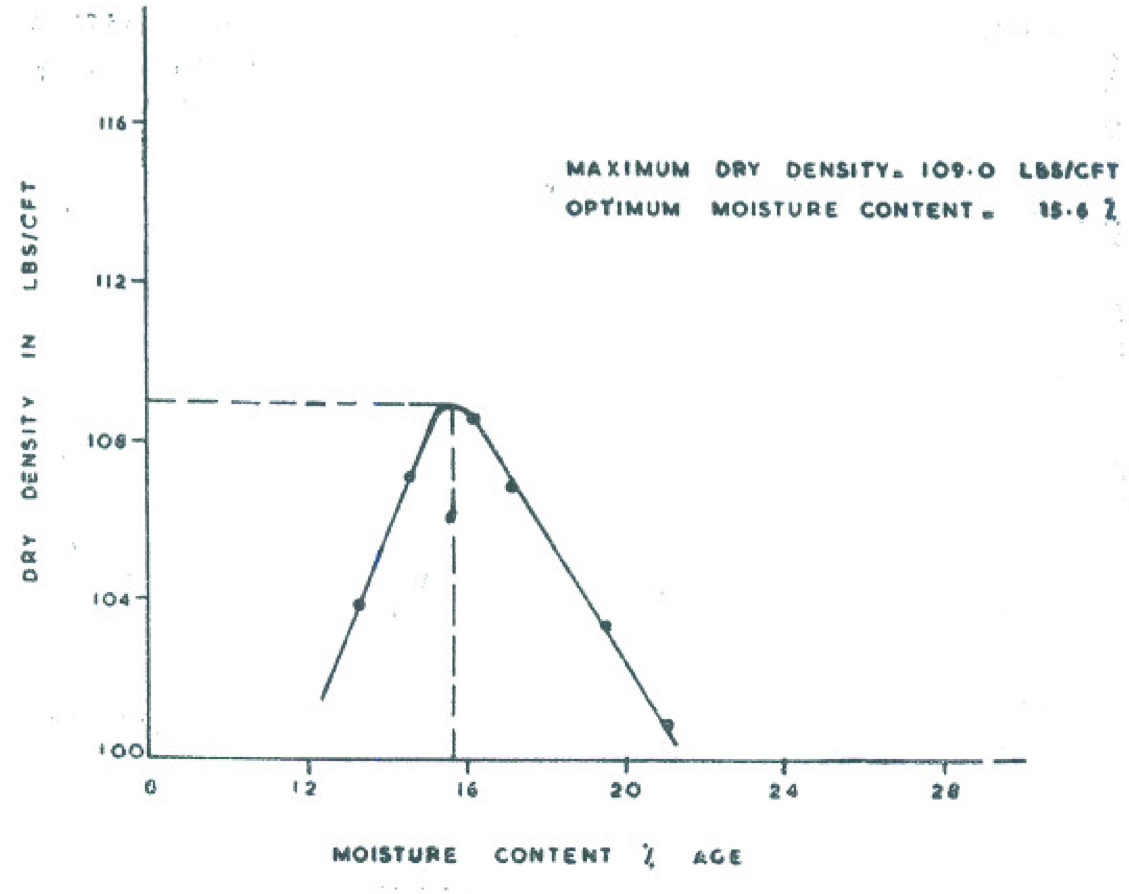
LAB; COMPOUND SOIL + 0% LIME



ROAD RESEARCH INSTITUTE, LAHORE.

STANDARD A.A.S.H.O.

