FORMATION OF WASHBOARD WAVES ON DESERT ROADS

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SYNOPSIS

The occurrence of surface corrugations has long been a serious problem on unpaved roads in arid regions. This paper describes the road surface conditions on the Transaharian Road in Africa and gives a résumé of the results obtained to date of studies to determine causes of and means of preventing the formation of corrugated surfaces.

The studies included tests by means of a large open air circular track in which it was attempted to duplicate conditions found in the desert; and tests and field observations of the Transaharian Road. Also included are tests and observations on the effect of the period of oscillation of the unsprung portion of the vehicle, vehicular speed, and tire pressure as well as the grain size and grading of the road materials. The work had not been completed at the time of preparation of this report which summarizes the findings to date.

Experiments have proved for a long time that in dry countries certain roads simply designed and located on the natural ground elevation have a tendency to develop surface corrugations, usually spaced about one meter apart and repeated over distances which are sometimes very large.

On account of their appearance these corrugations have received in France the characteristic name of "tôle ondulée." In the United States they are called washboards.

They constitute a great handicap to traffic. In fact, the length of the corrugation is such that the resulting period of oscillation is in resonance with that of certain parts of the vehicles. As a result, on passing over the corrugation the vehicle is subjected to periodical shocks of an ever increasing amplitude which deteriorate equipment quickly.

The problem of systematical study of corrugations was given to our laboratory in 1941 by Mr. Beau, General Inspector of Bridges and Highways, Director of Public Works to the Ministry of Overseas France, as well as by Messrs. Chadenson and Carpentier, Chief Engineers of Bridges and Highways (at the time General Director and Technical Director of the Mediterranean Sea-Niger Railroad).

That company was in charge of the maintenance of the Transaharian Road, Bechar-Gao, and for that reason was investigating means of avoiding the formation of washboards. Plans were made and a mission sent to the field in 1942 to determine the conditions causing formation of washboards. The mission found that the washboard was formed on soils of a well defined type, always the same, after a relatively short number of passes of the vehicle. While the road crosses terrains relatively varied, it was almost always on the "reg" (i.e., the product of superficial decomposition of saharian plateaus or "hamada") that corrugation took place.

On the "reg" the road was built on the natural terrain by clearing and removing the coarser elements. The soil is constituted of hard particles set in a sand-clay cement which weathers slowly in the air. As a result, the individual particles are progressively set free. Maintenance of the road consists of the removal of the coarser of the free particles leaving on the surface only the sands and gravels smaller than 25 mm. As soon as the natural soil is covered by free particles of medium sizes, a few weeks of traffic are sufficient to create corrugations.

Samples were obtained from the soil in place as well as from the corrugations.

Grain size analyses of those samples are included herewith (Fig. 1). They show a remarkably uniform composition of soil from the corrugations which is always characterized by the presence of pea-gravel and finer particles. It is the constancy of the composition and the fact, repeated in all cases, that the corrugation

[1] Translated by Phillip L. Melville, Associate Research Engineer, Virginia Department of Highways.

will only be formed in the presence of free particles on a hard base, which suggested the study of the formation of those samples on a small scale on the circular test road of the city of Paris.

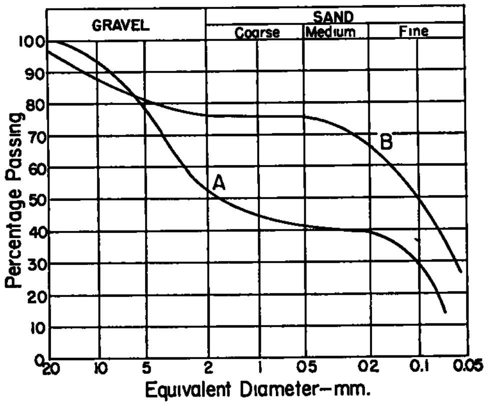

Figure 1. Grain Size Analyses
A. Sample from a road corrugation
B. Sample from natural ground near the road

Figure 2. Moving Frame Showing Non-Hanging Parts

TEST ROAD EXPERIMENTS

The open air circular test road of the city of Paris includes a circular track 80 cm. wide having an average diameter of 15 m. It also includes four steel frames (Fig. 2), 5.70 m. long, attached to a rectangular frame 3 m. long through the center of which is the axis of rotation of the circular test road. Two wheels are moved by electric motors, two others are free though all four frames are tied together. By means of extension set at the end of the frames, one can make the wheels run on different sections of the track. The apparatus has several counters to measure the number of revolutions and the speeds of the wheels.

