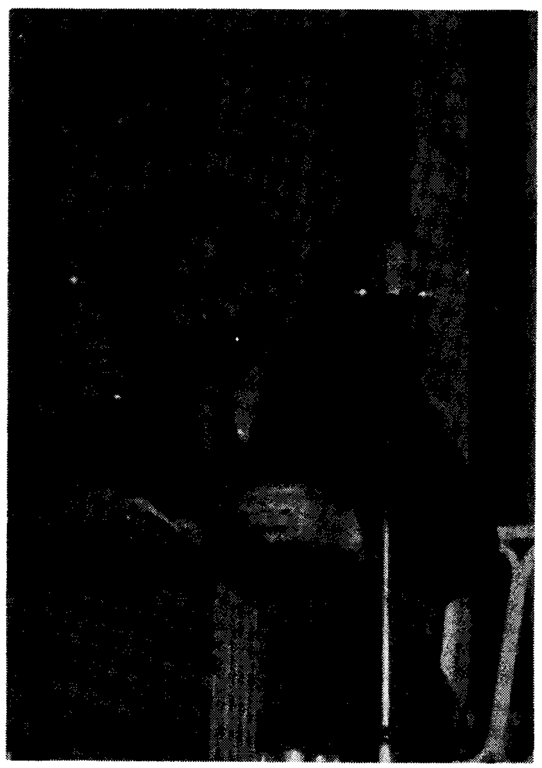
the curve shows that a maximum degree of absorption has been reached, that field conditions may be so different as to all at once make the mixture sop up more water. Furthermore, we can hardly conceive of a situation in the field where the base slab will be immersed in free water. If drainage in any particular area under a base course is in such condition that there is a mass of free water, an ordinary gravel base would sink out of sight, our waterproofed mechanical stabilized base of, we will say, 500 lbs. compressive strength, would start breaking, since even a concrete pavement goes out of shape and cracks under such conditions. Actually, our test is far more severe than necessary. What we should determine is the amount of water absorption of such base placed on soil that has been compacted to varying density, the compacted soil, itself, being in contact with water on the bottom.



Charles M. Baskin

mediums, clay and asphalt, in one and the same mixture? Hence, it isn't a case where we are out to build road bases by taking aggregates and cementing the mass with asphalt. We have built such asphalt-aggregate bases for years with excellent results and will, no doubt, continue with this form of construction. Our waterproof mechanical stabilization development, however, is entirely a matter of waterproofing and not of cementing. It so happens that the coöperative investigation has brought out a number of additional and important features. For instance, if 2 percent R.C. 1 is used instead of 2 percent S.C. 1, primarily to waterproof the mechanically stabilized mass, we not only obtain better waterproofing but without detracting from the cementing value of the clay, the strength of the whole mass is materially increased. If R.C. 1 content is raised to around 3 percent, structural strength starts to drop. Add to this the economic aspect and you have tangible facts which can scarcely be argued down.

Mr. Goldbeck states that he does not like the idea of a coarse aggregate not being as good as a fine aggregate. Well, I dare say that a number of things have come out in our coöperative investigation which, at the moment, I may not like, myself. As far as Mr. Goldbeck's criticism is concerned, however, I wonder if I made myself clear. Our purpose is to produce mixtures, which in cured state, hold together and are stable, irrespective of confining forces. A well-graded aggregate and especially one in which the particles are of irregular shape, will compact to form a non-yielding or undistortable mass without the use of any cement, clay, or otherwise. But the stability of such layers is largely due to confining influences and must rest on something that has appreciable resistance to distortion under a load. We are dealing definitely with a rigid material that retains its shape under surface stresses, irrespective of confining influences. Consequently, the standard compressive strength test is applicable to it. If our rigid mixtures show appreciable structural strength when applying a load on a small section of it, a 6-inch diameter cylinder, it merely means that on the road, as a continuous slab, the confining influences of the rest of the material will simply give it additional strength, but it does not detract from its unit area strength as tested by the standard compression test.

Mr. Newman's question in regard to P.I., whether the figures were on the final mix or on the clay itself, I believe the figures indicated are on the clay and not the final mix. In respect to absorption, we found, as you might have noted on some of the tables, that after 10 days the curve flattens out, which is a pretty definite indication that water absorption, whether in the laboratory or the field, will reach a static state. I do not see any reason to expect that though already in this mixture. It would be the resulting P.I. of the mixture that we are interested in. Another question—one of his charts showed in one case that he obtained a lower percentage of absorption where he had a P.I. of 17 than where he had a P.I. of 7, which is contrary to all the results of work we have done on this subject. It may be that the sand in the two mixes was different in quantity or that the absorption time was not long enough to let the specimen with more clay take up all the water it would. Naturally it will take it up more slowly. Also I would like to know what the sizes of these specimens were, because I feel that this factor has considerable bearing on the compressive strengths that were obtained, in that the addition of asphalt slows down the absorption rate, and to obtain the full amount of absorption on a fairly large specimen would take a great deal of time, possibly more even than the hundred and twenty days that were mentioned.

MR. BASKIN: Starting with the remarks made by Mr. Klinger, I will admit that it was very negligent not to have a copy, but then from my past experience in attending conferences, I am not the only offender, so I will hide behind that. Secondly, his story about a case in the south sounded to me as if they were digging trenches rather than stabilizing. I want to remark that our work so far has been paralleled with construction in the field, not of the type that Mr. Klinger described, but rather covering a number of airports that have been in service from coast to coast. The amount of actual work done and based on the process I described would aggregate a surface area of approximately three million square yards. We have been observing the behavior of that type of construction in the field, studying it, and we are continuing to do so. I said by way of introduction that this is a paper on how to reduce the amount of asphalt, how to use less asphalt, not more asphalt. Now, being a producer, it appears as if I were speaking out of turn. I should be concentrating on methods of how to use more asphalt, not how to use less. Perhaps I should apologize for such a line of work. It is to be observed, however, that the basis for our work was mechanical stabilization which is essentially the technique of cementing together a graded aggregate with clay binder. Our activity concentrated on eliminating the outstanding weakness in mechanical stabilization, namely, that unless moisture is entirely blocked off from such structures, top, surface, or even sides, the clay bond is entirely destroyed and we merely have a mass of aggregate that may retain its shape only if in a confined state. Thus, asphalt is brought into the picture purely as a waterproofing material, not as a cement. What sense is there of using two cementing procedure followed with these granular type mixtures and the test methods used with the soil mixtures such as the sands, silts, and clays we have encountered in our study of soil-asphalt mixtures.

MR. A. T. GOLDBECK: You will notice that the criterion for stability used by Mr. Baskin has been the compressive strength test, and I am wondering whether that is the proper criterion to use for this particular purpose? You know that when you make a compressive strength test, you have the matter of Poisson's ratio coming into play. That means that when a load is applied on the axis of the cylinder, naturally the tendency is to increase the diameter of that cylinder, and if there is no resistance to increasing the diameter, naturally you get a very low load. Mr. Baskin, in one of his tables, pointed out that with large-sized aggregate you get a very much lower compressive strength than with small-sized aggregate. I do not like that, but think perhaps it can be explained. You know that when you put a layer of coarse material on a subgrade and subject it to load, especially if it is of angular character, there is a considerable amount of stability. Yet if you put that same aggregate in test cylinder and take the mold off, it will simply fall to pieces and will not have any compressive strength at all. So I think there is something there that needs further investigation. I just want to point that out.

MR. FRANK NEWMAN (Texas State Highway Department): We are particularly interested in the gentleman's paper because the object of using clay as the binding medium, with asphalt for waterproofing, is something we have been trying to accomplish in our work, although we have been dealing principally with soil fines. It would appear from one of the previous discussions that the material might make a satisfactory base material without the addition of any asphalt at all, since it contains only 20 to 28 percent soil binder, I believe, and we consider that a satisfactory base material. I notice one of his P.I.'s was 7. What I would like to do is to ask him a question or two, to help clarify some things, if he can remember these two or three I am going to ask. One is the P.I. that you showed there of 7 and 17; is that the P.I. of the final "minus forty mesh" portion of the mixture, or is it the P.I. of the clay?

MR. BASKIN: The clay, which was added.

MR. NEWMAN: Mr. Baskin states that that is the P.I. of the clay which was added, and I should think it would make considerable difference how much sand passing the forty was amounts of bitumen is quite at odds with what we have observed and what has been reported before. Successful use of approximately 4 percent bituminous material has been reported but Mr. Baskin submits laboratory data showing 2 percent cutback asphalt to be sufficient as measured by the tests applied.

This reminds me of one of the favorite stunts employed by the personnel of one of the southern states. When inspection trips of their field work on soil stabilization are made, one of the trips is to a surface treated soil road which has given satisfactory service for many years. On this road, for a length of about two miles, they have stabilized the materials in the roadway by scarifying and applying varying percentages of bitumen. Construction was according to customary road-mix methods and, if we remember correctly, bitumen percentages varied from 1 tc 7 percent. After the inspection is completed and during a discussion of this project, the statement is made that they were able to successfully stabilize this particular soil with bitumen contents ranging anywhere from 1 to 7 percent. However, on either side of the stabilization project, the undisturbed roadway which contains zero percent bitumen, is still giving satisfactory service. Obviously, the correct answer is that regardless of the amount of bitumen used in the experimental sections, this particular soil was naturally stable and did not require bituminous stabilization.

