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STABILIZED ROADS

BY

R. H. Picher

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FOREWORD

Of the 400,000 miles of public roads in Canada, only one-fourth fall within the class termed " improved roads ". In 1935 the roads were classed approximately as follows: 77 per cent, unimproved; 20 per cent, gravelled; and 3 per cent, hard-surfaced.

The main problem in road improvement in Canada is to provide a low-cost surface that will be serviceable at all times. Although most of the roads carry a comparatively small amount of traffic, motor travel demands a type of surface that will make the roads passable in all kinds of weather. Because of the great mileage of roads in proportion to the population it is imperative that treatment be low in cost. Gravel has proved the most satisfactory material to answer these requirements. It is of widespread occurrence, is easy to handle, and has good wearing quality under moderate motor traffic. Many trunk highways and most of the main tributary roads are gravel-surfaced.

Not all gravels, however, are suitable for roads, and even good gravels have their limitations in traffic-carrying capacity. A gravel that will stand up well under light traffic may fail under more exacting conditions. With increasing traffic, maintenance charges also go up and may reach such a point as to be out of proportion to the cost of the gravel surfacing or the value of the service that it gives. In fact the annual maintenance charges rather than the construction costs of gravel roads are responsible for the efforts made by engineers in recent years to find ways and means of increasing, by proper treatment, the traffic-carrying capacity of these roads while reducing their cost of upkeep. Fast-moving motor vehicles loosen the road surface material and gradually disperse it to the sides, so that under these conditions the lack of stability or cohesion contributes more to the deterioration of gravel and other types of water-bound roads than does the amount of wear. Weather changes are another cause of unstability, although not affecting gravel roads to such an extent as roads made of finer grained materials. Efforts have, therefore, been directed towards improvement in stability under all conditions, and, where traffic conditions made it necessary, resistance to wear was increased by a surface treatment or a specially built thin wearing-course on top of the improved surface.

Of the various means employed to increase the stability of road soils, the method of stabilization of graded granular soils with clay binder and moisture film has been experimented with to a greater extent and has made more progress than other methods on account of its easy adaptability to local conditions, comparatively simple technique of construction, and low cost.

The following report treats specially of this method, which has given gratifying results and is now becoming generally adopted.

Considerable progress has been made recently in the technique of soil treatment with so-called artificial or permanent stabilizers, and the use of Portland cement and of several types of bituminous materials for this purpose is increasing rapidly in the United States. Only brief mention is made, however, of the methods followed in the use of permanent stabilizers.

Stabilized Roads

SOIL STABILIZATION

Soil stabilization consists in properly combining natural soils so that the granular material is surrounded with just enough binder to produce a dense, weather-resisting layer. To possess maximum density and stability, the mixture must have a minimum amount of voids after compaction, which means that it must be well graded according to grain size, and must be held together by a cohesive agent, such as clay.

It has long been observed that the proper combining of certain soils gives to the mixture a greater stability than that of any of the individual soils of which it is composed. The well-known practice of adding granular material, such as sand, gravel, or broken stone, to a clayey road soil, or of adding clay to a granular soil, to increase supporting power is a form of soil stabilization. The same may be said of the treatment of soils that are too unstable in their natural state to support building foundations. It is only very recently, however, that important contributions have been made to our knowledge of soil properties and principles underlying soil stabilization.

Properties of soils have been studied by investigators in several countries, and tests developed in these investigations have been used in later researches on soils for road purposes. The first important investigation on these properties for road purposes was begun in 1906 by Dr. C. M. Strahan in the State of Georgia, United States, who studied the behaviour of different road soils in relation to their grading as determined by granulometric analysis. In a period of intensive road-paving activity, which marked the decade of 1920 to 1930, certain defects and even failures that developed in pavements were found, after careful examination, to be caused by poor sub-grade conditions. On account of the large outlay of money involved in building these pavements, investigations of sub-grade soils and means of treating them to increase their stability were deemed worthy of serious consideration. With the proper treatment the improvement in sub-grade conditions might be such as to warrant the building of a thinner pavement, so that the saving in paving costs would more than make up for the cost of sub-grade improvement. It was realized, however, that a thorough study of soil properties and reactions under different moisture conditions was essential in order to arrive at a satisfactory solution of the problem. As a result the Bureau of Public Roads of Washington, D.C., undertook an intensive investigation of the properties of soils. The purpose of the investigation was to classify the natural soils according to their characteristics, determine the properties or qualities required for maximum stability, indicate the remedies necessary to improve stability in each class, and develop simple tests to be used by road engineers in identifying the different soils with which they have to cope and finding the proper treatment to give them in order to ensure the desired qualities. The investigation was primarily concerned with soil properties affecting their ability to support structures, but the great improvement in road

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sub-grade stability obtained in service tests led to the idea of applying the same principles in the stabilization of waterbound road surfaces, such as broken stone, slag, gravel, sand-clay, and natural soil surfaces. These so-called low-cost types of roads cover a much greater mileage than that of the higher types of roads, and it was felt that the improvement in stability might increase the traffic-carrying capacity of the road to such an extent as to do away with the eventual necessity of paving.