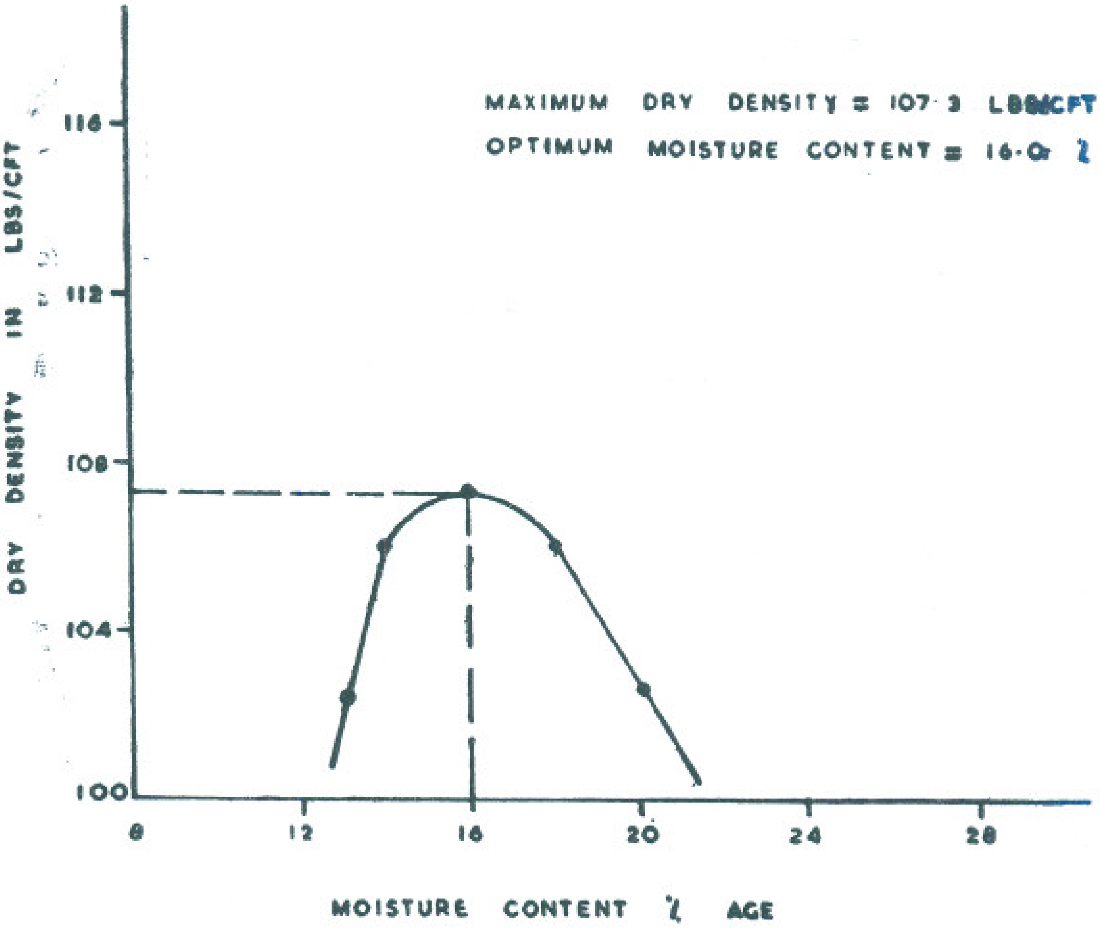
LAB, COMPOUND SOIL+ 2 % LIME



ROAD RESEARCH INSTITUTE, LAHORE

STANDARD AASHO

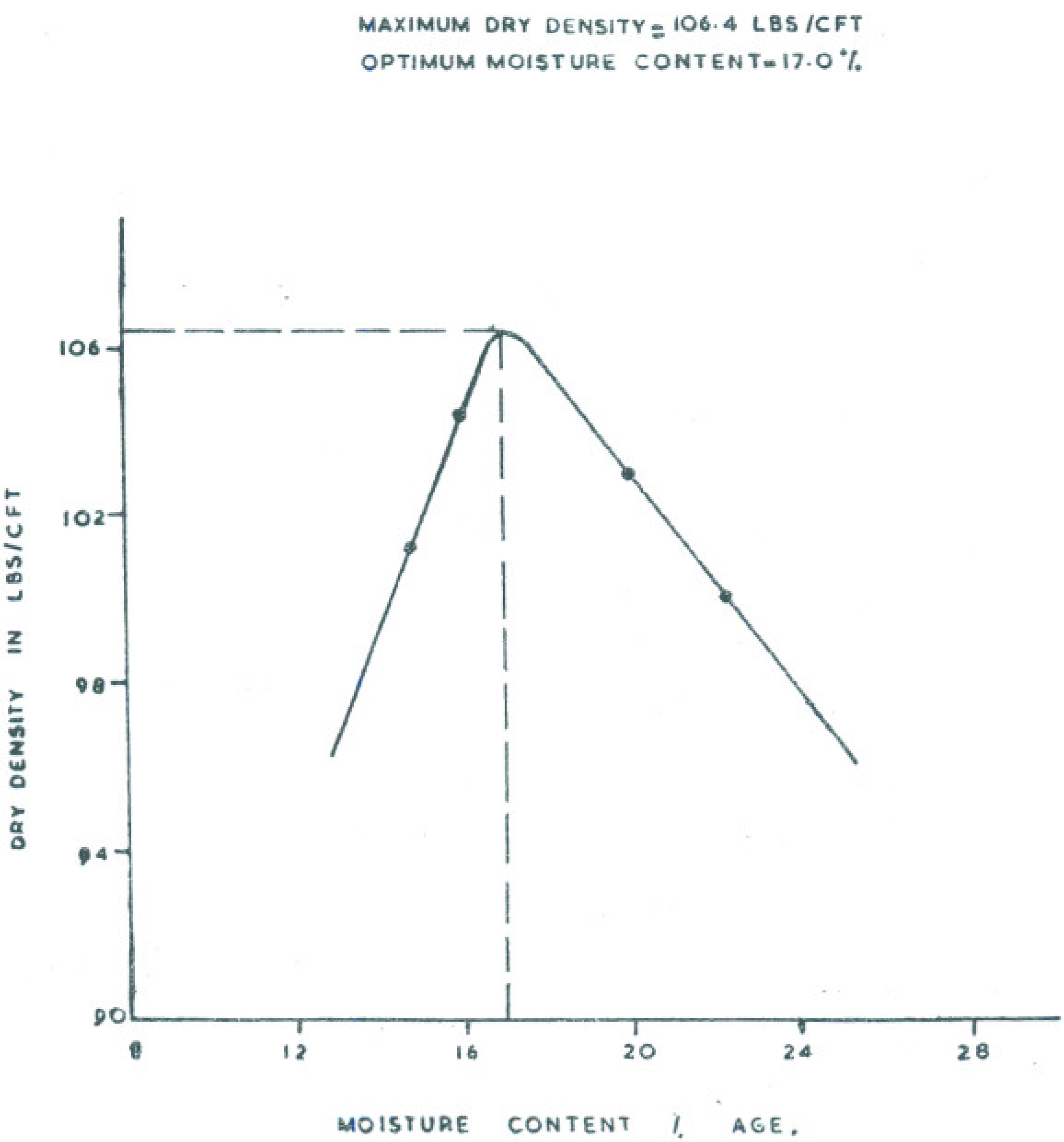
LAB; COMPOUND SOIL + 4% LIME



ROAD RESEARCH INSTITUTE, LAHORE.

STANDARD A.A.S.H.O.