Several questions come to mind in connection with Mr. Baskin's presentation. The mixtures are described as clay-gravel to which small amounts of cutback asphalts have been added. We wonder if bitumen was actually required in these mixtures? We also wonder if it would have been possible to produce better mixtures if clay were not used thereby developing a dense-graded asphaltic concrete mixture? We do not remember any description of the method used for curing. The type of laboratory curing employed for mixtures containing clay has been found to have an important bearing on subsequent test results. We wonder if the percent moisture absorption was reported on the basis of total weight of the six by six cylinders?

MR. BASKIN: That is correct.

MR. KLINGER: And there has been no field work in this investigation?

MR. BASKIN: There has been.

MR. KLINGER: I am sorry. There has been. We may wish to submit later a written discussion comparing the design

9. The substitution of all crushed for all round particles for the portion of a stabilized mixture coarser than a No. 4 sieve, increased the compressive strength by from 20 to 25 percent.

10. S.C. liquid asphalts added for waterproofing, usually gave a slight lowering of compressive strength, M.C. liquid asphalts either had no effect or gave a slight increase, while R.C. liquid asphalts invariably gave an increase in compressive strength.

11. The various liquid asphalts were approximately equally efficient as waterproofing materials, when used in amounts of 1 to 2 percent.

12. The use of admixtures having a strong affinity for water, which cause stabilized mixtures to either absorb or maintain a high moisture content, should be avoided, because of their very detrimental effect on the bearing capacity of stabilized base courses containing them.

13. Tests made so far have not indicated positively that adding the clay and bitumen in the form of a clay-water-bitumen slurry gives a waterproofed stabilized mixture with qualities superior to those made with pulverized clay and bitumen added separately.

14. In conclusion, it should be emphasized that if waterproofed stabilized base courses are placed on poorly constructed subgrades, they will fail just as every other type of base course has failed under this condition. When placed upon properly constructed subgrades, however, waterproofed stabilization for base courses appears capable of providing highways and airport runways with more satisfactory service performance for a given or even smaller expenditure in most localities where the required materials are available, than has been obtained with other types of base courses in the past.

Discussion

MR. E. W. KLINGER: This paper calls for considerable study and since Mr. Baskin did not prepare copies for distribution before this meeting we may wish to submit a written discussion after we have had an opportunity to study the data presented.

We believe that verification in the field will be required for this design procedure. The use of such small

1. The absorption or maintaining of a high moisture content leads to a very serious decrease in the bearing capacity of mechanically stabilized base course mixtures.

2. The incorporation of small quantities of liquid asphalt of the order of 1 to 2 percent reduces the water absorption of mechanically stabilized mixtures, and thereby tends to preserve the high bearing capacity these possess when dry.

3. Differences of over 100 percent in compressive strength were obtained as the gradation was varied over the usual grading band for stabilized mixtures.

4. Highest compressive strength has been consistently obtained with the grading represented by the minimum of coarse material combined with the minimum of soil fines permitted by the grading band.

5. Mechanically stabilized mixtures containing no particles larger than a No. 4 or even a No. 10 sieve gave higher compressive strengths than any of the stabilized mixtures containing coarser aggregates.

6. The fact that high compressive strengths can be obtained for stabilized mixtures containing no particles larger than No. 4 or No. 10 sieves, is of considerable economic importance, because coarse aggregates are usually the most expensive ingredient of a mechanically stabilized base course mixture. There are also many areas where large deposits of sand are readily available.

   Furthermore, it is to be observed that without the use of a binder, granular materials below the No. 4 and No. 10 sieves are not suitable as base course materials by the old methods of construction.

7. The compressive strength of a mechanically stabilized mixture increases rapidly with an increase in density up to 145 pounds per cubic foot. This latter density is about the practical maximum that can be specified for waterproofed stabilization in the field.

8. A much higher plasticity index can be tolerated in a waterproofed stabilized mixture than for ordinary mechanical stabilization. This is highly desirable because of the much higher compressive strength obtained when a higher plasticity index is used.

(2) Because it is dense and waterproof, a waterproofed mechanically stabilized base course cannot function as a water reservoir between the subgrade and wearing surface as has so frequently happened with porous gravel and crushed stone, or consolidated gravel bases, because of their porosity, and has led to their failure.

Like other types of soil stabilization, a waterproofed stabilized base course is friable, and must be protected from the wear of traffic by a surface course. However, the base course and subgrade should be designed to support the full wheel load, and the wearing surface should not be of greater thickness than will just withstand the abrasion of the traffic to which it will be subjected.

The consistent success of waterproofed mechanically stabilized base courses depends upon adequate laboratory inspection and control during their construction. A complete sieve analysis on the finished mix being turned out by the stabilization plant should be made for at least every four hours of plant operation, together with a determination of its moisture content, and at least one density determination should be made on each layer of base course being consolidated per 1,000 to 2,000 square yards of roadway. Adequate inspection is so important that one would be justified in even going so far as to state that unless suitable provision has been made for ample laboratory control over each phase of construction, that no attempt should be made to construct a waterproofed mechanically stabilized base course.

V - Summary

The more important results, of the investigation carried out thus far, are summarized below. Some of these results should probably be considered as tentative for the time being, since most of the results have been obtained for thoroughly dried mixes. It is possible, as has been pointed out in the paper, that at the 1 to 3 percent moisture which these stabilized mixtures appear to contain under normal field conditions, that some of the conclusions which can be drawn from the data already obtained, may have to be modified. The effect of the presence of from 1 to 3 percent of moisture on the engineering properties of mechanically stabilized mixtures, is being intensively studied at the present time in a continuation of this coöperative investigation.

distance of any proposed project. It is particularly suited to Canada and the northern United States, where owing to repeated glaciation, large deposits of gravel, sand and clay binder are available almost everywhere.

Waterproofed mechanically stabilized base course mixtures should preferably be made in one of the continuous mix stabilization plants now on the market. Three ingredients, gravel or crushed stone, sand or stone screenings, and clay binder, are almost invariably required to give the grading desired and should be fed to the plant in three separate streams. The use of three ingredients provides the degree of flexibility required for more accurate control of the grading of the finished mix. The finished mix turned out by the plant should contain 6 to 7 percent of water, (the optimum moisture or 1 or 2 percent above), and approximately 1 percent of liquid asphalt thoroughly distributed as waterproofing material.

The mixed material should be spread on the prepared subgrade in layers of not more than 2 inches compacted thickness by spreading machine or motor patrol, and should be rolled with pneumatic-tired rollers to a minimum dry density of 145 pounds per cubic foot. Each 2 inch layer after being compacted to this density, should be allowed to dry as thoroughly as prevailing weather conditions permit before the succeeding layer is placed. Laying this material in 2 inch layers provides the opportunity for much more rapid consolidation to high density, and for more rapid loss of moisture after compaction is complete, than could be obtained with the use of thicker layers. The loss of moisture after consolidation is essential to the development of high bearing capacity.

Waterproofed stabilization has several distinct advantages over the consolidated gravel and porous crushed stone and gravel bases which have been so widely used, particularly when the subgrade contains sufficient clay to become plastic when wet.

(1) When even a single 2 inch layer has been put down during construction, and has received a few passes of the roller, it sheds all rain which may fall, instead of allowing it to pass through base course and soften the subgrade as happens with the usual porous crushed stone or gravel and consolidated gravel bases. The layer of waterproofed stabilized base course remains firm and protects the subgrade from surface moisture, is dry almost as soon as a rain stops, and thereby reduces construction delays to a minimum.

Suppose axle load	=	30,000 pounds
Then wheel load	=	15,000 "
If tire pressure	=	90 " per square inch
The contact area	=	$\frac{15,000}{90}$ = 167 square inches
Radius of contact area	=	7.3 inches
Diameter of contact area	=	14.6 "
Circumference of contact area	=	46 "
If subgrade bearing capacity	=	25 lbs./sq. in.
The load carried by the subgrade	=	(167) (25) = 4,180 pounds
Then load to be carried by the base course	=	15,000 - 4,180 = 10,820 pounds
If shearing resistance of base course	=	40 lbs./sq. in. (based on a compressive strength of 100 lbs./sq. in.)
The thickness of base course required	=	$\frac{10,820}{(46)\ (40)}$ = 5.9 inches

Consequently, a waterproofed stabilized base course 6 inches in thickness is capable of supporting an axle load of 30,000 pounds under the field conditions specified in this problem.

IV - The Construction of Waterproofed Mechanically Stabilized Base Courses

Waterproofed mechanical stabilization, consisting essentially as it does of granular materials and clay binder, is particularly adaptable to those widespread regions where geological disturbances have provided deposits of suitable clay binder and mineral aggregates within a reasonable

A number of tests also indicate that the presence of a small amount of moisture in a waterproofed stabilized mixture increases the degree of water absorption above that obtained for a dry mix.

18. The Thickness of Base Course Required

One of the ultimate reasons for the carrying out of this research investigation, was to obtain the data which would enable an engineer to calculate the thickness of base course for any project under the conditions to which it is exposed in the field.

A sample calculation,for determining the thickness of waterproofed stabilized base course required, is worked out below. Figure 9 illustrates the method of solution.