This method of improvement of low-cost roads was of particular importance in a time of depression when paving programs had to be curtailed. Several highway organizations with the co-operation of the Bureau of Public Roads began building experimental stretches of stabilized road surfaces about 1931, and the results obtained were so gratifying that the mileage of such roads built each year has steadily increased. Onondaga County in New York State, where one of the first experimental sections was built, has now 400 miles of stabilized roads.

Stabilized road surfaces make an excellent base for further improvement as traffic warrants it. Some of these surfaces are built to receive a bituminous surface treatment or bituminous retread as soon as the stabilized layer has been sufficiently compacted by traffic. The bituminous-treated surface may eventually serve as a base for paving.

ROAD SOIL STABILITY

Briefly stated, a soil to possess stability must be well graded as regards grain size, and well compacted, must contain some plastic material, such as clay, as the binding or cohesive agent, and the moisture contained in the soil must be within certain limits which vary somewhat with the character of the soil. The cohesive or binding agent is not only clay, but moisture films supplemented by the finer clay particles. Cohesion may vary within wide limits depending on the moisture content. A good example of the cohesive action of moisture is that of beach sand. These sands are cohesionless when dry, but with the optimum moisture content they have such a stability that racing motor vehicles scarcely leave any track on them. This is due to the surface tension of the moisture film surrounding the soil particles and is comparable to the action of a rubber band. The thinner the film, the greater is its surface tension and the stronger the cohesive force. It is easily understood then why the moisture content should be kept within certain limits, the optimum moisture content varying somewhat with the grading and texture of the soil. If the soil is too dry the moisture film is destroyed; if too wet, the film is so thick that its surface tension is nil and it exerts no cohesion. The proper grading of the compacted soil, in addition to imparting greater stability due to increased density and decreased pore spaces, also keeps the free surface moisture from penetrating to a detrimental extent.

The constituents of natural soils may be grouped as follows according to their size:

Gravel. Particles larger than 2·0 millimetres in diameter (No. 10 sieve*).
Coarse sand. Particles between 0·42 (No. 40 sieve) and 2·0 millimetres in diameter.
Fine sand. Particles between 0·05 and 0·42 millimetre in diameter.

* Sieve with 10 meshes to the linear inch, United States Standard Series designation.

Silt. Particles between 0·005 and 0·05 millimetre in diameter.
Clay. Particles smaller than 0·005 millimetre in diameter.

As regards composition, mica flakes, peat, diatoms, and chemical constituents may be mentioned because of their influence on the behaviour of the soils.

Generally, gravel and coarse sand impart hardness and supporting power, especially in wet weather. Fine sand adds an embedment support to the coarse sand. Silt acts as a filler to prevent the granular particles from rocking. Clay furnishes a cohesive and adhesive bond variable with its moisture content. Mica, peat, and diatoms, because of their high capillarity and sponginess, have a detrimental effect on soil stability.

The grading of a soil, i.e. the proportion of the different particle sizes, is determined by sieve analysis. The proportion of the finer constituents is more conveniently determined by the hydrometer method. This method consists in dispersing the soil fines in water and taking specific gravity readings with a hydrometer after different times of settlement.

The amounts of suspended material corresponding to different hydrometer readings are given in specially prepared tables or charts.

In addition to the sieve and hydrometer analysis, other physical tests are necessary to determine all the important properties of soils influencing their stability. These tests are made to determine the reaction of the soils as regards cohesion, frost heaving, and shrinkage under different conditions of moisture content. Some of the tests which are of particular significance for certain soils are of minor importance for other soils and are dispensed with in the routine testing.[1]

Experience with soils indicates that they are stable when so constituted as to present:

1. Sufficient embedment stability and density to resist traffic pressure and impact.

2. Internal bond produced by the interlocking of particles and moisture film during wet weather, when the cohesion of the clay may be greatly reduced.