The total weight of the device is about 7 metric tons. A set of hoists allows adjustment of the effective weight on the soil. Besides, on each of the frames has been fixed a container inside of which one can add additional weights to overload any one wheel.

In the tests it was attempted to reproduce on the track the characteristics found during our trip to North Africa. A base of natural compacted materials was realized by means of soft limestone. This material, when compacted at a low moisture content, furnishes a monolithic foundation of elasticity similar to that of the natural ground in the arid zones. The foundation was obtained with these materials for a thickness of 35 cm. spread in thin layers and compacted with a hammer. The ground was rolled by means of a cast iron roller set in place of the wheels. Then finer particles were spread on the surface as a mixture of pea-gravel from the Seine River and foundry sand to reproduce as nearly as possible the grain size range which was observed on the Transaharian road. The thickness of the sand was from 2 to 3 cm. From the first trials it was found that the requirements for the formation of washboards were perfectly fulfilled. After about 100 passes the track began to wave. Soon after that the corrugations became visible on the ground and the tests had to be stopped at about 200 passes on account of the movements of increasing amplitude in the frame which might have caused its failure.

Having thus reproduced in the laboratory the phenomenon of corrugation, it was attempted to vary the contributing factors to see how to prevent the formation of washboards. It was first attempted to study the elements constituting the track, then the characteristics of the frame proper. The following observations were made:

1. The distance between two waves corresponds (taking into account the average speed of the vehicles) to the distance travelled during one cycle of oscillation by the non-hanging parts. The non-hanging parts constitute an oscillating system with one degree of freedom. It might be considered as being composed of a mass on which two springs were acting: the suspending spring and the tire.

The tire pressure, as well as the stiffness of the springs determines the distance of two waves since they determine the period of the oscillating system.

These facts which have already been previewed in the field have been verified in the laboratory. In particular, it was found that when the period of oscillation of the system was increased, either by reducing the tire pressure, by increasing the stiffness of the suspending springs, or by overloading the wheels (that is to say, by increasing the mass of the oscillating system) the corrugations were further apart.

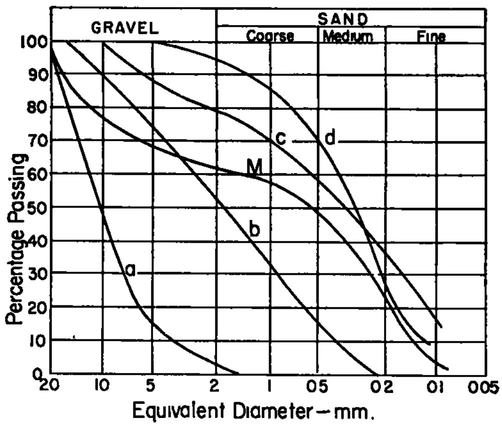

Figure 3. Grain Size Analyses
- **a. Gravel 5–20**
- **b. Seine River sand**
- **c. Juvisy sand**
- **d. Sand smaller than 5 mm.**
- **M. Mixture—similar to A (Fig. 1)**

Though the suspending spring intervenes in determining the oscillating period of the non-hanging system it is practically imposed by the springing action of the loaded tire, the stiffness of which is much greater than that of the suspending spring.

Tests with a cathode ray oscillograph have allowed the determination of the true period of vibration of the non-hanging parts of the framework (wheels and axle counter-weights). It was thus possible to determine the overwhelming influence of the tire pressure. The lowering of the pressure from 4 to 1 kg. per sq. cm. multiplied the length of oscillation by 1.36. The ratio of wave lengths measured in the field under the same conditions is actually close to 1.3 (0.96 to 1.25 meters). On account of the close dependence of the four wheels located on two rectangular diameters and of the means of tying them, the results do not offer a rigorous mathematical precision. Notwithstanding some observed variations, those tests showed that the variations of the true period of vibration of the non-hanging system and that of the wave lengths measured are similar.

2. The test road experiments have shown that a formation of washboards was only possible with a resistant base and free materials on the surface. With the selected materials for the construction of the road, the least moisture which would soften the surface would also prevent the formation of corrugations. Rolling sank the free particles into the foundation instead of displacing them. In all cases, after a rain, it was necessary to wait for complete drying of the base before resumption of the tests.