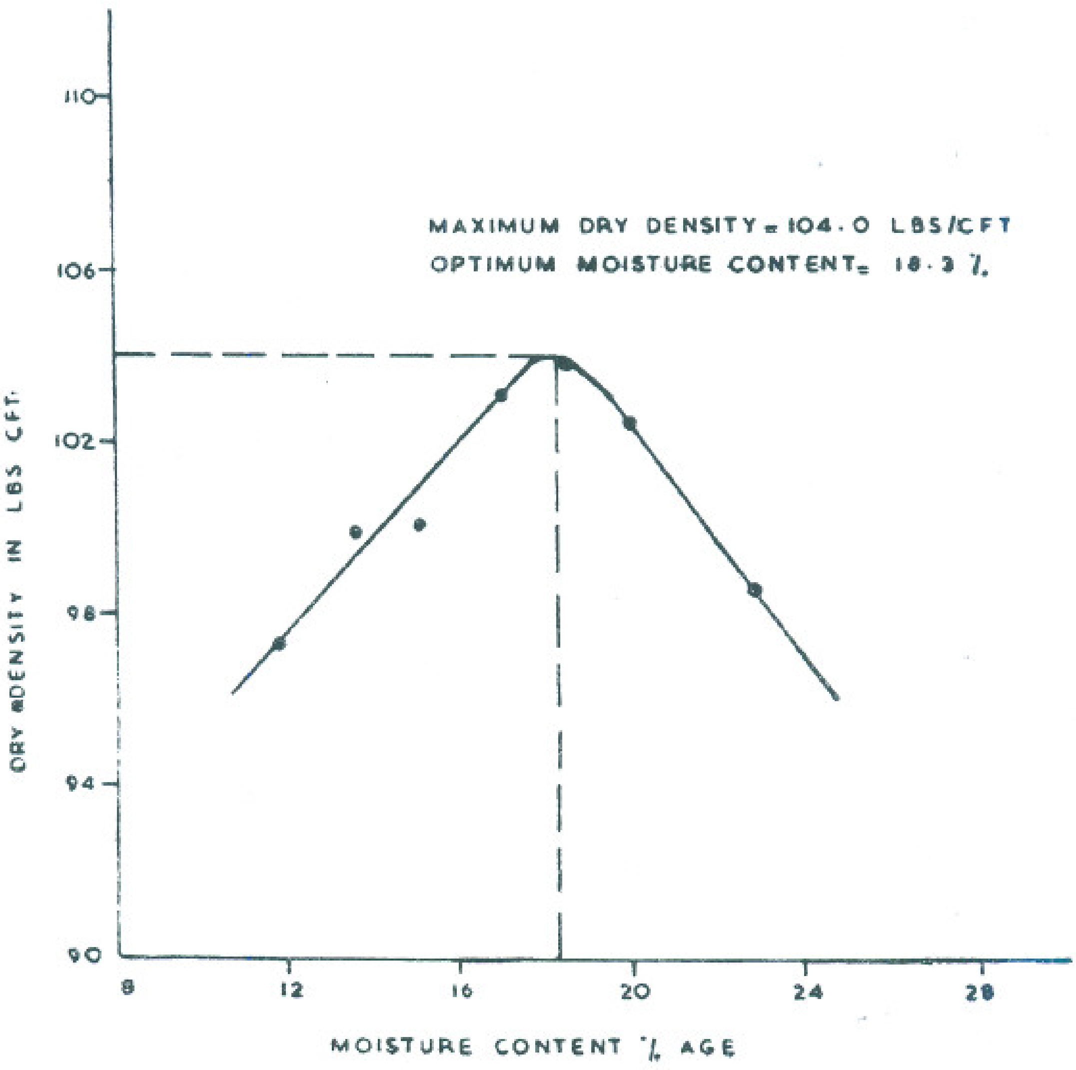
LAB; COMPOUND SOIL + 5 % LIME



ROAD RESEARCH INSTITUTE, LAHORE

STANDARD A.A.S.H.O

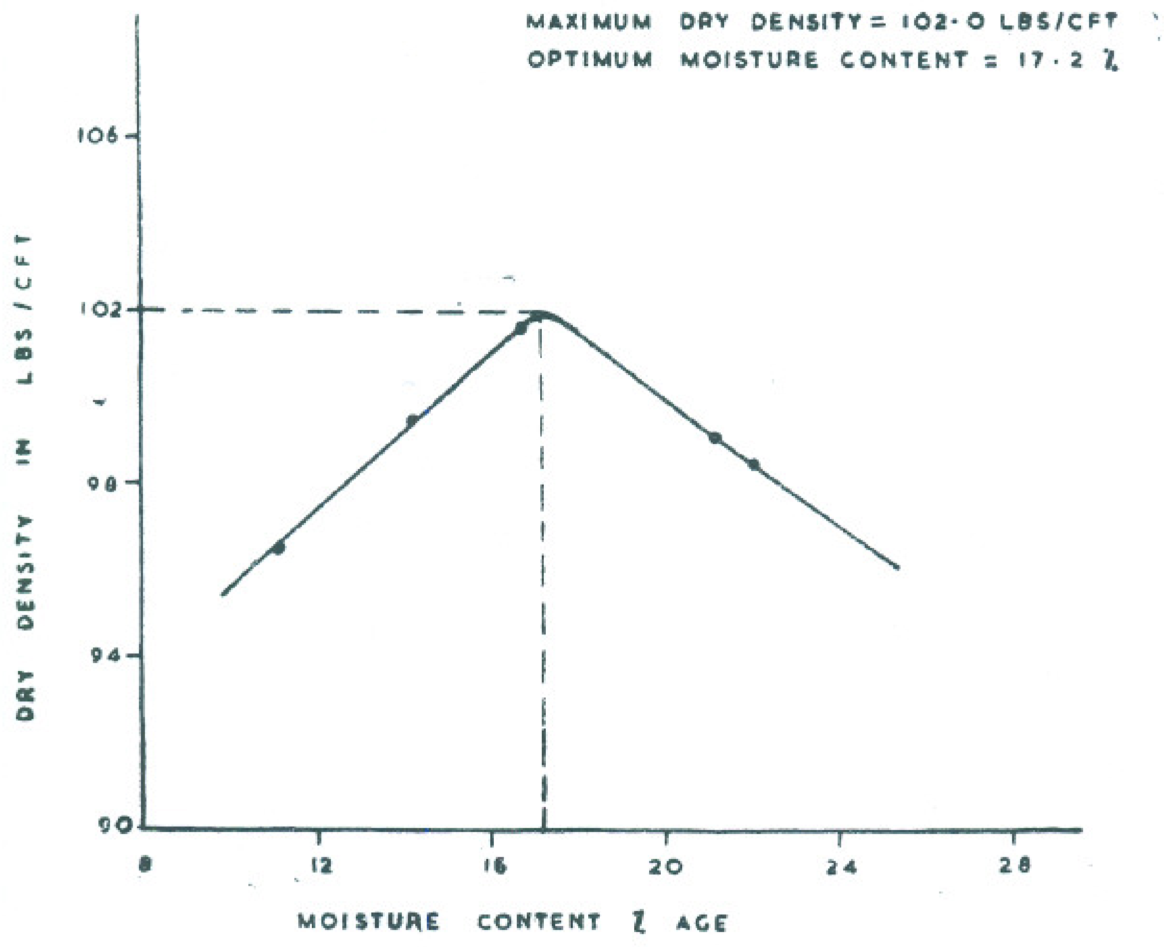
LAB; COMPOUND SOIL+ 6% LIME



ROAD RESEARCH INSTITUTE, LAHORE

STANDARD A.A.S.H.O.