3. Sufficient cohesion in the clay binder to maintain stability of the road when in a dry or almost dry state.

4. Constant volume, that is, there should not be an excess of clay which under variations in moisture content might shrink and expand to such an extent as to unseat the granular particles.

The design of soil mixtures presenting the foregoing characteristics is based on the grading as determined by the granulometric analysis and on the binding quality of the fines as disclosed by plasticity tests made on the portion of the soil passing No. 40 sieve.

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[1] Soil tests and test constants, their significance and their application in practice are described and discussed in "Public Roads," of June, July, October, 1931, and February, 1935, published by the Bureau of Public Roads, Department of Agriculture, Washington, D.C.

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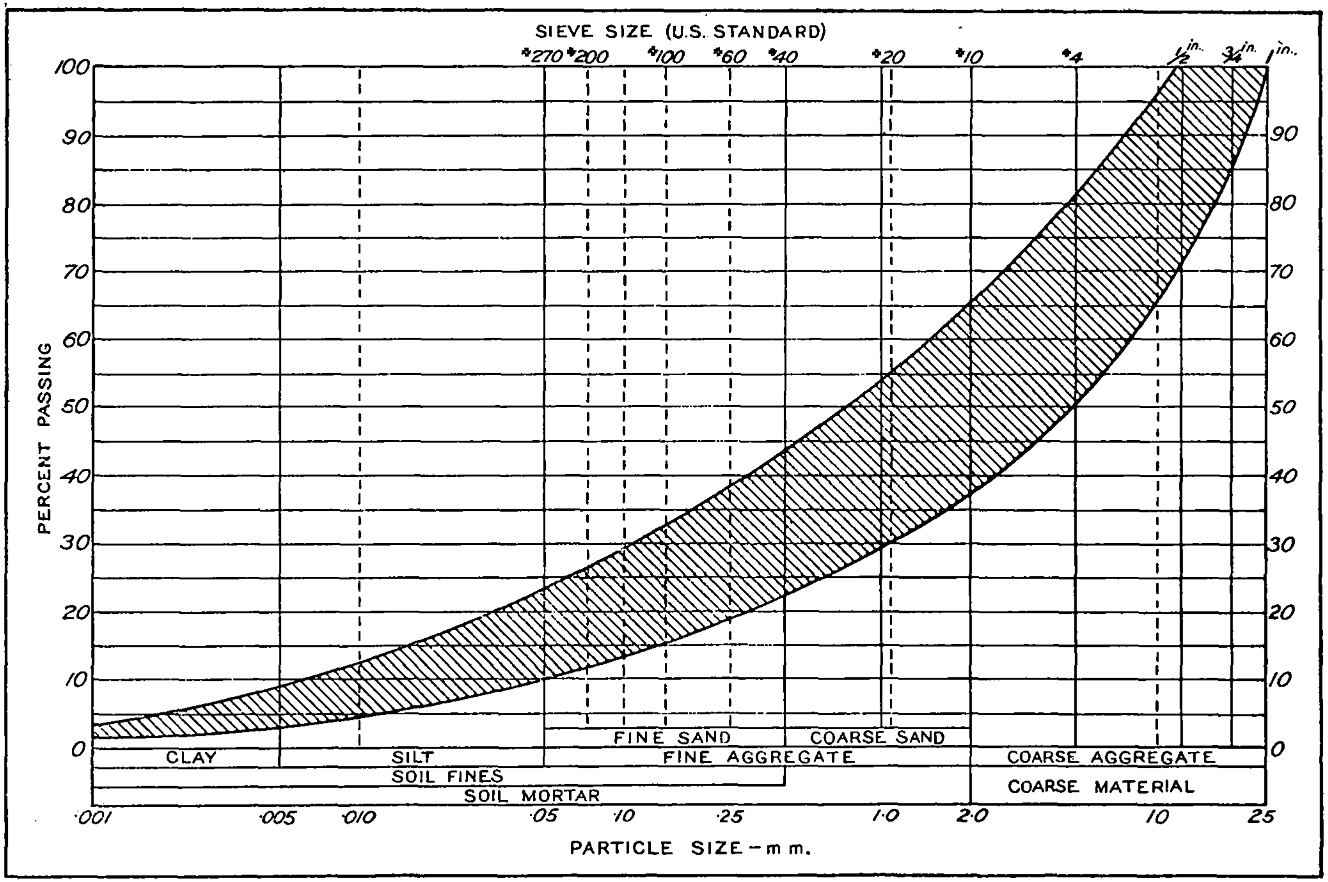

Figure 1. Graph showing ideal particle size grading. The grading curve of the material should come within the shaded area.