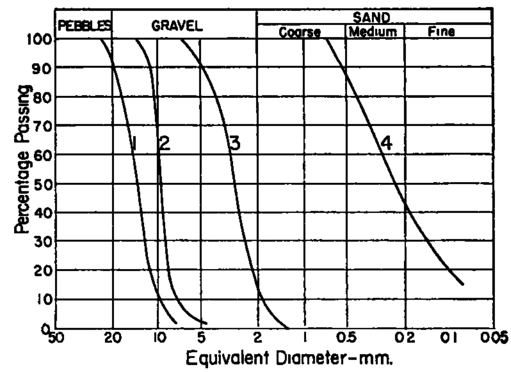

Figure 4. Grain Size Analyses (calibrated materials)
1. **Gravel 10–20**
2. **Gravel 8–12**
3. **Gravel 2–5**
4. **Foundry Sand**

The various materials studied, well graded and uniform materials (the grain size analyses of which are shown on Figures 3 and 4), have furnished the following conclusions: The shape of the waves depends on the grain size of the finer materials. For all materials the particles of which are larger than 5 mm., the undulations take the shape of cross-bands, the base being exposed between two crests (Figs. 5A and 6). For the materials containing an increasing proportion of particles smaller than 5 mm., the undulations tend toward a sine wave shape (Figs. 5B and 7). The better defined undulations were obtained with a material the grain size of which was close to 10 mm. The speed of formation of the washboard is slowed with an increasing amount of finer particles.

Figure 5. Shape of Corrugations
A. Cross band shape found where preponderance of material is larger than 5 mm.
B. Sine wave shape found where preponderance of material is smaller than 5 mm.

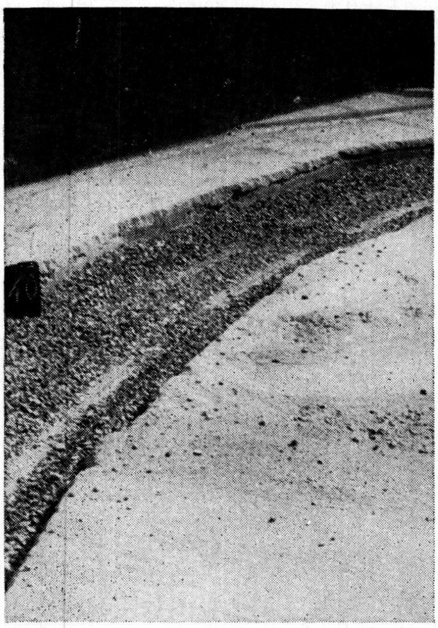

Figure 6. Cross Band Corrugations Obtained on Gravel 5–20—Tire Pressure 1 kg. per sq. cm.

The coarser particles are not thrown. This offers a solution which has been used in certain cases to avoid washboards. On the other hand, travel on a pavement thus built but not rolled is unpleasant and results in a quick wearing out of the tires. The finer particles, on the contrary, are usually thrown on either side of the rut without creating true undulations. Though in the laboratory it was possible in certain cases to recreate undulations with only sand on a terrain constituted by fine sand, there was no formation of washboard.

The tests also included taking movie films which were later shown in slow motion. The films were taken after the finer particles had been removed and replaced by washed gravel to avoid dust. The film showed that on each pass of a wheel the particles of gravel were picked up rather than thrown behind the wheel. The particles, which are also moved

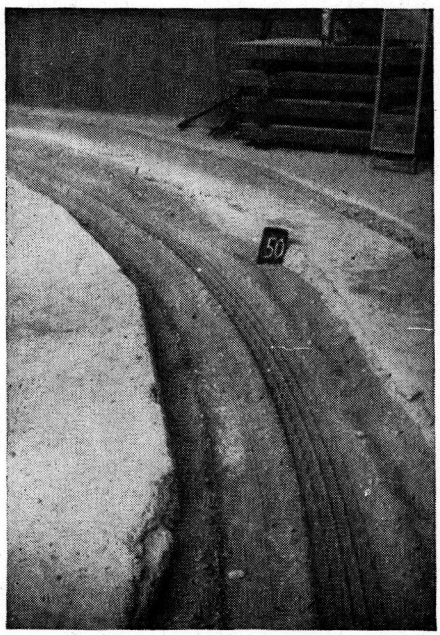

Figure 7. Sine Wave Corrugations Obtained on Juvisy Sand—Tire Pressure 4 kg. per sq. cm.

by a rotative movement around themselves in the same direction as that of the wheel, came together at certain points. Though it was impossible to observe it on the photographs, it appears certain that this displacement increases when the tire is flat on the ground and decreases when it is raised as a result of the oscillation of the non-hanging part.