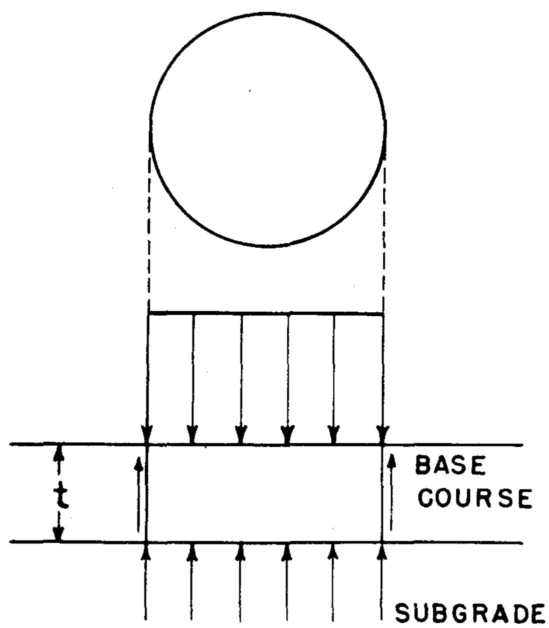


DIAGRAM ILLUSTRATING THE FORCES INVOLVED WHEN DEVELOPING THE LOAD CARRYING CAPACITY OF BASE COURSE AND SUBGRADE

FIG. 9

There is some indication that for waterproofed stabilized mixes dried no further than to the 1 to 3 percent moisture found in the field, these made with a clay-water-bitumen slurry tend to absorb more moisture than waterproofed stabilized mixtures made with pulverized clay. This would seem to be due to the fact that all aggregate materials in a stabilized mix must be waterproofed at least at their points of contact, whereas in a clay-water-bitumen slurry, probably the waterproofing effect is confined largely to the clay itself.

If slurries are to be considered as a means of introducing clay binder into a stabilized mixture, it may be found essential to limit them to clay-water slurries, the bitumen for waterproofing to be added to the mixing unit after the clay slurry.

17. Influence of Moisture on Compressive Strength and Water Absorption of Waterproofed Stabilized Base Course Mixtures

Under field conditions a waterproofed stabilized base course would seldom be thoroughly dry even after construction is complete. The moisture content where waterproofed stabilized base courses have been down for over a year are approximately 2 percent but may be as low as 1 percent.

It is important, therefore, to know what effect moisture contents between 1 and 3 percent will have on the compressive strength and water absorption of waterproofed stabilized mixtures.

There has not yet been time to systematically study this phase of waterproofed stabilization, but it will be thoroughly investigated in a continuation of this coöperative investigation during the present winter.

The study of waterproofed stabilized mixtures which have only been dried to the 1 to 3 percent of moisture which they may be expected to contain under the usual field conditions, may provide information that will require some modification of the conclusions that can be drawn from the data which have already been obtained.

The few tests made up to the present time, indicate that properly designed waterproofed stabilized mixtures of 145 pounds per cubic foot dry density, and 3 percent moisture content, have compressive strengths of the order of 100 pounds per square inch.

This compressive strength may decrease rapidly with a decrease in the density of waterproofed stabilized mixtures otherwise identical, and at 135 pounds per cubic foot and 3 percent moisture, compressive strengths as low as 30 pounds per square inch were obtained. However, there is no justification for permitting the construction of waterproofed stabilized base courses of less than 145 pounds per cubic foot dry density, provided their gradation is within the grading band of figure 5.

pulverized clay used for this study was ground in a hammer mill, and was reduced to a much finer size than the clay shredder on a stabilization plant is generally able to do.

16. Effect of Slurry vs. Ordinary Mix on Water Absorption

Generally speaking, as shown in table 17, a stabilized mixture made with a clay-water-bitumen slurry shows a slightly lower water absorption than one made in the ordinary manner with pulverized clay, provided the stabilized mixtures have been thoroughly dried before the water absorption test begins. The differences in water absorption are not usually large.

Table 17

Effect of Slurry vs. Ordinary Mix on Water Absorption

Type of Mixture	Density	P. I. of Finished Mix	Admixture	Percent Water Absorption				
				Time of Absorption in Days				
				7	14	21	28	35
Slurry	140 lbs./ft.^{3}	7	1% R.C. 1	0.25	0.47	0.56	0.72	0.76
Ordinary	140 "	7	"	0.19	0.27	0.42	0.58	0.82
Slurry	140 "	17	1% M.C. 1	0.35	0.60	0.82	1.1	1.1
Ordinary	140 "	17	"	0.53	0.64	0.88	1.1	1.4
Slurry	145 "	17	"	0.38	0.67	0.84	0.98	1.1
Ordinary	145 "	17	"	0.35	0.80	1.05	1.1	1.3
Slurry	140 "	7	"	0.53	0.71	0.88	1.0	1.3
Ordinary	140 "	7	"	0.58	1.2	1.6	1.9	2.0
Slurry	145 "	7	"	0.17	0.28	0.39	0.46	0.56
Ordinary	145 "	7	"	0.52	0.66	0.88	1.1	1.1
Slurry	145 "	7	"	0.55	0.87	1.1	1.3	1.6
Ordinary	145 "	7	"	0.35	0.58	0.75	0.91	1.1

There are many exceptions to this general trend, however, the ordinary mixture sometimes showing a lower water absorption than the one made with the slurry. The last four items at the bottom of table 17 are for mixes otherwise identical in every respect, but made in two different laboratories. The first of these two pairs of mixes shows a decided advantage in favor of the slurry, the second pair an almost equally decided advantage in favor of the ordinary mix. No positive reason can be suggested for this difference unless the slurries were not made exactly alike in both laboratories.

of the clay binder in the stabilized mix to which it was added, should result.

A further refinement would be the incorporation into this clay paste or slurry, of the liquid asphalt required for waterproofing.

To find if clay-water and clay-water-bitumen slurries had any particular advantage over stabilized mixtures made with pulverized clay, an investigation was undertaken in the laboratory.

Data providing a comparison of the slurry versus ordinary mixing procedure on the compressive strength of stabilized mixtures, otherwise the same in every detail, are given in table 16.

Table 16

Effect of Slurry vs. Ordinary Mix on Compressive Strength

Type of Mixture	Density	P. I. of Finished Mix	Admixture	Compressive Strength
Slurry	140 lbs./ft.^{3}	7	nil	337 lbs./in.^{2}
Ordinary	140 "	7	"	295 " "
Slurry	140 "	17	"	409 " "
Ordinary	140 "	17	"	429 " "
Slurry	140 "	17	1% M.C. 1	252 " "
Ordinary	140 "	17	"	217 " "
Slurry	145 "	17	"	377 " "
Ordinary	145 "	17	"	456 " "
Slurry	140 "	7	"	179 " "
Ordinary	140 "	7	"	151 " "
Slurry	140 "	7	1% R.C. 1	261 " "
Ordinary	140 "	7	"	293 " "

So far, there is no marked trend in favor of either method of preparing stabilized mixtures, as far as compressive strength is concerned. Sometimes the slurry mix shows a higher compressive strength, at other times the pulverized clay mix, as the data in table 16 show, although for all the mixes made up to the present time in the various laboratories, this comparison shows a slight advantage in favor of the pulverized clay mix. It should be added, however, that the

Table 15

Effect of Moisture Retaining Admixtures on Water Absorption

Admixture	Percent Water Absorption			
	Time of Absorption in Days			
	7	14	21	28
nil	4.9	5.4	5.5	5.5
0.7% sodium chloride	4.0	4.8	5.3	5.3
0.4% calcium chloride	3.9	4.3	4.6	4.9

Therefore, the addition of sodium chloride and calcium chloride neither increases the compressive strength, nor decreases the moisture absorption of stabilized base course mixtures. As a matter of fact, due to their affinity for water, it is to be expected that admixtures of sodium chloride and calcium chloride will cause stabilized mixtures to absorb and maintain a higher moisture content, and therefore a lower compressive strength and bearing capacity than similar stabilized mixtures without these admixtures.

It is undoubtedly true, that the use of these salt admixtures will reduce evaporation losses of the water required for compaction. However, due to the later detrimental loss in bearing capacity likely to result from their use in even this manner, it would be much preferred to use the extra water which may be required to compensate for evaporation during compaction.

15. Effect of Slurry vs. Ordinary Mix on Compressive Strength

Mechanically stabilized mixtures at the present time are usually made by mixing together gravel, fine sand and pulverized clay and water, preferably in one of the modern stabilization plants. Waterproofing bitumen is also incorporated for waterproofed mechanical stabilization.

There is always some question as to the ultimate degree of distribution of the clay in the finished stabilized mixture, even when a clay shredder is used to pulverize the clay, for much of the pulverized clay from the shredder is still in small lumps.

It would seem that a worthwhile improvement would be made if the clay binder could be converted into a soft paste or slurry before being added to the gravel and sand in the mixing unit of the stabilization plant. The clay would be completely dispersed in such a slurry, and better distribution

Any admixture, therefore, which will either maintain or increase the moisture content of a stabilized base course mixture should be avoided.