Materials falling within the following composition limits, by weight, should produce good results:

Passing:	Per cent
1-inch screen	100
¾-inch screen	85–100
No. 4 sieve	55– 85
No. 10 sieve	40– 65
No. 40 sieve	25– 50
No. 200 sieve	10– 25

The fraction passing No. 200 sieve should be less than two-thirds of the fraction passing No. 40 sieve. The fraction passing No. 40 sieve should have a plasticity index between 1 and 15 and a liquid limit not exceeding 35, as determined by physical tests. Generally, plasticity indexes of 1 to 3 indicate sufficient binder cohesion for use in road construction under unusually wet conditions; 4 to about 8 under conditions of average moisture; and 9 to 15 inclusive, only under dry or arid conditions. Plasticity indexes exceeding 15 indicate soils not suitable for road surfacing.

The above recommendations as regards grading apply particularly to stabilized surfaces. For pavement sub-grades, or where the stabilized course is to receive bituminous surface treatment or to be covered with a bituminous retread, the present tendency is for a coarser mix, a smaller proportion of fines passing the No. 40 sieve, and a lower plasticity index than for unprotected stabilized wearing courses. The bituminous covering takes care of the wear and tear of traffic and prevents the moisture content of the stabilized layer from varying within too wide limits due to rain or rapid evaporation. A less plastic mix also lends itself more readily to bituminous surface treatment.

A certain amount of moisture in the soil is necessary to maintain its stability, as already mentioned. Low moisture in a road surface leads to dust and ravelling under traffic, and too much moisture causes rutting. The drier a road becomes as a result of evaporation, the more water it will absorb when it rains. This is because minute cracks are formed in the clay binder in times of excessive dryness, allowing rain water to penetrate and soften the structure. A properly graded surface holding the right amount of moisture is sufficiently impervious as not to be adversely affected by rain water. Another reason why a certain degree of dampness should be maintained is that stabilized road surfaces, in fact all water-bound types of surface, acquire their maximum density and stability only after a certain period of compaction by traffic. If a certain degree of moisture and cohesion be maintained in the mass during this so-called seasoning period, traffic load pressure and impact are effective in wedging in the soil particles and decreasing the pore spaces, so that the binder film becomes gradually thinner and its cohesive action stronger.

The incorporation of certain chemicals into the road mixture greatly assists in compacting it by retaining the moisture content over a more extended compaction period, thus permitting the attainment of maximum density. Calcium chloride and common salt are the two chemicals most commonly used for the purpose. The high density attained by compaction may be judged by the fact that dry weights of 145 to 150 pounds per cubic foot have been reached in wearing courses treated by calcium or sodium chloride. A simple laboratory test, called the Proctor test, shows the importance of proper moisture content in producing maximum density by compaction. Briefly stated, the test consists in compacting in a cylindrical container of known capacity soil samples of various degrees of moisture content and determining the density or weight of dry soil corresponding to the different moisture contents. The test is started with the soil in a slightly damp condition. After compaction the damp density is determined by weighing. The moisture content is then obtained by drying a small portion of the sample and then calculating dry density. The procedure is repeated, adding each time about 1 per cent more water. It is found that the density increases with increasing moisture content, reaches a maximum and then decreases. For each soil there is an optimum moisture content at which maximum density can be obtained by a given degree of compaction, and well graded soils have a lower optimum moisture content and compact to a higher density than others.

In stabilizing a soil by the above outlined method a certain proportion of granular material in the mixture is necessary, but the granular material need not reach gravel size in order to obtain good results. In other words, stabilization can be attained with so-called soil mortars, that is, mixtures of sand and clay, but the stability is increased with the addition of coarser material. Dr. Strahan, who did much investigational work in connection with the stabilization of road surface mixtures of sand and clay, states that: "When coarse material is added to a good soil mortar in appreciable amount (10 per cent or more) the hardness and durability of the surface is increased and continues to increase until a full gravel-type surface is reached."

PERMANENT STABILIZERS

Stabilization of soils may be attained by the admixture of other than soil materials. Soil mixtures thus treated are not affected by moisture. These water-insoluble admixtures furnish a more substantial film than water alone and destroy permanently the colloidal properties of the soils, hence their name of permanent stabilizers. The method is particularly suitable for fine clay soils, containing very little or no granular material, but can be applied as well on granular soils.