3. After having studied the importance of the component parts of the terrain, we have tried to study those of the vehicle proper.

It appeared at first that the tire pressure had a great importance in the formation of the washboard though this influence was not established as a linear function independent of the nature of the terrain.

In the general case where a soil is made of free granular materials in which all the particles are larger than 5 mm. on a strong base, the tires cause more washboard as the tire pressure is decreased. This checks the observation often made in Africa that the appearance of vehicles using low pressure tires such as balloon tires have often created washboards where they have never been observed before.

On the contrary, when the soil is covered with a material including the finer particles, tires with very low pressure have no influence. In all cases, the formation of the washboard is very fast if one uses non-pneumatic tires. There lies a contradiction which calls for care in drawing general conclusions.

Tests made with springs with various stiffnesses have shown that stiffer springs delay the appearance of the phenomenon.

We have even found on the test track that by limiting the run with springs one could entirely suppress the formation of washboard. It is impossible to go that far in practice, but it is certain that stiff springs would lessen the formation of washboards. The use of shock absorbers was found to have no value.

Finally, in all cases, it has appeared that speed had a very clear influence on the formation of washboard. The track did not permit speeds greater than 50 km. per hr. Below 20 km. per hr. we have never observed the formation of corrugation. On the contrary, the speed at which they form appears to increase steadily at from 20 to 50 km. per hr. It is likely that if we had been able to get still higher speeds the corrugations would have been formed still faster but the spacing between oscillations would have increased.

TESTS IN PLACE

The laboratory tests were followed by field observations made by the Maintenance Service of the Transaharian Road. They have checked the observations made and have drawn the following conclusions.

First, it has appeared that the sure way to avoid corrugations was to bind the free surface particles by means of a bituminous coating as thin as it may be. After the coating it is important not to leave an excess of gravel on the surface because it has been found that it would also gather in waves which would be troublesome to traffic. Because of a lack of bituminous binder the Service of Maintenance has been led to find that the soils which would give the best results were those made of fine particles, alluviums, plastic tuff or clay.

This checks the observations made previously which have been gathered by Mr. Prunet, Principal Engineer of Public Works in the Colony, and which has been the subject of a memorandum to the various French colonial services.

Mr. Prunet recommends the use for colonial roads of a clay cover which can be found in all the lateritic regions at a depth of about 10 cm. The roads thus covered are worn out by dessication and progressive elimination as dust of the finer particles which constitute the pavement, but there is never a formation of washboards.

The same observations have been made on the Transaharian Road where the washboard has never appeared in the regions covered with clay such as the bottoms of former marshes or even the sections which had been artificially covered with marl.

On the other hand, all the attempts at building pavement by the standard procedure of stabilization have entirely failed. In all cases, the dryness has broken apart the particles and freed the hard ones which came to form the corrugations. The stabilization, as one should not forget, has been established to permit a soil to withstand the rolling under action of water and not to avoid degradation due to dryness. It is not surprising that in these conditions the results have been clearly unfavorable.

CONCLUSION

These are the results of tests made to date. The study is far from being completed. New tests are in progress in the laboratory, as well as on the North African road. To report the entire work would require much more space than we may use in this report to the Board. Yet we shall outline the conclusions which have been reached to date with the hope that further tests will not cause us to amend them:

1. The Vehicle: Prescribe stiff springs and low tire pressure since roads are for the most part built of materials containing a large proportion of fine particles. For the roads consisting of fine sand, very low pres-

sure tires are especially recommended, but, for reasons which have nothing to do with the formation of the washboard.

2. The Road: In all cases, the free granular surface particles must be avoided. The best solution is the use of bituminous binders. A thin top layer of clay or alluvium which would stop the liberation of small gravel may be used as an alternate. Tests made with clay on the Transaharian Road have shown very good results in all cases.