Table 14

Effect of Moisture Retaining Admixtures on Compressive Strength

Admixture	Moisture Content	Compressive Strength
nil	0.10%	273#/in.^{2}
0.7% sodium chloride	0.02	284 "
0.4% calcium chloride	0.02	404 "
nil	1.00	124 "
0.7% sodium chloride	1.13	112 "
0.4% calcium chloride	0.90	117 "
nil	2.90	81 "
0.7% sodium chloride	3.20	78 "
0.5% calcium chloride	3.03	81 "

The data in table 14 indicate that commonly used moisture retaining chemicals like sodium chloride and calcium chloride do not increase the compressive strength of a stabilized base course mixture at any moisture content over the range of moisture to be expected in the field. The data in table 14 were obtained at thoroughly dry, 1 percent and 3 percent moisture contents. Observe that at 1 percent and 3 percent moisture contents, there is no significant difference in compressive strength between the control containing no admixture, and the stabilized mixtures containing sodium chloride and calcium chloride.

The somewhat higher compressive strength of the calcium chloride treated mixture when thoroughly dry (0.02 percent moisture) is of no practical value. Calcium chloride has such an affinity for water, that moisture contents even approaching this low order would never be obtained in a stabilized base course under field conditions.

14. Effect of Moisture Retaining Admixtures on Water Absorption

Neither do admixtures of these salts cause any significant reduction in the amount of water which a stabilized mixture will absorb, as the data of table 15 indicate.

Table 13

Effect of Type and Quantity of Bitumen on Water Absorption

Type of Bitumen	Water Absorption % in 35 Days Quantity of Bitumen		
	½%	1%	2%
S.C. 1	4.8	0.8	0.25
S.C. 2	4.4	0.98	0.37
M.C. 1	4.1	1.1	0.20
Control (No Bitumen)		5.3	
M.C. 2	2.8	0.98	0.18
R.C. 1	2.5	1.00	0.44
R.C. 2	3.1	1.6	0.23

reduce moisture absorption from 5.3 percent to about 1 percent.

The addition of 2 percent liquid asphalt lowers the water absorption still further, as would be expected, to about 1/3 percent on the average.

Because they are as effective as the other bitumens for waterproofing but, at the same time, tend to increase compressive strength, the R.C. 1 and R.C. 2 are the liquid asphalts which are recommended as waterproofing materials at the present time.

Because there is increasing difficulty with increasing viscosity, in mixing a liquid asphalt uniformly through a stabilized mixture, it appears at the present time, that a viscosity of about 200 seconds at 122 Saybold Furol is approximately the upper limit, and possibly more satisfactory results will be obtained if the viscosity is limited to 100 seconds. This is a matter which requires more field study before a definite upper limit of viscosity can be specified.

13. Effect of Moisture Retaining Admixtures on Compressive Strength

Mechanically stabilized base course mixtures develop their highest compressive strength and, therefore, their highest bearing capacity when perfectly dry as was shown in table 1 and figure 3.

Table 12

Effect of Bitumen on Compressive Strength

(Crushed Stone 45%, Stone Screenings 27%, Sand 19%, Clay 9%)

P. I. = 7

Admixture	Compressive Strength
nil	368#/in.
1% R.C.1	1086 "
2% R.C.1	1238 "

M.C. 2. R.C. 1 and R.C. 2, on the other hand, almost invariably give an appreciable increase in the compressive strength.

Due to the fact that M.C. 1 in Canada has a viscosity of only ½ to 1/3 that of S.C. 1 and R.C. 1 (Saybolt Furol), due allowance should be made for this fact when interpreting the results of table 11. At a viscosity equivalent to the other two, it would probably always provide a slight increase in compressive strength.

The very high increase in compressive strength given by the addition of 1 percent of R.C. 1 as shown in table 12, may be due to some absorption of the solvent into the crushed stone and stone screenings, thereby providing a harder film of R.C. 1 and higher compressive strength. All of the mixes for which data are given in table 12 were non-absorbent sand and gravel materials.

The data of table 12 indicate that an R.C. 1 made from a low penetration asphalt base might give a much higher increase in compressive strength to stabilized gravel and sand mixtures than any increase shown in table 11. Such low penetration bases, however, might also give stabilized mixtures which are brittle.

12. Effect of Type and Quantity of Bitumen on Water Absorption

The data of table 13 illustrate the waterproofing effect of additions of small amounts of liquid asphalts.

½ percent of liquid asphalt lowers water absorption only slightly for the S.C. materials, but somewhat more for the M.C. and R.C. asphalts.

When the quantity of liquid asphalt is increased to 1 percent, there is very little difference between the waterproofing effectiveness of the various bitumens. All of them grading which is all crushed, that the increase in compressive strength is not as great as might be expected, ranging only from 20 to 25 percent.

Notice also in table 10, that higher compressive strength has been obtained for the mixtures containing the smaller quantity of soil fines, which is further evidence of the trend pointed out when discussing the data of table 3.

11. Effect of Type and Quantity of Bitumen on Compressive Strength

After observing the rapid loss of compressive strength with increasing moisture content illustrated in table 1 and figure 3, one might have been justified in expecting that the use of a liquid asphalt as a waterproofing material would have a similar effect.

The data of tables 11 and 12, however, indicate that while small quantities of some liquid asphalts do lower the compressive strength by a small amount, that others may increase the compressive strength by from 50 to 100 percent.

Table 11

Effect of Type and Quantity of Bitumen on Compressive Strength

Type of Bitumen	Compressive Strength lbs./in.^{2} — Quantity of Bitumen		
	½%	1%	2%
S.C. 1	236	184	206
S.C. 2	245	200	219
M.C. 1	226	217	176
Control (No Bitumen)		230	
M.C. 2	289	246	301
R.C. 1	319	283	475
R.C. 2	399	324	413

In general, the S.C. 1 and 2 give a slight lowering of compressive strength. M.C. 1 and 2 may lower it slightly in the case of M.C. 1 or increase it somewhat in the case of

Table 9

Effect of Plasticity Index on Water Absorption

Admixture	P. I. Finished Mix	Density	Maximum Water Absorption
nil	7	140 lbs./ft.^{3}	5.7%
nil	17	140 "	5.6
1% M.C. 1	7	140 "	2.4
1% M.C. 1	17	140 "	1.4
1% M.C. 1	7	145 "	1.3
1% M.C. 1	17	145 "	1.3

10. <u>Effect of Crushed vs. Round Aggregate on Compressive Strength</u>

Table 10 indicates that by replacing 45 percent of entirely round coarse aggregate retained on a No. 4 sieve in a stabilized mixture by 45 percent of material of the same

Table 10

Effect of Crushed vs. Round Aggregate on Compressive Strength

Grading	Material Retained No. 4		Compressive Strength lbs./in.^{2}
	All Crushed	All Round	
Medial Grading (28% minus No. 40)	45%		299
Medial Grading (28% minus No. 40)		45%	237
Medial Grading Coarse to No. 10 Limiting Minimum Soil Fines (20% minus No. 40)	45%		363
Medial Grading Coarse to No. 10 Limiting Minimum Soil Fines (20% minus No. 40)		45%	305

8. Effect of Plasticity Index on Compressive Strength

Plasticity Index is a rough measure of the cohesiveness of a soil mixture. Compressive strength should, therefore, increase as the P. I. of a mix is increased. Table 8 indicates that as the P. I. of a stabilized mixture is increased from 7 to 17, the compressive strength may increase by from 50 to over 100 percent.

Table 8

Effect of Plasticity Index on Compressive Strength

Admixture	P. I. Finished Mix	Density	Compressive Strength
nil	7	140 lbs./ft.^{3}	295 lbs./in.^{2}
nil	17	140 "	429 "
1% M.C. 1	7	140 "	157 "
1% M.C. 1	17	140 "	217 "
1% M.C. 1	7	145 "	203 "
1% M.C. 1	17	145 "	456 "

At the present time, most specifications for mechanically stabilized base courses limit the P. I. of the final mix to 6. Field experience has indicated that stabilized base course mixtures with a higher P. I. than 6 have poor service behavior under the moisture conditions which usually prevail in the field at certain times of the year.

It should be emphasized that if these mechanically stabilized base course mixtures are waterproofed, so that the detrimental effect of water on them is minimized, the advantage of higher compressive strength for mixtures of high P. I. can be utilized, and the former necessity for limiting the P. I. to the low value of 6 is eliminated.

The last four items at the bottom of table 8 are further evidence of the advantages of specifying and enforcing the highest density which can be reasonably obtained by compaction equipment in the field, because of the higher bearing capacity.

9. Effect of Plasticity Index on Water Absorption

The data of table 9 indicate that an increase in plasticity index does not necessarily cause an increase in water absorption. The second pair of items show that even the reverse can occur.

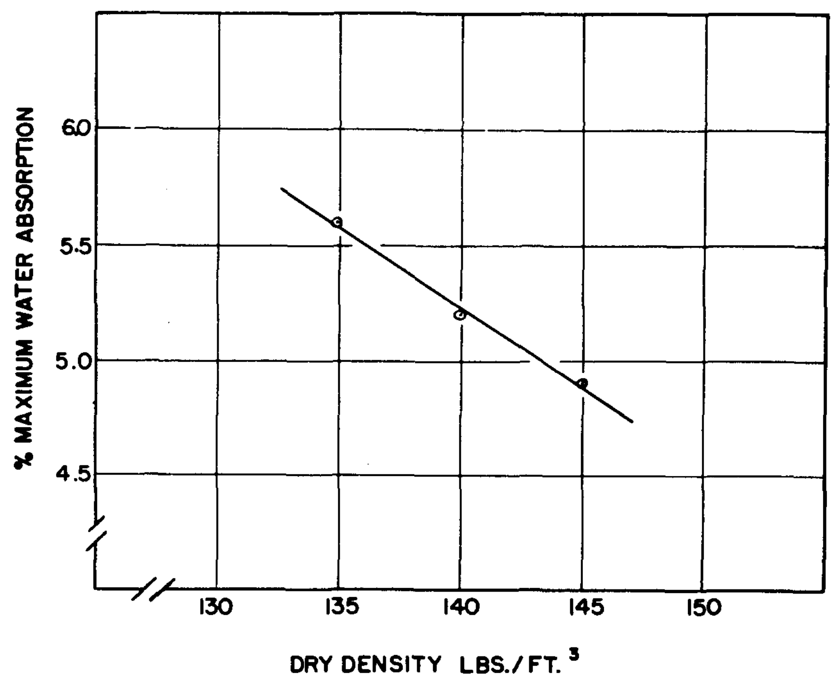
7. Influence of Density on Water Absorption

Since a decrease in density of a stabilized mixture provides an increase in void space, it would be expected that there would also be an increase in the water absorption. This is borne out in table 7 and figure 8.