A number of admixtures have been tried on road sections during the past ten or fifteen years, and although service tests did not yield the results that were expected after laboratory research and testing, they were promising enough to warrant further investigation. More recently, considerable research work in soil stabilization has been done using such admixtures as Portland cement, asphalts, tars, and bituminous emulsions. This work, combined with better field control measures and greatly improved construction methods, has yielded such encouraging results as to create a widespread interest in this form of soil stabilization, which has been successfully used also in various works other than road construction.

ADAPTABILITY TO LOCAL CONDITIONS

In the stabilization of graded soils with binder and moisture film, a suitable mixture can in most cases be obtained by using local materials. This easy adaptability to local conditions is one of the great advantages of this type of surface and brings it in line with other low-cost, waterbound types of surfaces. The reduced maintenance charges, increased useful life or traffic-carrying capacity, and other advantages of the stabilized road, make up for its higher first cost.

Almost any kind of granular soil coarser than fine sand and fairly free from organic matter or mica makes a suitable constituent for a stabilized mixture. As regards coarse material, any pit-run gravel or crusher-run stone or slag which is suitable for waterbound surfaces can be used for stabilized roads. In pit-run gravels, the oversize stones may be screened off in the pit or raked off on the road. A certain proportion of angular stones in the gravel is highly desirable, as their interlocking in the compacted surface contributes materially to the stability of the structure. Passing the pit-run gravel through a crusher provides the angular material desired and has the further advantage of giving a more uniformly graded product. It also provides the fines, which are deficient in many stratified gravels, and thus it is only necessary to add the binder and the water-retentive chemical to obtain the complete mixture for stabilization. As a binder, any clay which falls within the plasticity test requirements answers the purpose. The sub-grade soil may be plastic enough for use as binder. In such cases the sub-grade is scarified to a depth just sufficient to loosen the necessary amount and the loose material is bladed into windrows along the road shoulders until ready for mixing. It often happens that the overburden on top of a gravel bank has suitable binding properties, in which case both gravel and binder can be excavated and mixed in one operation by a few strokes of the power shovel. A similar mode of operation may be followed where gravel deposits lie on top of clay beds. Dried and pulverized clay binder ready for mixing may be available from local brick and tile plants. When a suitable binder cannot be obtained from the road sub-grade or from the gravel pit, it is necessary to open a separate clay pit.

ROAD STABILIZATION PRACTICE

The stabilization of graded road surfaces with soil binders is now being generally adopted. The progress made in the technique of construction and the encouraging results obtained justify the assumption that it is a well established method of road surfacing. In many cases the results have been very gratifying and the public has been quick to appreciate its advantages over the older types of waterbound surfaces even to the point of requesting that this type of surfacing be not changed in the future. A number of such roads built during the last six or seven years in different parts of the United States, also in the Provinces of Ontario and Quebec, were examined during 1936. The roads visited in the State of New York had been built by county highway organizations in the Counties of Onondaga, Tompkins, Livingston, and Chautauqua. On most sections the stabilized mixture consisted of gravel, silty or sandy clay, and calcium chloride or salt;

a few sections were built of crusher-run limestone, clay, and calcium chloride. The gravel stabilized layer is built 9 inches thick at the centre line, 6 inches thick 5 feet from the centre and comes to a feather edge 10 feet from centre, giving a width of 20 feet and requiring slightly over 1,700 cubic yards of gravel per mile. Calcium chloride has been used on most of these roads, and sodium chloride on the remainder. The calcium salt is usually spread over the surface immediately after construction at the rate of 1·5 pounds per square yard while the sodium salt is incorporated into the top 3 inches before finishing and used at the rate of 2 pounds per square yard. On some roads the binding material was derived from the sub-grade or ditches, in others from the gravel overburden or clayey layers interstratified with the gravel, in but few cases was it found necessary to open a special pit for the binder. Elsewhere than in the crusher-run limestone sections, uncrushed pit-run gravel was used in all cases, and on some sections pebbles up to 1½ inches in size were not uncommon in the stabilized surface. Some of the roads in summer are said to carry over 1,000 vehicles as a daily average.

In Ohio a number of stabilized sections of road a few miles in length have been built in the last two years in different parts of the State by the State highway department. Most of these sections are given a bituminous surface treatment or finished with a bituminous retread-surface after the stabilized road has been in service for some time and the stabilized surface well compacted by traffic. The materials used are gravel, sand, clay, with either calcium chloride or common salt, the clay binder being obtained from the road sub-grade or ditches. The stabilized layer is built to a uniform thickness of 3 inches over the prepared and crowned sub-grade. At the time the roads were visited, salt was being tried on a 3-mile section south of Chesterville. Gravel, sand, and clay were used for this stretch of stabilized road, except for a distance of one mile where, owing to lack of suitable clay binder, limestone dust was used for binder as an experiment. The limestone dust was taken from a waste pit at a local quarry.