ACKNOWLEDGEMENTS

The study and the tests, which are the object of the paper, have been requested by Mr. Beau, General Director of Public Works in the Colonies, and Mr. Chadenson, then General Director of the Mediterranean Sea-Niger Railroad. The laboratory studies have been made by Messrs. Florentin, L'Heriteau, and Guilbert, Engineers of the Laboratories of Building and Public Works.

The field observations have been made by the service of the Northern Subdivision headed by Mr. Velle. Finally, Mr. Phillip L. Melville, Associate Research Engineer of the Virginia Department of Highways, has translated the paper from the French.

I take advantage of this opportunity to thank all of those who have given me a chance to undertake this work and then to bring it to a successful conclusion.

DISCUSSION

Gregory P. Tschebotarioff.[1] The writer wishes to compliment Dr. Mayer on a very interesting contribution to the available knowledge concerning washboard formation. Both the field studies carried out in French North Africa and the large-scale model laboratory tests performed at Paris are of considerable value for the analysis of this phenomenon.

There is, however, one important contributing factor which does not seem to have been given in the above studies the full attention it deserves. This factor was brought out some ten years ago by a former colleague of the writer, Dr. F. E. Relton,[2] who showed considerable interest in washboard formations on roads in the Egyptian desert. His discussion of the problem was published in Reference (*2*).[3] Dr. Relton analyzed various previous explanations given for washboard formation and came to the conclusion that there is no reason to believe that vibrations of vehicles are its primary cause. He pointed out that the phenomenon of corrugations, also known as "washboard" occurs not only on roads, but even on steel rails and on any other medium subjected to rolling and simultaneously offering resistance to sliding. Any vehicle, therefore, appears capable of producing washboard, but to a different degree, of course, and Dr. Relton states that he personally "... would exonerate push bikes, perambulators, and scooters."

Dr. Relton explains the formation of washboard or of corrugations by means of the Cerruti theorem, which it may be mentioned, is the counterpart of the Boussinesq theorem but for the case of a horizontal force applied to the surface of a semi-infinite solid. To quote Dr. Relton:

"Readers will be spared the horrors of a mathematical demonstration. The results can be seen most simply by passing one's finger along the back of one's hand, preferably the other hand. The surface tends to heap up in front of the advancing point of application which is followed by depression. If the point of application advances continuously, one of two things may happen. Firstly, the rigidity may outweigh the plasticity; the strain in the material may become so great that the material prefers to slip back rather than suffer further deformation. Equilibrium being then temporarily restored the advancing force can start again to heap up until the slipping is repeated, and so on . . . .Alternatively, the progress of the driven heap is accompanied by a certain amount of permanent set. The steadily increasing resistance finally reaches a point where the advancing point of application prefers to ride the obstacle. Thereafter it is in a position to start anew and the process is repeated."

[1] Associate Professor of Civil Engineering; Princeton University, Princeton, New Jersey.

[2] Former Professor of Mathematics and Mechanics, Faculty of Engineering, Egyptian University, Cairo, Egypt. At present: University Examiner; King's College, London University; London, England.

[3] At the end of the discussion.

Anyone interested in the related subject of a detailed mathematical study of the stress distribution in soils beneath a locked wheel subjected to a horizontal thrust can find it in Reference (*1*). From Figure 1 of Reference (*3*) and Figure 63 of Reference (*4*) it can be seen that the shearing stresses transferred to the soil surface by the tires of a locked wheel rapidly decrease with depth and exceed the stresses produced by purely vertical loading only above a depth equal to approximately 17 percent of the major tire diameter. A similar effect should be produced by incompletely locked wheels of a moving vehicle to which brakes have been applied. The stresses created in the ground or pavement surface by wheels of an accelerating vehicle are somewhat more complicated, but it is obvious that a tangential force is applied to the soil surface in that case too, although in an opposite direction.