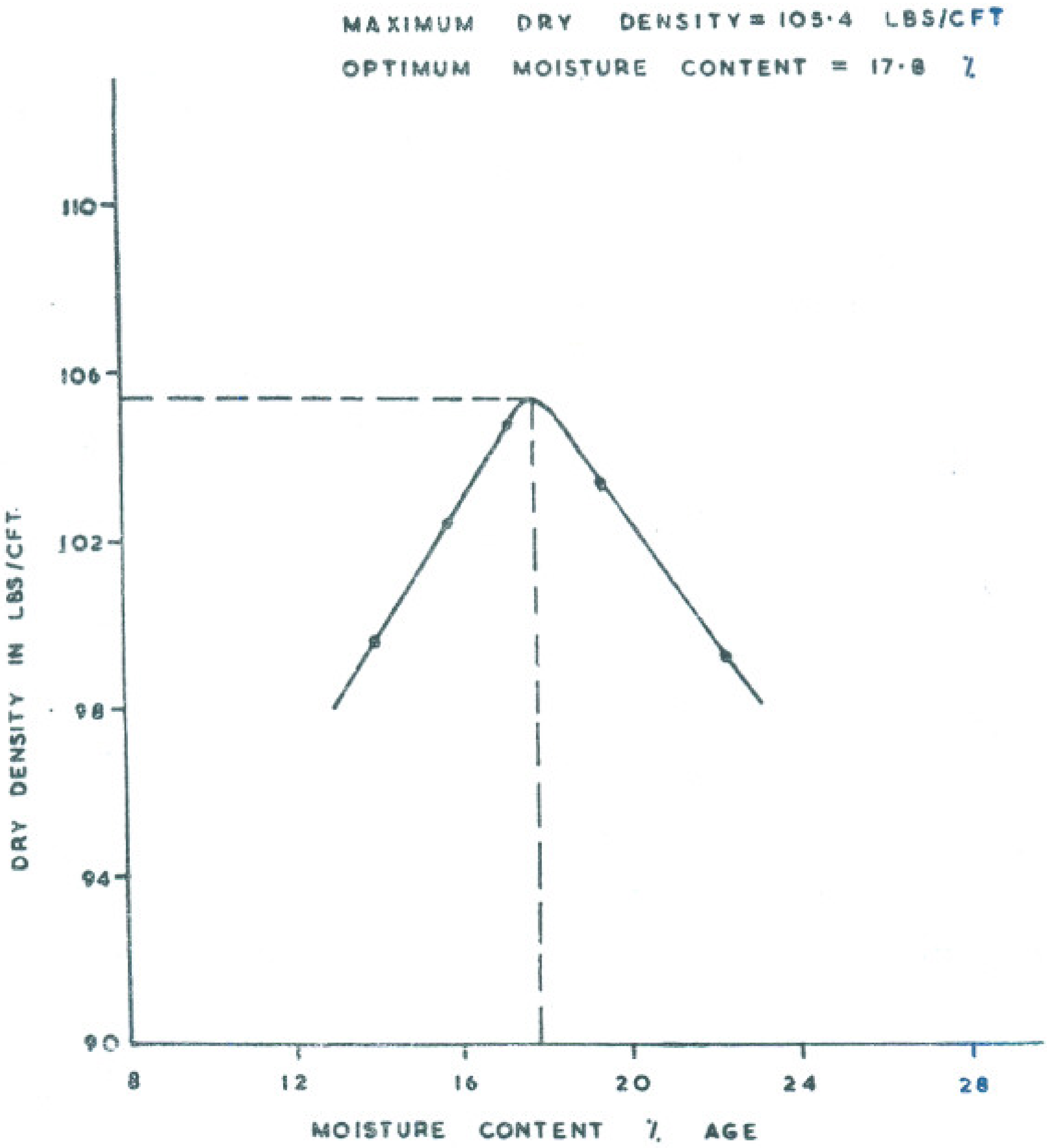
LAB; COMPOUND SOIL+ 8% LIME



ROAD RESEARCH INSTITUTE, LAHORE.

STANDARD A.A.S.H.O.