Table 7

Effect of Density on Water Absorption

Density	Percent Maximum Water Absorption
135#/ft.[3]	5.6%
140 "	5.2
145	4.9



INFLUENCE OF DENSITY ON WATER ABSORPTION

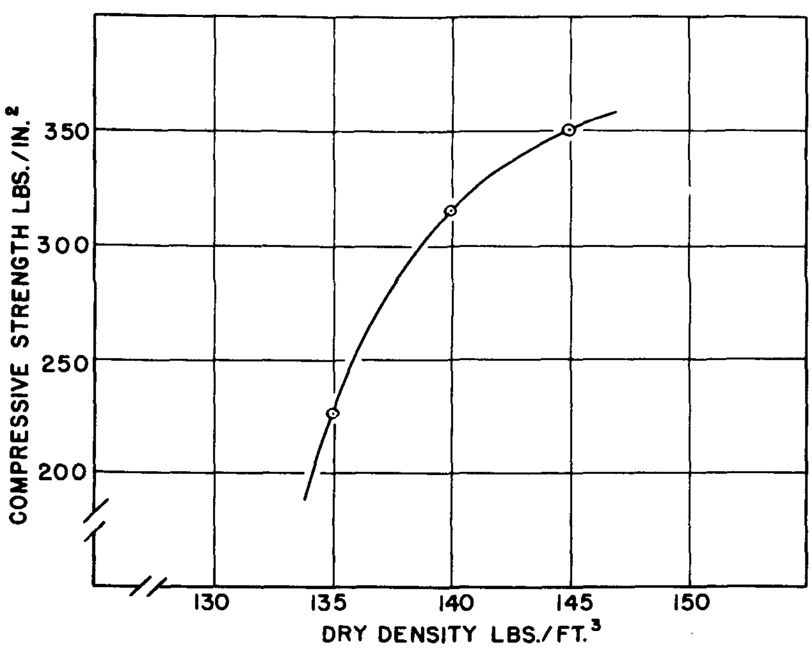
FIG. 8

stabilized base courses. On the basis of this data, it would also appear that the slightly greater compressive strength to be obtained by rolling to densities much higher than 145 pounds per cubic foot, is probably not worth the cost of the extra rolling required.

Table 6

Effect of Density on Compressive Strength

Density	Compressive Strength
135#/ft.^{3}	226#/in.^{2}
140 "	314 "
145 "	350 "



EFFECT OF DENSITY ON COMPRESSIVE STRENGTH

FIG. 7

Table 5

Maximum Particle Size vs. Compressive Strength	
Maximum Particle Size	Compressive Strength
1 inch	366#/in.^{2}
No. 4	406 "
No. 10	373 "

No. 10 sieve, higher compressive strengths were obtained than for the strongest stabilized mixture containing gravel of 1 inch size (Table 3).

The data of tables 5 and 3 prove rather conclusively that coarse aggregate is not an essential ingredient for satisfactory mechanically stabilized mixtures, when these are reasonably dry. This is of particular importance in localities where a great deal of coarse sand occurs, but where gravels are difficult or expensive to obtain.

Just in passing, it should be added that where dry densities of 145 pounds per cubic foot can be obtained readily in the field for stabilized mixtures made with gravel, that densities of 135 to 138 pounds are about the maximum that can be obtained when the maximum particle size is No. 4 sieve, and densities of about 130 pounds per cubic foot represent reasonable compaction when the maximum particle size is No. 10 sieve. If they are waterproofed to keep out the moisture, these lower field densities for No. 4 and No. 10 maximum particle size are of no particular disadvantage, and are the equivalent of 145 pounds per cubic foot for mixtures containing coarse aggregate.

Due to the greater percentage of fines they contain, approximately 2 percent of R.C. 1 should be used for waterproofing stabilized mixtures containing no particles larger than No. 4 or No. 10 sieves.

6. Influence of Density on Compressive Strength

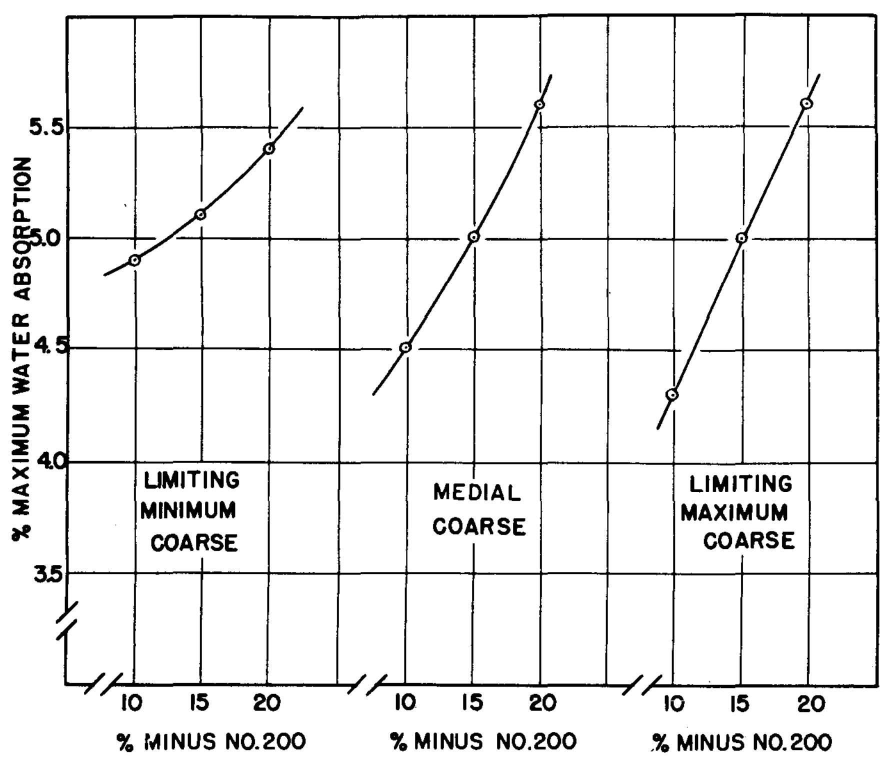
Table 6 and figure 7 illustrate the effect of density on the compressive strength of mechanically stabilized mixtures. As might be expected, the compressive strength increases as the density is increased, although above 145 pounds per cubic foot, the rate of increase in compressive strength appears to fall off rapidly.

The data illustrated in figure 7 justify the density requirement of 145 pounds per cubic foot which has been recently specified in most Canadian specifications for waterproofed

Table 4

Effect of Gradation on Water Absorption

Grading Coarse Aggregate to No. 10	% Maximum Water Absorption — Grading of Soil Fines: Limiting minimum fines	Medial fines	Limiting maximum fines
Limiting minimum coarse to No. 10	4.9	5.1	5.4
Medial coarse to No. 10	4.5	5.0	5.6
Limiting maximum coarse to No. 10	4.3	5.0	5.6



EFFECT OF GRADATION ON WATER ABSORPTION

FIG. 6

Table 3

Gradation vs. Compressive Strength

Grading Coarse Aggregate to No. 10 Sieve	Compressive Strength #/in.^{2} Grading of Soil Fines		
	Limiting minimum fines	Medial fines	Limiting maximum fines
Limiting minimum coarse to No. 10	366	281	248
Medial coarse to No. 10	298	220	191
Limiting maximum coarse to No. 10	256	176	200

Since coarse aggregate is in general the most expensive ingredient in a stabilized mixture, it is a matter of considerable economic importance that a high percentage of coarse aggregate is not required, and that according to table 3, the compressive strength of these stabilized mixtures is actually increased very appreciably by using the least quantity of coarse aggregate permitted by the grading band.

In the case of portland cement concrete, the greater the percentage of cement, the stronger is the concrete. The data in table 3 indicate, however, that when clay binder is the cement, compressive strength increases as the quantity of binder decreases within limits. Clays tend to shrink upon drying, and it is possible that the incipient shrinkage cracks formed upon drying when the larger percentages of clay are used, may account for the lower compressive strengths obtained.

4. Effect of Gradation on Water Absorption

Table 4 and figure 5 illustrate the differences in water absorption for the nine gradings across the grading band previously described.

In all cases, the percentage of water absorbed by the stabilized mixtures increases as the percentage of soil fines is increased.

5. Influence of Maximum Particle Size on Compressive Strength

In table 5 the effect of variations in maximum particle size on compressive strength are shown.