Indiana has experimented with stabilized mixtures using bitumen, calcium chloride, and common salt (sodium chloride). The roads were not examined, but from published accounts, good results have been obtained with both salts, particularly on the later projects where common salt was used. The mix, with either crushed gravel or stone as coarse aggregate, is laid in two 3-inch courses with salt applied as brine at the rate of ¾ pound of dry salt per square yard per inch of thickness, which makes 4½ pounds per square yard or 26 tons per mile. It is believed, however, that sufficient moisture-retaining properties would have been provided if but 2 pounds per square yard had been used in the top few inches. The first 3-inch course of loose material is placed on the grade, moistened with brine, rolled, and then allowed to season for several days before the second 3-inch course is laid in the same manner. This method is followed to ensure that the entire thickness of the road is well compacted.

Michigan has a large mileage of stabilized roads: Oakland County alone has 50 miles. Most of the stabilized surfaces were applied to existing gravel roads. Where the old surface was not too badly worn and there was enough gravel left on the road to stabilize to the required depth and width, it was only necessary to add the binder and in some cases also sand in order to have the materials required for the mix; if the old road was worn too thin, enough new gravel was brought in to make up for the deficiency, or else the old surface was used as a base course and the coarse material of the stabilized layer made up entirely of new gravel. In the majority of projects no suitable clay binder was available in the road subsoil or at the gravel pit, so that it had to be obtained from a separate source. Enough material was mixed to make a stabilized layer 3 inches in thickness after compaction, which required 880 cubic yards of gravel and sand for an 18-foot road. As a moisture retainer calcium chloride was used on all the older projects, and spread over the finished surface at the rate of about 1·5 pounds per square yard, with lighter applications later as needed, depending on traffic and weather conditions. On the later projects either calcium or sodium chloride is used and is added with the other constituents before mixing and spreading. The calcium salt is applied at the rate of 10 tons per mile, and the sodium salt at a rate between 12 and 15 tons per mile.

Mixing plants have been installed lately in the State and plant-mixed material used on several of the later projects, particularly where the old road surface had very little gravel suitable to incorporate into the stabilized mix. Mixing plants for stabilized material require comparatively little equipment and can be economically operated when installed at suitable points so as to avoid costly hauls to bring in the different materials to the plant. Plant mixing has several advantages over road mixing; allows a more thorough mixing, eliminates the use of road machinery and inconvenience to traffic; avoids construction delays due to unfavourable weather conditions; stabilized roads can be built by small communities which do not own the equipment required for road mixing. Plant-mixed material contains all the required constituents, including the moisture-retaining chemical, and can be delivered on the road ready for compaction.

In Ontario, several sections of stabilized roads, totalling well over 200 miles in length and embracing provincial, county, and township roads, have been built in the last few years. Most of the sections treated had been improved with gravel for a number of years. The material from the old surface, wherever suitable, was loosened and made part of the stabilized layer, in which was mixed just enough new gravel to bring the layer up to the required width and depth. In other cases the old surface was used as a base course and the stabilized layer was built up entirely with new materials. Crushed limestone instead of gravel was used in stabilizing a few sectons. It was possible in a few instances to utilize the clayey sub-soil of the road as binding agent but usually clay had to be brought in from a separate source. Suitable binder clay, however, was available in the vicinity of all the projects, in fact, the average hauling distance was shorter for the clay than for the gravel. The stabilized layer was built to a width of 20 feet and a uniform depth of 3 inches. Either salt or calcium chloride was used for moisture control purposes. The salt was incorporated into the mix at a rate of 12 to 15 tons per mile; the method and rate of application of calcium chloride varied with the different projects. A few heavily travelled sections after a few months to a year of service were covered over with a bituminous surface treatment.

In the Province of Quebec, a 10-mile stretch of stabilized road was built in the early fall of 1935 between Victoriaville and Princeville. The old gravel surface was partly worn and served as a base course for a stabilized wearing course made up entirely of new materials. River gravel, crushed to a maximum size of 1½ inches, was used at the rate of 1,000 cubic yards per mile for a compacted layer 3 inches in thickness and 20 feet in width. A highly plastic clay obtained from a deposit 17 miles distant was used as binding agent. As this was the first experiment in road surface stabilization, it was deemed advisable to vary the proportion of binder entering into the mix over different parts of the project. The road was divided in 4,000-foot sections, and the clay used at a rate varying from 100 to 130 cubic yards per mile, but in the majority of sections the rate corresponded to 117 cubic yards per mile, which from laboratory determinations appeared to be the optimum amount. In one section local red clay, less plastic than the imported clay, was used at a rate corresponding to 225 cubic yards per mile. Calcium chloride was used at the rate of 8 tons per mile, except in one section where salt was used at a rate corresponding to 12 tons per mile for one half section and 18 tons per mile for the other half section.