LAB: COMPOUND SOIL + 10% LIME

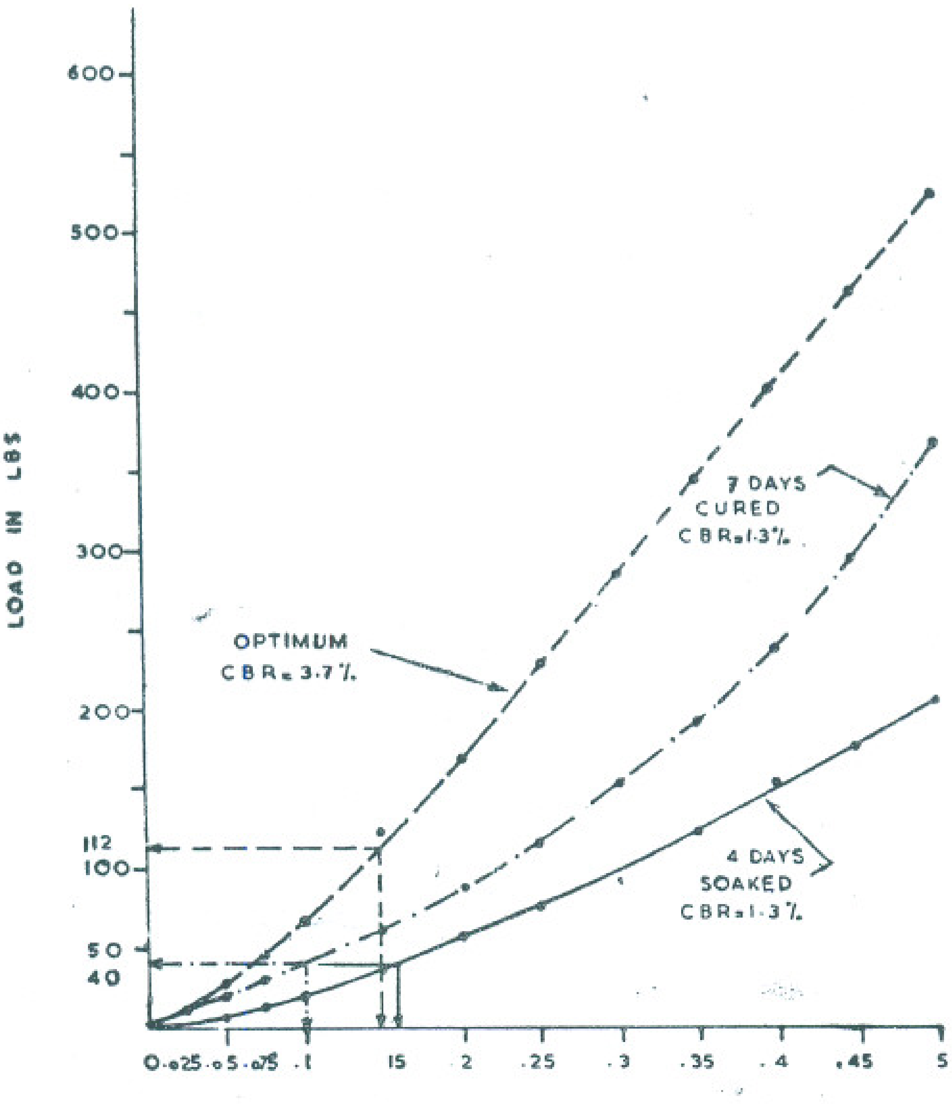


APPENDIX C

ROAD RESEARCH INSTITUTE, LAHORE

C. B. R. CURVES.

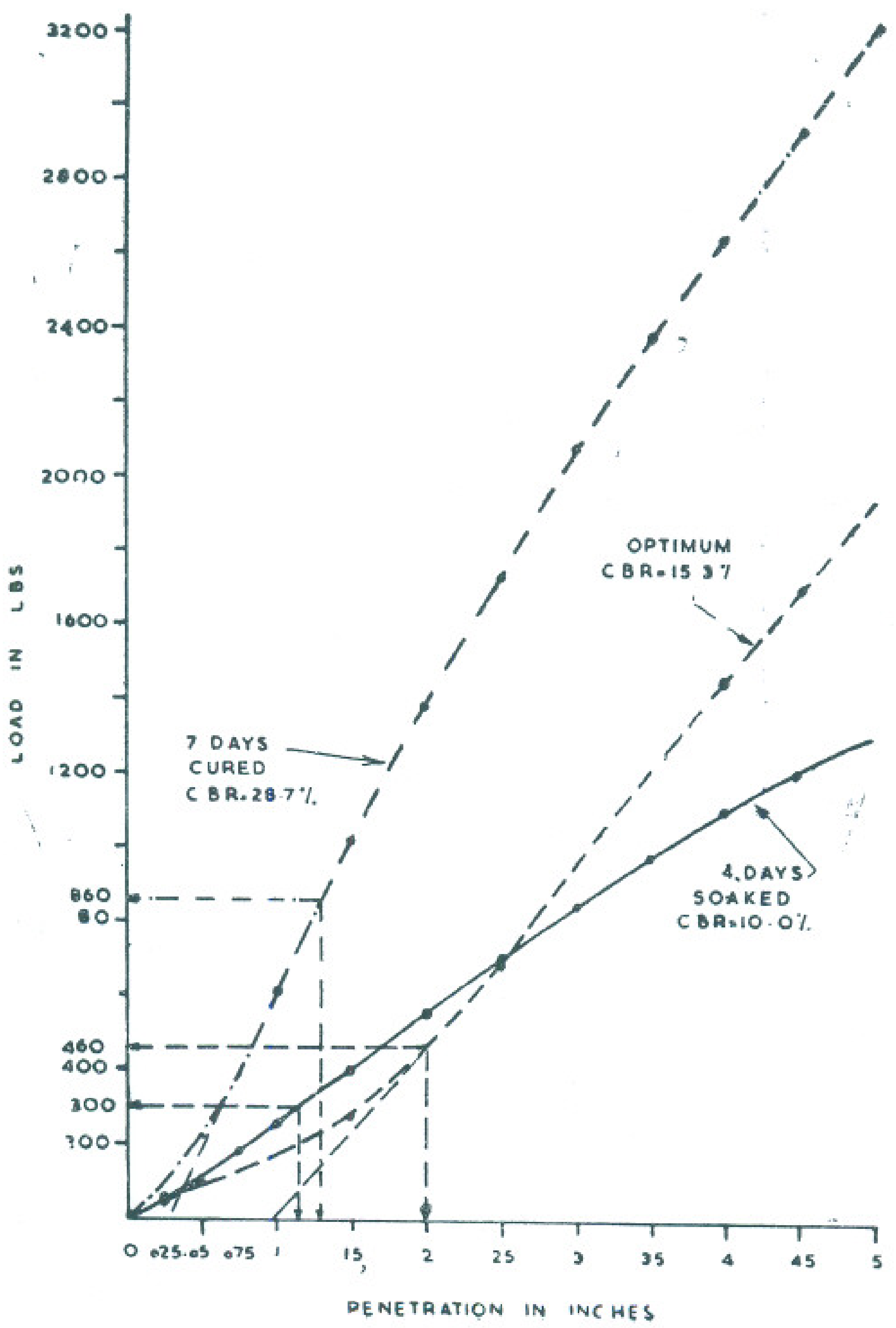
LAB; COMPOUND SOIL + 0% LIME

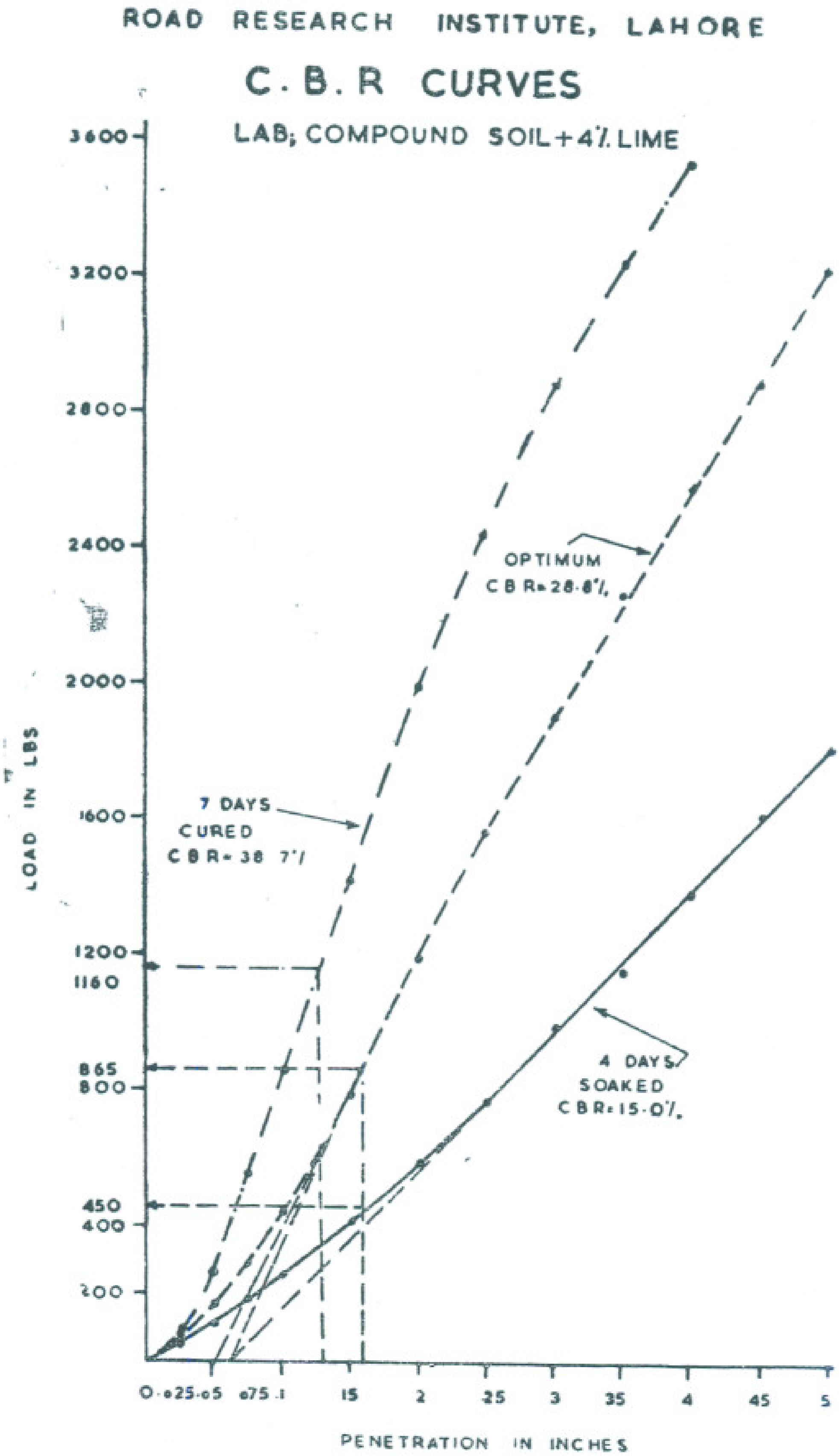


ROAD RESEARCH INSTITUTE, LAHORE

C.B.R. CURVES

LAB; COMPOUND SOIL + 2 % LIME