It will be observed that with no particles larger than the No. 4 sieve, and even with no particles larger than the

(3) The limiting maximum of coarse aggregate permitted by the grading band (60 percent retained on No. 4 and 68 percent retained on No. 10 in the final stabilized mixtures).

With each of these three quantities and gradings of coarse aggregate, there was combined for this study the following three different quantities and gradings of the soils fines (passing No. 40 sieve).

(1) The limiting maximum of fines permitted by the grading band for all sizes below No. 40 (35 percent minus No. 40, 20 percent minus No. 200).

(2) Medial grading of fines for all sizes below No. 40 (28 percent of minus No. 40, 15 percent of minus No. 200).

(3) The limiting minimum of fines permitted by the grading band for all sizes below No. 40 sieve (20 percent minus No. 40, 10 percent minus No. 200).

The material between the No. 10 and No. 40 sieves was varied appropriately to permit these variations in the proportions of soil fines to coarse aggregate.

These variations in gradation were all accomplished by the use of the same stock materials.

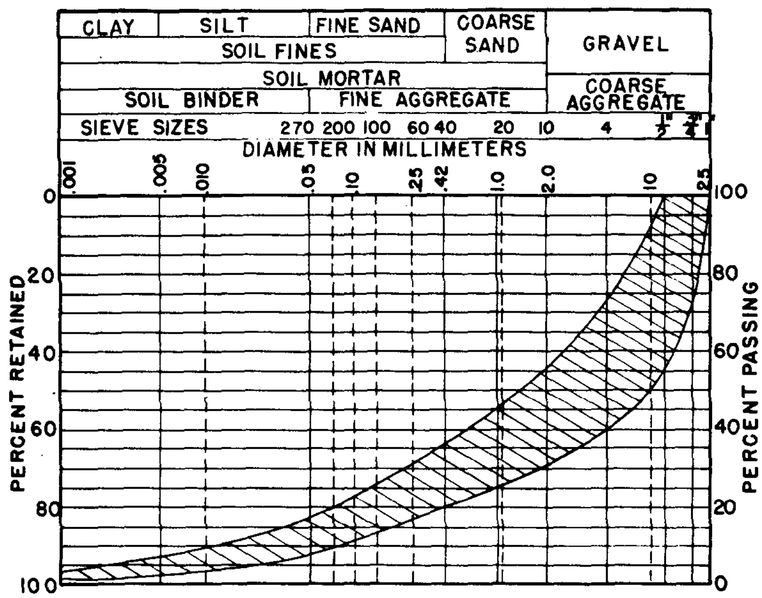
The reference to "medial" quantity of coarse material and to "medial" fines in the above paragraphs, refers merely to the grading of these materials along a curve through the middle of the grading band. The grading band implies that such a curve would give the most ideal grading for a stabilized mixture. However, there is a great deal of evidence to indicate that it is not the ideal grading curve to use for mechanically stabilized base course mixtures.

The results of these variations in gradation on the compressive strength of stabilized mixtures are given in table 3.

Two very important trends stand out in the data shown in table 3.

(1) For a given quantity of soil binder, the compressive strength in general increases with a decrease in the percentage of coarse aggregate in a stabilized mix.

(2) In general, the compressive strength increased as the percentage of soil fines decreased, for all three varying amounts of coarse aggregate.



GRADING BAND FOR MECHANICALLY STABILIZED BASE COURSES

FIG. 5

studied. Nine different gradings which covered every portion of the grading band were selected for this study. They were as follows, all using 1 inch material as the maximum size of aggregate.

Three different gradings of coarse aggregate down to the No. 10 sieve were selected.

(1) The limiting minimum of coarse aggregate permitted by the grading band (28 percent retained on No. 4 and 45 percent retained on No. 10 in the final stabilized mixtures).

(2) The medial quantity of coarse aggregate indicated by the grading band (45 percent retained on No. 4 and 56 percent retained on No. 10 in the final stabilized mixtures).

Figure 4 illustrates water absorption versus time for the control, and for the same stabilized mixture as the control waterproofed with $\frac{1}{2}$, 1, and 2 percent of R.C. 1.

In referring back to figure 3, it can be seen that the incorporation of 1 percent R.C. 1, by reducing the water absorption to a little over 1 percent, would appear to maintain a satisfactory compressive strength in a dry stabilized mixture, particularly in comparison with the low strength at the 5 percent moisture content absorbed by the control. Field tests have shown from 4 to 6 percent moisture content in ordinary mechanically stabilized base course mixtures, particularly in the spring, while waterproofed mechanically stabilized base course mixtures have shown moisture contents only between 1 and 2 percent.

While it is true that 2 percent of R.C. 1 does reduce the water absorption still further, it must be remembered that the bases of the cylinders in this test are immersed in $\frac{1}{4}$ inch of water, which is a rather severe condition likely to be found only infrequently in the field when subgrades are properly constructed. 1 percent of R.C. 1 is therefore probably all the waterproofing material which can be economically and technically justified.

Every engineer who is even reasonably familiar with ordinary mechanically stabilized base courses which have been properly designed and constructed, must have occasionally marveled at their ability to maintain high structural strength under moderate field moisture conditions, although they tend to almost completely lose bearing capacity at any location where they are exposed to moisture conditions which are severe. To these engineers it will appear quite reasonable that even a very moderate degree of waterproofing is probably all that is required to maintain a high uniform bearing capacity throughout this type of base course, under the normal range of moisture conditions likely to be expected.

Consequently, up to the present time there has seemed to be no reason for recommending the use of more than 1 percent of liquid asphalt for the $3\frac{1}{2}$ million square yards of waterproofed mechanically stabilized base course construction laid at various highway and airport projects across Canada during the past two years.

3. Effect of Gradation on Compressive Strength

In figure 5 is shown the well known grading band which is supposed to indicate the range of gradation required for satisfactory mechanically stabilized base course mixtures.

Because of the various ways in which gradation may influence practical design, the effect of variations in gradation on the compressive strength of these mixtures was

(1) They should be laid in thin layers of not over 2 inches compacted thickness, so that each layer can be easily dried to a low moisture content before the next layer is placed. This develops the high compressive strength these mixtures have when dry.

(2) However, even if ordinary mechanically stabilized base courses are constructed in this manner, and are dry when surfaced, they readily take up moisture from the subgrade and other sources, and the compressive strength may eventually become quite low as they approach the 4 to 6 percent moisture often found for them in the field.

(3) If it were possible to waterproof these stabilized mixtures and thereby preserve the high compressive strength they possess when dry, a worthwhile advance in stabilized base course construction could be made.

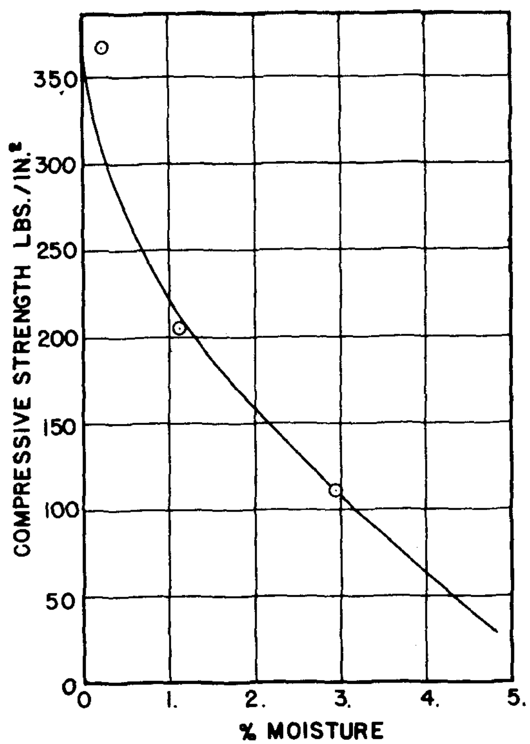
2. Effect of Bitumen for Waterproofing Stabilized Base Course Mixtures

Table 2

Effect of Bitumen for Waterproofing

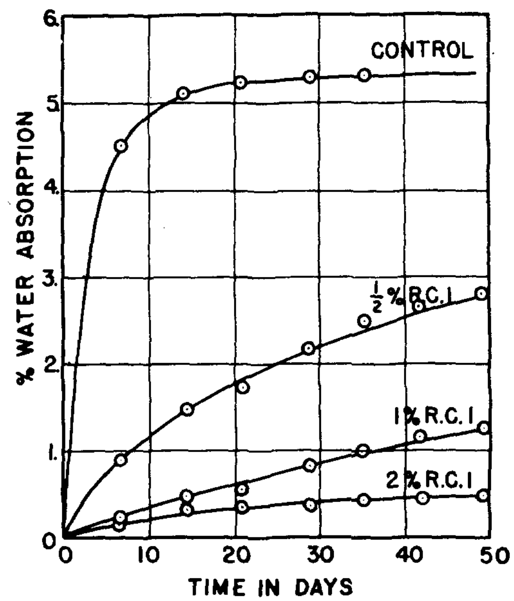
Admixture	Percent Water Absorption						
	Time of Absorption in Days						
	7	14	21	28	35	42	49
Control (No Admixture)	4.53	5.12	5.21	5.25	5.33		
½ percent R.C. 1	0.92	1.45	1.87	2.19	2.51	2.70	2.88
1 percent R.C. 1	0.22	0.40	0.51	0.83	1.00	1.08	1.22
2 percent R.C. 1	0.23	0.32	0.36	0.40	0.44	0.45	0.47

The cheapest waterproofing materials are the bitumens, and the data of table 2, illustrated graphically in figure 4, indicate that mechanically stabilized base course mixtures can be effectively waterproofed with small amounts of liquid asphalts.