Since 1935 several stretches of stabilized road bases have been built with gravel, clay, and salt in several other parts of the province. A bituminous paving mixture was subsequently laid as the wearing course on these stretches, generally one year after their construction.

RESULTS OBTAINED

One outstanding feature observed in the examination of stabilized road surfaces is their great firmness, or their ability to withstand the destructive forces of weather and traffic when compared with other water-bound surfaces. A few failures reported to have occurred during the spring thawing were ascribed to sub-soil conditions, i.e. highly capillary fine soils difficult to drain by ordinary means. Under these conditions the water-retentive chemical tended to draw an excess of moisture to the stabilized layer which cut up badly under traffic. Good drainage, although particularly important for all types of road, is a vital question for stabilized roads in which moisture film plays such an important role as a cohesive agent. As already mentioned, moisture content of the stabilized layer must be kept within certain limits if the film is to exert its full cohesive force.

Another feature of these roads is their smoothness, comparable to that of a pavement. The most common surface defect observed is pitting or "pot-holing" which occurs usually in the flat part of the crown. These are easily corrected by ordinary maintenance work. "Pot-holing" was common on some sections built in 1934 and 1935 and on which there was said to be no maintenance work done since. The importance of having the proper amount and kind of crown on these roads cannot be overemphasized.

In examining defects of stabilized road surfaces it was observed that they occurred in nearly all cases in the centre of the road where the crown is flattest and this fact gave rise to the opinion that they might be due to insufficient surface drainage. An investigation made on the subject by the Calcium Chloride Association of Detroit, Michigan, confirmed this view. The investigation consisted of taking crown measurements at a large number of points and collecting samples from the road surface. The purpose of taking samples was to determine whether "potholing" was not due, as might be expected, to insufficient mixing or compaction in some parts of the road. The results of the findings, published in Bulletin No. 23 of the Association, shows a definite relation between the surface condition of the road and the amount of crown, but no such relation with the composition and density of the mix, as samples taken from both affected and unaffected areas of the same road section checked within reasonable limits as regards uniformity of composition and degree of compaction. The "A" type of crown is recommended for these roads, with a uniform minimum slant of 0·4 inch per foot, the crest at the road centre being slightly rounded off. The usual circular or parabolic crown, in which the rate of slope increases from zero at the centre to a maximum at the edge is particularly suitable for pavements with gutters, but for stabilized and other waterbound surfaces the wide flat strip at the centre does not permit quick enough drainage, and the excessive slope at the edges makes for unsafe driving and tends to concentrate traffic in the centre strip of the roadway. The "A" type of crown practically eliminates the flat centre strip and presents the same rate of slope over the full width of the travelled way.

Occasional "pot-holes" observed at the foot or top of fairly steep grades are due to the tearing action of vehicle wheels when the speed is accelerated in going up or when the brakes are applied in going down grade. These holes will form independently of the amount of crown and are easily taken care of if the road is suitably maintained. Pitting or "pot-holing" does not affect appreciably the firmness of the stabilized layer unless allowed to reach too large a size through neglect, but makes driving unpleasant, particularly at low speed.

BITUMINOUS SURFACING OF STABILIZED ROADS

Of the stabilized roads examined, those which have received a bituminous surface treatment or which are covered with bituminous retread are in excellent condition. In some quarters greater importance is attached to this kind of improvement than to bare stabilized surfaces as it gives all the advantages of a regular pavement at much less cost. The most serious cause of deformation and even failure of thin bituminous wearing courses is spring thawing where frost action is intense, as in Canada and in the northern States. All the bituminous surfaces built on stabilized courses which have been examined are a few months to one year old, and those which have gone through one winter are in as good condition as the more recent ones. A longer period of test is probably advisable in our northern climate before passing judgment on the merits of this type of improvement. Since a less plastic mix is prescribed for a stabilized layer which is to receive a bituminous cover, this would tend to minimize any possible damage arising from frost action.