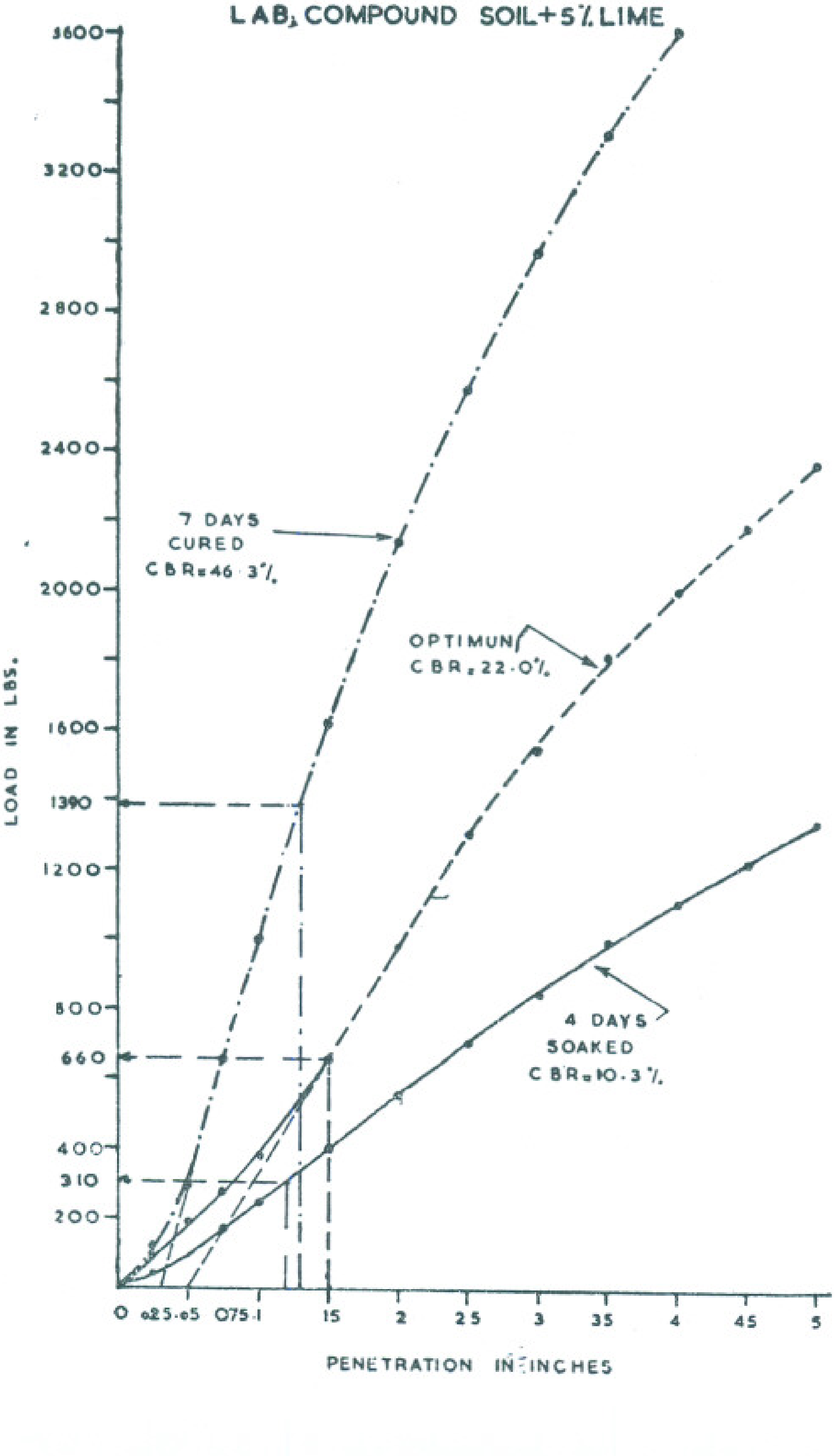


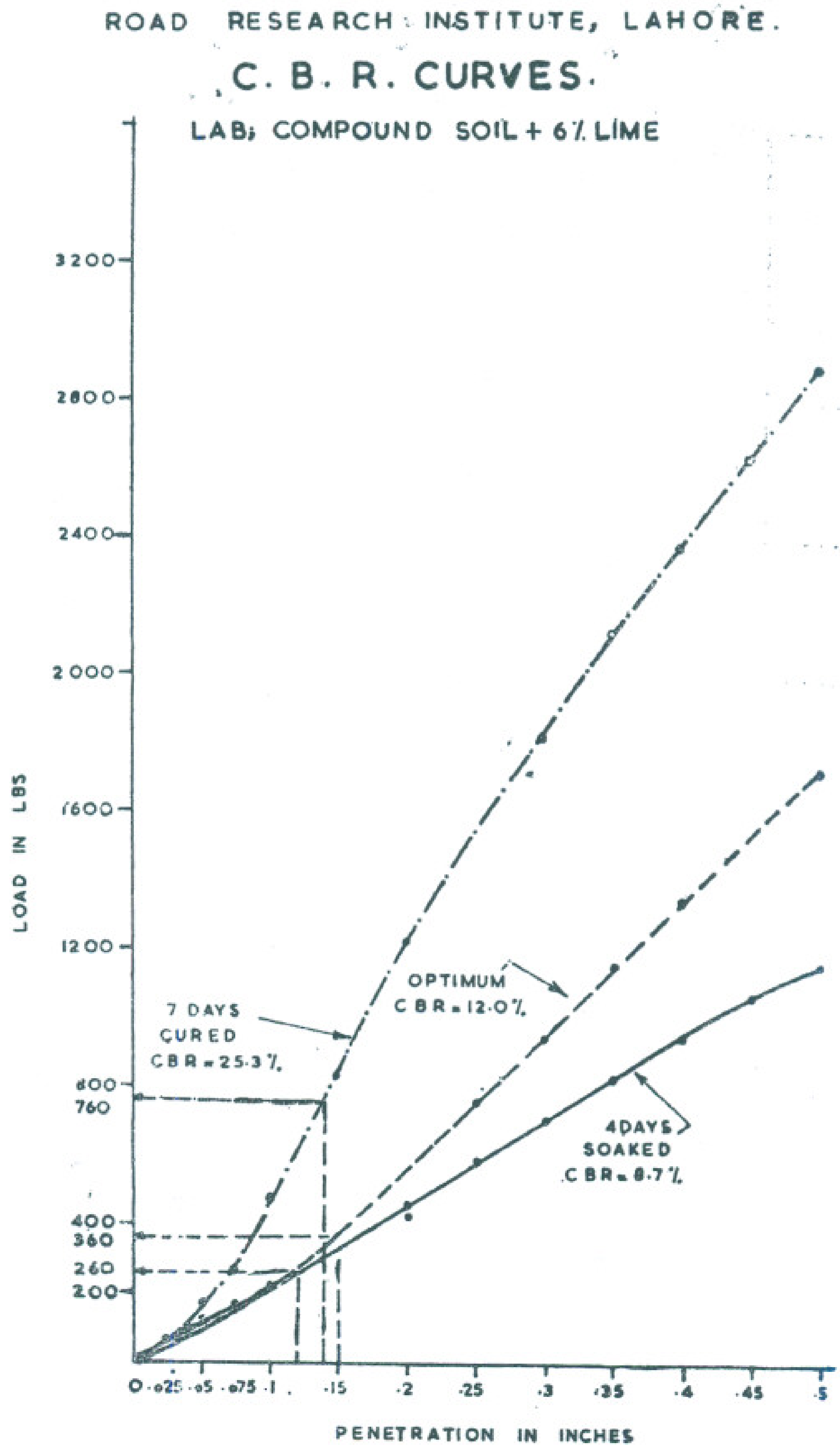

ROAD RESEARCH INSTITUTE, LAHORE
C.B.R CURVES
LAB; COMPOUND SOIL+4% LIME
OPTIMUM
CBR=28.8%
7 DAYS
CURED
CBR=38 7%
4 DAYS
SOAKED
CBR=15.0%
3600
3200
2800
2400
2000
1600
1200
1160
865
800
450
400
200
LOAD IN LBS
0 .025 .05 .075 .1 .15 .2 .25 .3 .35 .4 .45 .5
PENETRATION IN INCHES