EFFECT OF MOISTURE CONTENT ON THE COMPRESSIVE STRENGTH OF MECHANICALLY STABILIZED BASE COURSE MIXTURES

FIG. 3



EFFECT OF BITUMEN FOR REDUCING THE MOISTURE ABSORPTION OF MECHANICALLY STABILIZED BASE COURSE MIXTURES

FIG. 4

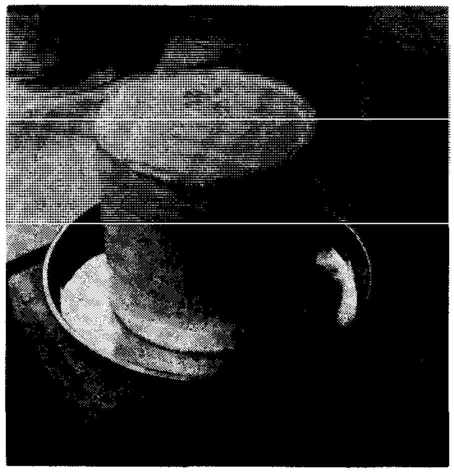


Fig. 2

III - Data and Discussion of Results

1. The Influence of Moisture Content on Compressive Strength

Table 1

Compressive Strength vs. Moisture Content

Moisture Content	Compressive Strength
0.33%	366#/in.^{2}
1.10	205 "
2.93	108 "

The data of table 1, illustrated graphically in figure 3, indicate how rapidly compressive strength decreases with increase in moisture content for any mechanically stabilized base course mixture.

Figure 3 illustrates a number of important characteristics of mechanically stabilized base course mixtures which should influence their design and construction.

all mixes compacted to 145 pounds per cubic foot, compression under from 10,000 to 20,000 pounds load was required. Densities less than this were obtained by varying the degree of compaction with a modified Proctor compaction apparatus.

After compaction, the cylinders were slowly dried to the moisture content required for testing. For tests made on cylinders of completely dry material, final drying was obtained by drying to constant weight in an oven at 160 to 180° F., which usually required from 3 to 4 days. Compressive strength measurements were made by first capping the cylinders and then breaking them in the usual type of standard universal or hydraulic testing machine.

For the water absorption tests, the smaller 6 x 6 cylinders, after being dried to the required moisture content, were coated with paraffin wax on the sides and top, the base covered with a filter paper held in place by cheesecloth, and then set in shallow pans with their bases immersed in ¼ inch of water. The paraffin coating of the sides and top approximates conditions in the field where no evaporation can take place from the sides or through a wearing surface placed on top. The layer of wax on top was punctured with several pin holes to allow any air to escape which might be displaced by the rise of capillary water. Water absorption was determined by weighing daily at first, later at longer intervals, over a period of 250 days in some cases.

All data given are for densities of 145 pounds per cubic foot and a P. I. of 7 for the finished mix, unless specifically stated to be otherwise.

The type of breaking obtained in the compression test is illustrated in figure 1. In figure 2 the water absorption test is illustrated.

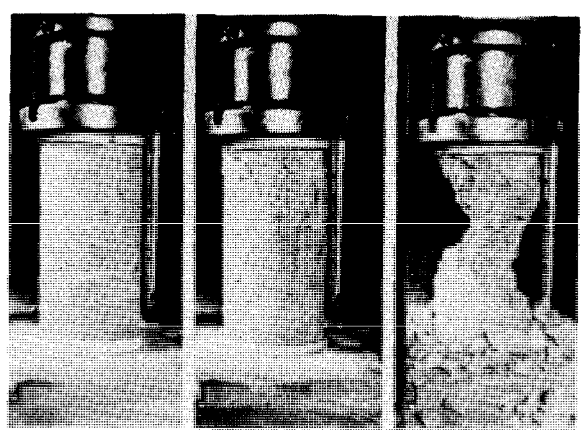


Fig. 1

At the same time, it must be kept in mind that the field condition which tends to most adversely affect the bearing capacity of stabilized base courses, is the presence of moisture, since if absorbed, it softens the clay binder employed as a cement.

Consequently, in every project of this coöperative investigation, the effect of changes in one variable at a time on the compressive strength and water absorption of stabilized mixtures was studied, while all other variables were maintained constant.

The use of the simple compression test as a measure of bearing capacity, neglects the confining influence to which base courses are usually subjected in the field. However, in comparison with values that can be derived from data in the literature of soil mechanics, and which indicate the magnitude of the effect of this confining influence on bearing capacity, it appears that the effect of the compressive strength which has been measured for these stabilized mixtures when they are reasonably dry, is several times greater than that of confining influence in establishing the ultimate bearing capacity of stabilized base course mixtures. Consequently, the compression test appears to be quite satisfactory.

Each value given for compressive strength in the following graphs or tables is the average for three cylinders 6 inches in diameter by 12 inches high, while each value given for water absorption is the average for two cylinders each 6 inches in diameter by 6 inches high.

The various materials, gravel, crushed stone, stone screenings, sands and clay binders, used in each laboratory, were from common stock sources, which permitted direct comparisons between different laboratories. The largest particle size used just passed a 1 inch square sieve. In order to easily obtain wide ranges in gradation between various mixtures, most of the stock materials were largely of one size.

For each mixture, 125 pounds of the various materials required were weighed into a large galvanized mixing pan. These were first thoroughly mixed dry for 10 minutes by shoveling from one end of the pan to the other. Water was then added (usually 6 to 7 percent), together with any admixture being investigated, and wet mixing was continued for at least 10 minutes, and longer if more mixing were required for more uniform distribution of the admixture.

When mixing was complete, the moisture content was determined, and the exact quantity of wet mixture was then weighed out for compaction into each cylinder, to just give the dry density required. Each cylinder was made by placing the wet mixture into steel molds in layers, each layer being well tamped by hand with the standard Proctor tamper. For in the stabilized mixture, if it were also first dispersed in this clay-water paste or slurry?

It was readily seen, that obtaining any comprehensive quantitative data on the effect of the large number of variables involved in the intelligent design of these stabilized mixtures, within a reasonable period of time, was beyond the capacity of any one laboratory. The possibility of a combined attack on this problem was, therefore, discussed with several interested organizations, and a coöperative investigation to cover all of the variables involved was decided upon. The investigation was divided into a number of research projects, one or more of which were undertaken by each of the following organizations: Quebec Provincial Highway Laboratory, Quebec City, P. Q.; Ontario Provincial Highway Laboratory, Toronto, Ontario; L'Ecole Polytechnique, Montreal, P. Q.; Queen's University, Dept. Civil Engineering, Kingston, Ontario; and Imperial Oil Research Laboratories, Sarnia, Ontario.

Dr. McLeod, co-author of this paper, acted as coördinator for the whole program.

A very large amount of work was carried out on a number of these research projects in the winter and spring months of 1940, and essential data was made available for the building of a number of airports and highways in Canada during the past construction season.

It should be noted that each of the various laboratories, participating in this coöperative research program, is publishing the results of its portion of the investigation in the Proceedings of the Canadian Good Roads Convention held last October, and the data presented in the following pages are taken from their results.

II - Test Procedure

It has been previously pointed out that the fundamental function of a base course is to supply the additional required bearing not inherent in the subgrade. For this cooperative investigation, therefore, it was necessary to adopt some suitable measurement for evaluating quantitatively the effect of each variable, moisture content, gradation, density, plasticity index, maximum particle size, type and quantity of bitumen added as a waterproofing medium, etc., on the bearing capacity of mechanically stabilized base course mixtures. The property of these stabilized mixtures which furnishes a measure of bearing capacity, and is, at the same time, affected by changes in each of these variables, and can be most simply and easily measured, is their compressive strength.

7. Clay Binder

The binding properties of clays and their behavior with water may vary widely, depending upon the source of the clay. At the present time, it is recommended that the plasticity index of mechanically stabilized base course mixtures be limited to 6.0 because of the detrimental effect of water on mixtures of higher P. I. By waterproofing these stabilized mixtures, this difficulty is minimized, and a much higher P. I. for the finished stabilized mixture can be used. With regard to this variable, the following quantitative data are required:

(a) Effect of variation in P. I. of the finished stabilized mixture on its compressive strength and water absorption.

(b) Effect of clays from different sources on the compressive strength and water absorption of finished stabilized mixtures of the same P. I.

(c) Comparison of the effectiveness of a given quantity of a given bitumen to waterproof stabilized mixtures of the same P. I., but made with clays from different sources.

8. Wetting Agents

We have heard a great deal about these products lately. Would the addition of wetting agents increase the effectiveness of the liquid asphalts used?

9. Incorporation of Salts in a Stabilized Mixture

What effect do admixtures of these materials have on the absorption and retention of moisture, and therefore upon the bearing capacity of a stabilized base course in which they are used?