Dr. Mayer's paper states that vehicle vibration periods have been found to have some relation to the washboard wave length. In the writer's opinion these observations do not contradict Dr. Relton's thesis that tangential forces are the primary cause of washboard. Once it has been formed, a number of other factors of secondary importance may contribute to its development and that not only in dry desert climates, but in any locality. Thus within two miles of Princeton there is a short length of road approach to the Princeton Junction platform for eastbound trains. This road is maintained by the Pennsylvania Railroad. It consists of a layer of cinders laid over natural compact silty clay soil. Last summer a definite washboard formation could be observed on the stretch of that road where various types of cars accelerated on leaving the station or where late commuters slammed on their brakes when approaching it. The wave length of this washboard formation was approximately 30 inches. After this spring breakup (1948) the writer observed that the whole surface of the road was pitted, whereby the depressions were uniformly spread over the whole surface and corresponded in their spacing to the original washboard. These depressions were filled with water.

This seems to indicate that after the first washboard was formed the subsequent impact at these points resulting from the bumping of vehicles over the wavy surface may have produced slight depressions in the original soil surface which, in turn, caused accumulation of surface water in them and further deterioration at these locations.

There may be other secondary contributing factors under special local conditions, but it is the writer's belief that in all such cases the primary cause lies in the tangential forces transmitted to the soil surface by all kinds of vehicles.

It is to be hoped that the excellent facilities of the Paris testing tract could be used to extend the comprehensive investigations already performed there to a study of the effects of acceleration or deceleration of the test wheels on washboard formation.

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Armand Mayer, *Closure.* I was very glad to receive Mr. Tschebotarioff's discussion as it will allow me to stress the very peculiar character of the waves on the desert roads we studied.

Whereas every road builder has experienced the effects on macadam of a too heavy roller, which results in hard points regularly spaced along the pavement, causing irregular wear under traffic, the waves which appear on desert roads are only an accumulation of loose material, sand and gravel, regularly spaced along the road.

There can be no question of plasticity of such a material. But this does not mean that the horizontal forces do not affect it. On the contrary, our films showed that the pebbles were pumped up by the tires and thrown backwards. If the forces had been constant the material would be regularly pushed back and would remain spread all over the road. As the tires have a certain elasticity the tangential forces increase or decrease together with the bouncing movement of the vehicle (this having nothing to do with the springs) so that the material is pushed back irregularly, causing the formation of waves.

I am sure that if Mr. Tschebotarioff or Mr. Relton could see our films, they would agree with our explanation, and with the practical lessons we drew from our tests.

Stabilization is not recommended for dry country, where it is to be used as a surface.

It is better to spread out clay, marl, or silt and roll it down. You will have dust but you will avoid the waves, and that means much for your equipment and for yourself.

RELATION BETWEEN THE PLASTIC INDEX AND THE PERCENTAGE OF FINES IN GRANULAR SOIL STABILIZATION

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SYNOPSIS

Specifications for granular soil stabilization usually give maximum permissible values for the plastic index of the fraction passing the No. 40 sieve without adducing logical reasons for this limitation.

Without a basic underlying theory, such specifications represent more or less localized experience which cannot be utilized in regions of different soils and different climates. The bad performance in periodically desiccated soil regions of granular soil stabilization which followed U. S. specifications, indicates the great practical need for such an underlying theory which would permit a general specification applicable to all soils and climates.

While it is not claimed that this problem has been solved by the writer, it is felt that a definite advance has been made toward its solution by analyzing the physical meaning of specifications limiting the percentage and the PI of the minus 40 sieve portion, and by evaluating the different rules of thumb which are being employed by a number of experienced engineers. These rules possess the general form of:

$$\text{PI} \times \text{Percent passing No. 40 sieve} = C$$

where C is either a constant or the difference between a constant and a function of the percentage of soil fines.

A number of problems confront the engineer constructing low cost roads in a country where they have not been previously tried on a scientific basis. Amongst these problems appear a number of questions concerning the plastic index and the clay content, such as:

1. Can or must we work to the American recommendations for PI and clay content?
2. What is meant by the plastic index?
3. Why should there be maximum and minimum values?
4. How does climate affect these limits?

It is felt there is no clear basic conception of the meaning of the plastic index requirements which, in application to roads. will satisfy an analyst or soil scientist. It is known that, for some reason, the PI permissable is dependent on the prevailing yearly temperature values and range and that a design satisfactory in Central or South America would not necessarily be satisfactory in the U. S. A. if the soil were transported to that country. It is thought that a higher PI or clay content may be permissable for a sodium clay than for a calcium clay, and that, in some way, the soil chemistry plays a part in determining these values. It is known that the plastic index and fines requirements differ amongst the States of the U. S. A. and that