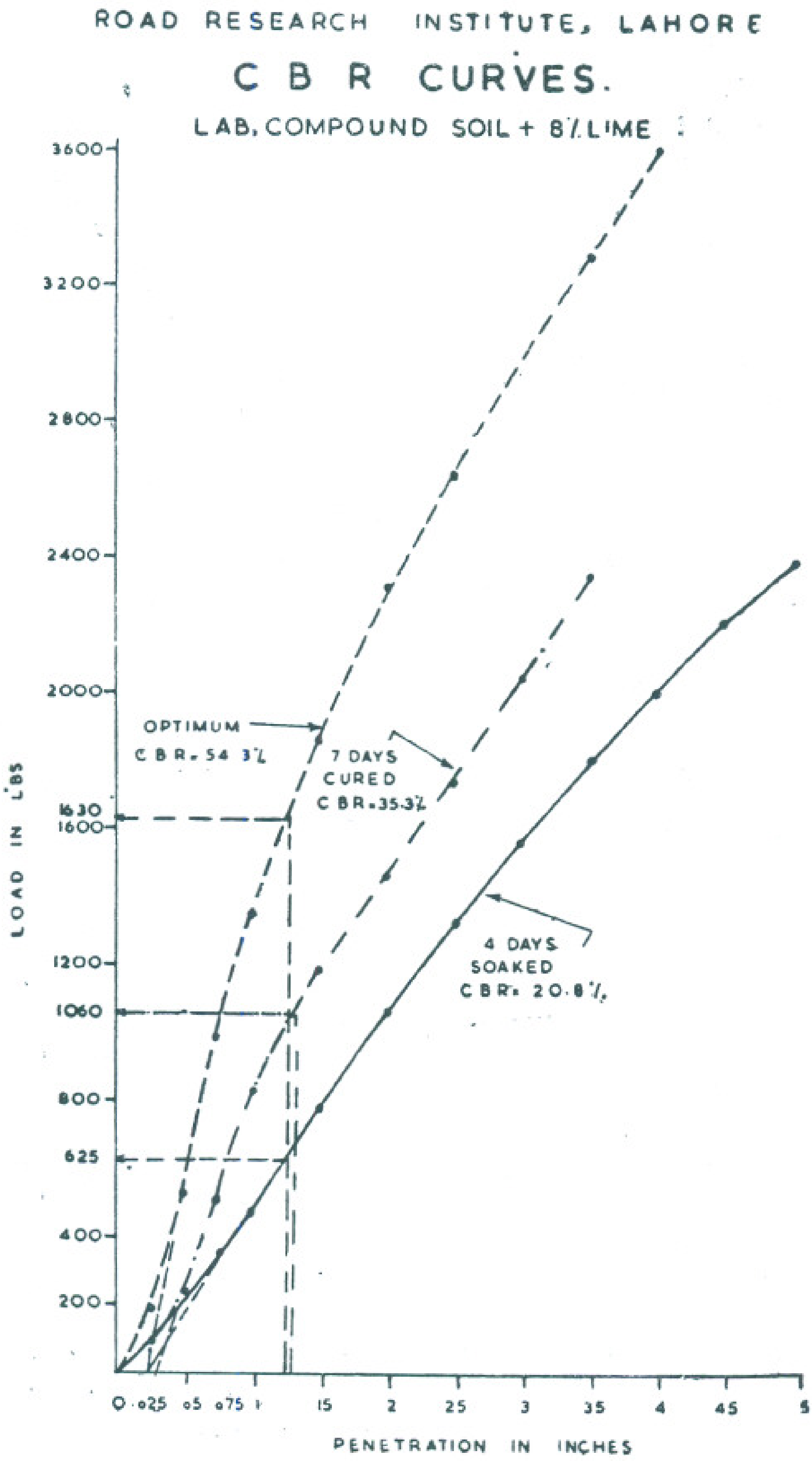
ROAD RESEARCH INSTITUTE, LAHORE

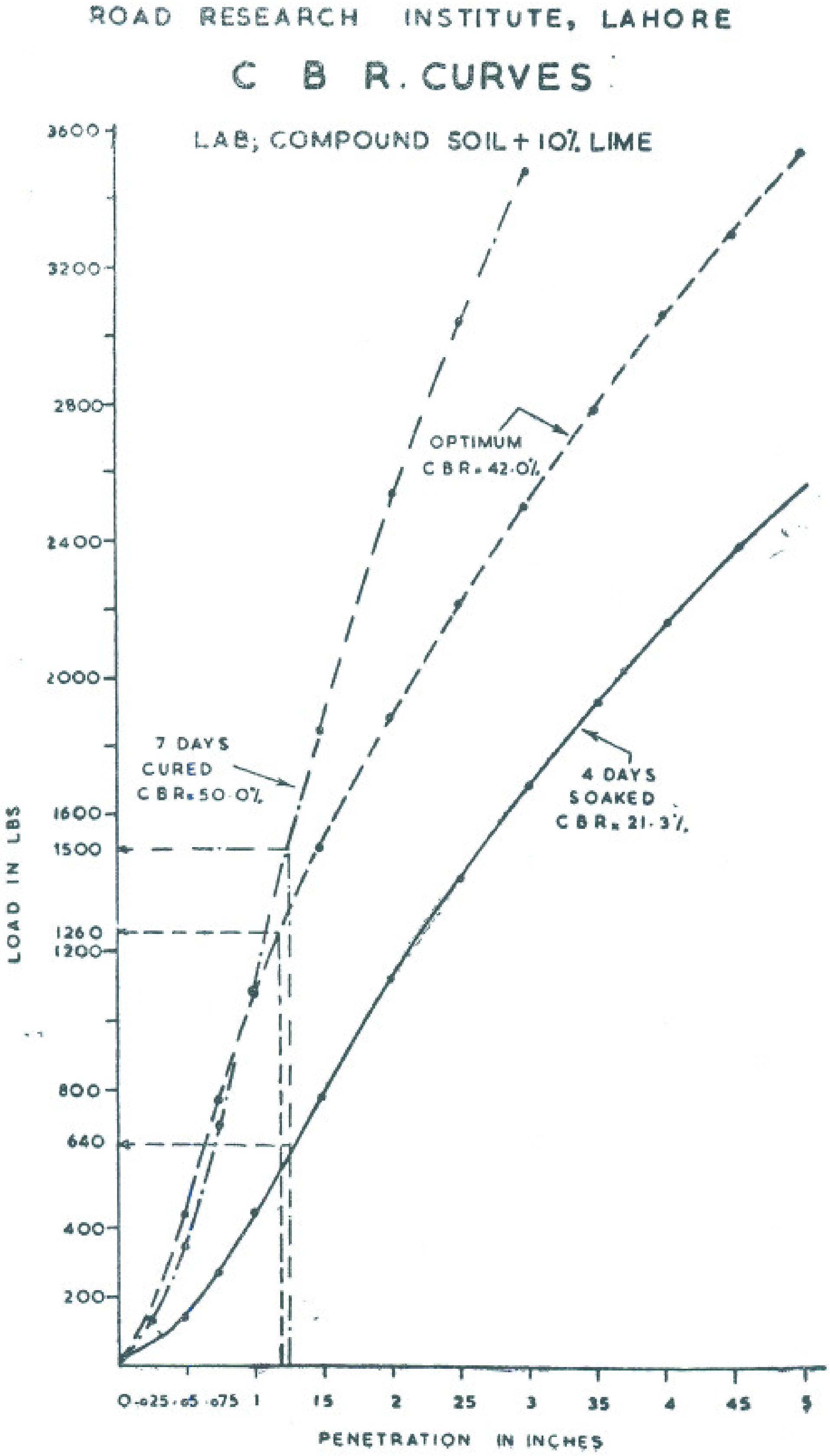
C. B. R. CURVES.