10. Method of Incorporating Clay and Bitumen into Stabilized Mixtures

There is room for considerable doubt as to the adequacy and uniformity of distribution of the clay binder in mechanically stabilized base course mixtures turned out by stabilization plants equipped with the usual roll type clay pulverizer or shredder. At least, there is considerable room for improvement in clay pulverizing equipment for stabilized mixtures at the present time. Would the clay not be more effectively and uniformly distributed through the stabilized mixture if it were first thoroughly dispersed in water as a clay-water slurry or soft paste? Also, might not the liquid asphalt added as waterproofing material be more effectively distributed this the term "Waterproofed," thereby describing the whole scheme.

When using this material in the field, it was soon found that there was a serious lack of the fundamental engineering data required for the intelligent design of waterproofed stabilized base course mixtures, as a guide to writing specifications, and for their construction in the field. Some of the variables entering into the sound design of these waterproofed stabilized mixtures upon which almost no quantitative engineering data was available, are discussed below.

1. Density

What is its effect on compressive strength? What is the minimum density below which the mass will be too weak, and the maximum above which the additional bearing capacity is not compatible with costs?

What effect has density on waterproofness? Will increasing density reduce the amount of bitumen necessary to produce a certain degree of waterproofness, and thereby justify extra effort to improve density?

2. Particle Size

The influence of maximum particle size. Data on this phase are clearly essential in order to widen the scope of granular materials that may be suitable for this type of construction, all of which is important in the reduction of costs. In some areas, sand is more readily available than gravel.

3. Surface Texture of Particles

Translated in terms of crushing. Will the irregularity of the surface texture of particles obtained by crushing, give a sufficient increase in the compressive strength of stabilized mixtures over that obtained with uncrushed materials, to warrant the extra cost of crushing?

4. Fluid Bitumens

How do the various S.C., M.C. and R.C. products compare on the basis of efficiency for waterproofing?

5. Bitumen Content

What is the effect of variation in bitumen content on the water absorption and compressive strength of stabilized mixtures?

6. Fluidity of Bitumen

How does the fluidity of a bitumen effect its dispersion in the stabilized mass, and the water absorption and compressive strength of the stabilized mixture?

At this point, it is important to observe that since reduction in cost is an important phase of our total objective, we are trying to obviate the necessity for building a structure capable of supporting thousands of pounds per square inch, if the maximum wheel load does not exceed 100 pounds per square inch. We consider it sound engineering if the subgrade and base course are designed to carry only the maximum anticipated wheel load. If this is all that is required, clay soil makes not only an entirely adequate binder for the base course, but is also the lowest cost cement per unit binding power within limits, that can be obtained.

The main difficulty with clay, however, is that moisture will reduce its binding capacity. Consequently masses of material bound together with clay must be waterproofed, or some other means must be adopted to block off any ingress of moisture into the clay-cemented mass of material. Actually, the whole scheme of using clay as a binder breaks down unless we develop a low-cost method of preserving the clay-cemented material from the absorption of moisture.

The next step, therefore, is to find a low cost method of waterproofing the clay-bound base course. Since bitumens are the cheapest waterproofing materials, we began to explore the possibilities of liquid asphalt. Our preliminary tests showed conclusively, that any low viscosity liquid asphalt will disperse quite readily in a wet mass of a mechanically stabilized mixture of gravel, sand and clay binder, and practically speaking, the bitumen makes the mixture waterproof. Furthermore, and this is important from the cost angle, the quantities of bitumen required were very small, about 1 percent by weight of the total mass appeared to be adequate. Nor does there seem at the present time any justification either economic or technical, for increasing the quantity of bitumen beyond from 1 to 2 percent for waterproofing mechanically stabilized base course mixtures.

Our preliminary results were sufficiently conclusive to warrant recommending this procedure for highway and airport construction, and in 1939 four airports, and forty miles of highway were constructed at various locations across Canada, using this type of base course construction. The wearing courses were, in some cases, bituminous surface treatments, and in others bituminous paving mixtures about 2 inches thick.

We designate this type of base course construction as "Waterproofed Mechanical Stabilization." Our reasons for such designation are, first, to indicate that the addition of bitumen is principally to waterproof the mass and not necessarily to act as a binder., second, that structural strength in the mass is obtained by the scientific design of mixtures of gravel, sand and clay binder, to produce what is generally known as "Mechanical Stabilization." We add to improvement are distinct from such measures as the incorporation of admixtures into the subgrade soil.

There is no need for dwelling at any length on this phase of road construction, for it is already a reasonably well-known practice. No doubt, as time goes on, the subgrade will be further improved as machinery is developed and power costs reduced.

At the present stage of our technique, and with due consideration to relative economics, we restrict ourselves to the measures for subgrade improvement which field practice has indicated we can do, namely, drainage, raising the grade line well above the water table, removal of deleterious subgrade soils and Proctor compaction.

In spite of the application of the most modern technique in subgrade construction, most subgrades lack the bearing capacity required for the support of modern wheel loads. Consequently, a base course must be constructed to make up for this deficiency in subgrade bearing capacity. This is the fundamental function of base courses.

At this point we can state frankly, that we are not satisfied with the classical road bases, whether these be waterbound macadam or gravel. The principle involved in the construction of both macadam and gravel bases, is simply that masses of mineral matter, either of rather uniform coarse size, or varying in size from coarse fragments to dust, will compact into a structure of considerable strength in terms of supporting value, when suitably confined. The factors responsible for this are density and interlocking or wedging together of irregular shape and size fragments, in addition to any confining influence. These factors all contribute in their turn, to the strength of the total mass. The denser the mass, the better the particles are wedged or lodged together, the better will be the resistance to movement of one particle over the other. While we have no definite data on the subject, experience has shown that under field conditions, the supporting value of macadam and gravel bases varies considerably over a wide range.

Even if the standard macadam or gravel base is at its maximum bearing capacity, in its present condition it hardly affords any margin of safety unless the base is made inordinately thick. During the relatively dry periods of the year the subgrade soil itself may have much greater bearing capacity than some of the worn-down gravel bases.

How then may the bearing capacity of the usual macadam or gravel base be increased? One solution would seem to be through the use of clay binders, since it is very easily demonstrated that the structural strength of stone or gravel base courses can be greatly increased by the addition of clay binder, when the mixtures are dry.

design in which the complete road is constructed of three superimposed structures or layers, subgrade, base course, and wearing surface, adequate for supporting the wheel loads and for resisting the wear of modern traffic, at the lowest possible cost.

The conception of a road as a composite structure is no special discovery, for many roads have been built in this manner. The soil subgrade, regardless of the type of soil, has some degree of bearing capacity under most field conditions, but its supporting power may fluctuate widely during different seasons of the year. The usual gravel or stone macadam base generally also has considerable bearing capacity. It is quite evident that the more supporting value any layer or course has, the less is the bearing capacity required in the layer above or in the layer beneath. Conversely, if the bearing capacity of one or more of the multiple layers or courses is radically reduced during certain periods of the year, another course, or other courses have to be made proportionately strong and massive to take up these fluctuations. Up to the present time, whenever the combined bearing capacity of subgrade and base course was not sufficient, the deficiency in supporting value has very frequently been made up by heavy thicknesses of costly wearing surface materials. The conditions described here have only too often been representative of the composite road structure built in the past.

Our present conception of a composite road structure is or should be, two primary layers of soil subgrade and base course, designed to have a combined bearing capacity adequate for the supporting of the heaviest anticipated wheel load, implemented with a wearing course of only sufficient thickness to withstand the abrasive action of the traffic to which it will be subjected.

We consider the design of modern roads as composite structures of properly constructed multiple layers, the only logical approach to low construction costs. It is only in this manner that we can obviate either over-design or under-design. It is only on this basis that we can make the most of the local materials at hand, and reduce to the minimum the use of expensive manufactured addition materials.

The soil subgrade is the primary support of our roads. Consequently, our first step in building the composite structure is to treat the soil subgrade by mechanical means, so that it will have the maximum resistance to distortion under loads at the most critical periods of the year. By mechanical means we have in mind drainage, elimination of undesirable soils and Proctor compaction. These methods of subgrade

WATERPROOFED MECHANICAL STABILIZATION - A DISCUSSION OF A COOPERATIVE INVESTIGATION

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I - Introduction

If frequency of mention denotes popularity, "soil stabilization" is indeed a very popular subject. In the past few years, the proceedings of every meeting or conference dealing with highway technology, almost invariably has had a section devoted to something on soil stabilization. Yet, with all the attention which has been given to this subject, there still seems to be considerable confusion in highway engineering literature and among engineers, as to exactly what highway construction operations the term "soil stabilization" should include. It has been used in connection with improvement of the subgrade through drainage, and in connection with subgrade consolidation. It has been applied to the treatment of soil or soil-aggregate mixtures for highway base courses which are structurally stable under all field moisture and weather conditions.

For the purposes of this paper, it should be emphasized that the term "soil stabilization" is limited to the design and construction of the class of base coursesdefined in the last sentence of the first paragraph. It should be further emphasized, that the results of the investigations discussed in this paper concern essentially only one type of soil stabilization, the type which is being most widely used in Canada at the present time, "waterproofed mechanical stabilization." The paper also points out the advantages of this type of stabilization over the type on which it is based as an improvement, and which has been extensively used for several years, "mechanical stabilization," consisting usually of a scientifically designed mixture of gravel, sand and clay binder, but sometimes of coarse sand, fine sand and clay binder.

It will make for better understanding, if we first define our objective in developing "waterproofed mechanical stabilization."

Broadly speaking, our objective is to develop a new method, or modify and improve existing methods, whereby roads are built as composite structures. We intend to arrive at a