LAB, COMPOUND SOIL+5% LIME




ROAD RESEARCH INSTITUTE, LAHORE.
C. B. R. CURVES.
LAB; COMPOUND SOIL + 6% LIME
LOAD IN LBS
3200
2800
2400
2000
1600
1200
800
760
400
360
260
200
7 DAYS CURED CBR = 25.3%
OPTIMUM CBR = 12.0%
4 DAYS SOAKED CBR = 8.7%
0 .025 .05 .075 .1 .15 .2 .25 .3 .35 .4 .45 .5
PENETRATION IN INCHES


ROAD RESEARCH INSTITUTE, LAHORE
C B R CURVES.
LAB. COMPOUND SOIL + 8% LIME
3600
3200
2800
2400
2000
1630
1600
1200
1060
800
625
400
200
LOAD IN LBS
OPTIMUM
C B R = 54 3%
7 DAYS
CURED
C B R = 35.3%
4 DAYS
SOAKED
C B R = 20.8%
0 .025 .05 .075 .1 .15 .2 .25 .3 .35 .4 .45 .5
PENETRATION IN INCHES


ROAD RESEARCH INSTITUTE, LAHORE
C B R. CURVES
LAB; COMPOUND SOIL + 10% LIME
OPTIMUM
C B R = 42.0%
7 DAYS
CURED
C B R = 50.0%
4 DAYS
SOAKED
C B R = 21.3%
LOAD IN LBS
3600
3200
2800
2400
2000
1600
1500
1260
1200
800
640
400
200
0 ·025 ·05 ·075 ·1 ·15 ·2 ·25 ·3 ·35 ·4 ·45 ·5
PENETRATION IN INCHES

APPENDIX D

EXPERIMENTAL ROADS.

WITH VARIOUS SPECIFICATIONS OF LIME-STABILIZATION

A. DASKA – PASRUR ROAD MILE. 10

1

3 COATS OF SPRAY GROUT BIT. SURFACING

(3 coats of spray grout bit. surfacing)	1/2"
CRUSHED STONE 3/4" TO 3" SIZE	3"
CRUSHED BRICKS WATER BOUND MACADAM	6"
LIME STABILIZED SOIL WITH 3% LIME	6"

SUBGRADE COMPACTED TO 95% MODIFIED A.A.S.H.O. DENSITY

2

3 COATS OF SPRAY GROUT BIT. SURFACING

(3 coats of spray grout bit. surfacing)	1/2"
CRUSHED STONE 3/4" TO 3" SIZE	3"
LIME STABILISED SOIL WITH 5% LIME	6"
LIME STABILISED SOIL WITH 3% LIME	6"

SUBGRADE COMPACTED TO 95% MODIFIED A.A.S.H.O. DENSITY.

3

3 COATS OF SPRAY GROUT BIT. SURFACING

(3 coats of spray grout bit. surfacing)	1/2"
CRUSHED STONE 3/4" TO 3" SIZE	3"
BRICK ON EDGE	4 1/2"
LIME STABILISED SOIL WITH 3% LIME	6"

SUBGRADE COMPACTED TO 95% MODIFIED A.A.S.H.O. DENSITY

B. SHEKHUPURA – SHAHKOT ROAD MILE. 54

4

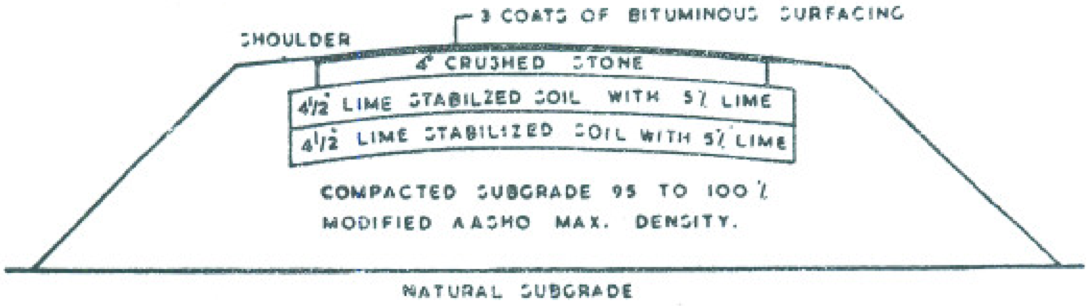
3 COATS OF SPRAY GROUT BIT. SURFACING

(3 coats of spray grout bit. surfacing)	1/2"
CRUSHED STONE	4 1/2"
BRICK ON EDGE	4 1/2"
LIME STABILISED SOIL WITH 5% LIME	5"
LIME STABILISED SOIL WITH 3% LIME	5"

COMPACTED SUBGRADE TO 95% MODIFIED A.A.S.H.O. DENSITY BED & SIDES OF TRENCH SPRAYED WITH BITUMEN AND H.S.D. OIL MIXTURE AT 40 LBS % SFT

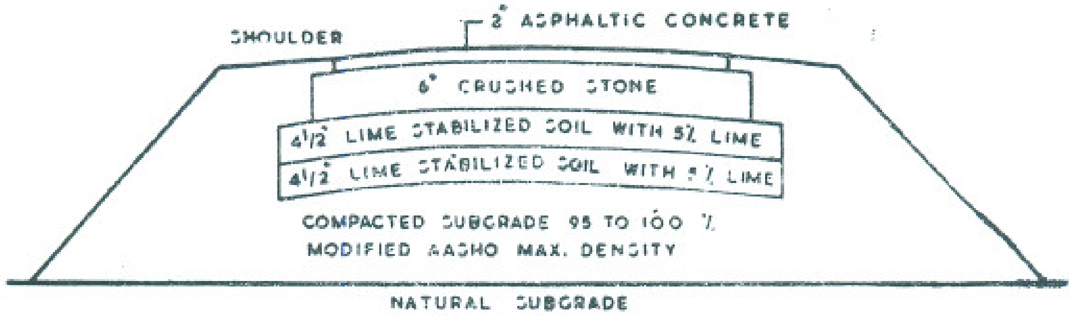
RECOMMENDED SECTIONS FOR PAVEMENT DESIGN

A PAVEMENT SECTION FOR LIGHT TRAFFIC.



B. PAVEMENT SECTION FOR MEDIUM TRAFFIC.

IF REQUIRED 3 COATS OF BIT. SURFACE TREATMENT MAY BE GIVEN FOR THE PRESENT BUT SUBSEQUENTLY, 2 INCH ASPHALTIC CONCRETE IS NECESSARY.



C. PAVEMENT SECTION FOR HEAVY TRAFFIC

IF REQUIRED 3 COATS OF BIT. SURFACE TREATMENT MAY BE GIVEN FOR THE PRESENT BUT SUBSEQUENTLY, 3 INCH ASPHALTIC CONCRETE IS NECESSARY.