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In building a stabilized layer which is to receive a bituminous surface treatment, greater care is required in determining the right amount of binder, proportioning and mixing, than in stabilized bare surfaces or wearing courses, because any irregularlity or defect cannot be easily remedied once the bituminous carpet has been laid. A smaller amount of clay binder is used in such cases to ensure against any detrimental volume changes or deformation that may be caused by frost action. A smaller amount is also sufficient to keep the moisture content within the prescribed limits, since the bituminous mat acts as a protective cover against possible moisture content variations due to weather changes.

ADVANTAGES AND COST

In judging the results obtained in stabilization work, the benefits received must be measured in relation to the money expended. In the case of sub-grade for pavement foundations the benefits derived are so obvious that stabilization may be considered as highly desirable in any paving project and more than pays for itself by giving adequate support to the costly pavement structure. In stage construction where the stabilized road serves only temporarily as a wearing course, it is generally recognized as the first logical step in road improvement since it makes an ideal base for further improvement and its cost is more than offset by the fact that a thinner wearing course than required for an ordinary unstabilized base may be built on it to take care of traffic wear and tear. Another advantage claimed for the stabilized base over the ordinary base is that it is less subject to frost heaving, and the thin wearing course built on it, such as bituminous surface treatment or retread, is less subject to deformation. It is generally admitted that the cost of stabilizing sub-grades, foundations, or base courses, is fully justified by the results obtained, but the opinion is by no means yet unanimous with regard to the economy of stabilized bare surfaces or wearing courses.

In considering a stabilized road surface built as a wearing course, it should be kept in mind that this is essentially a low-cost road and its cost and characteristics should be compared with those of other similarly classed roads. There are certain advantages inherent to stabilized roads which are difficult to appraise in dollars and cents and yet they constitute real assets; the freedom from dust, for instance, so much appreciated by road users and abutting property owners. Since the greater mileage of stabilized road surfaces in this country and in northern United States is of the gravel type, it is in order to compare the stabilized with the ordinary gravel road, particularly with the mulch or surface float type. The surface float gravel road has been developed to take care of the wear of fast-moving motor vehicles. It consists of a compacted gravel surface over which is maintained a thin layer of mulch or loose gravel, which acts as a cushion and protects the surface from the impact and abrasion of traffic. A patrol maintenance is necessary to keep these roads in serviceable condition, since under the action of the moving vehicles the loose gravel is continually tossed about and finally dispersed to the sides of the road. With a traffic of over 500 vehicles per day it is necessary to go over the roads daily with a drag or light blader to keep the loose gravel well distributed over the surface. The gravel should be hard, to obtain a surface of good wearing quality, to keep the float material from crumbling, and to alleviate the dust nuisance. Even with the best care and the best materials these roads are always dusty when dry unless treated with a dust palliative. As a dust layer calcium chloride is most commonly used and gives good results. Experience shows, however, that its effect is not so lasting on a more or less loose, porous surface as on a dense, tightly compacted, impervious surface, such as a stabilized road surface.

As contrasted with the mulch gravel road, the stabilized road presents a dustless, firm, smooth surface, making for more comfortable and safer driving. The stabilized road also, because of its imperviousness and constant moisture content, is much less adversely affected by weather conditions, such as dry or wet spells and spring thawing. Stabilized surfaces have no loose material and require less attention than mulch gravel surfaces. Ordinary maintenance consists in blading only after heavy rain when the surface is sufficiently soft to be cut, and in occasional light applications of chemical for retaining moisture. The bonded, compacted condition of the stabilized road practically eliminates loss of surface material by winds, rain, or traffic. Saving in maintenance cost is thus effected by a substantial reduction in maintenance work, such as dragging or blading, and in loss of surface material due to various causes. From this saving should be deducted the cost of surface applications of chemical, in comparing with ordinary gravel roads on which no dust layer is used. Leaving out of consideration the increase in value of the road resulting from the improved service, the saving in maintenance costs should equal the cost of the improvement before resurfacing becomes necessary, if stabilization is to be economically justified. The cost of the improvement is the cost of stabilizing an existing ordinary gravel road requiring no new gravel for that purpose, or approximately the difference in building cost between the two types of road. Obviously, building costs vary greatly, depending on local conditions, the main cause of variation in cost being the length of haul necessary to bring in the required materials.

In the above-mentioned projects for several States and the Provinces of Ontario and Quebec, costs of stabilized roads vary from $300 up to $2,500 per mile and even higher. The lower figures are for stabilizing 16-foot roads requiring no new gravel; for the higher figures no detailed accounts are at hand to ascertain the proportion which applies to new construction and that which applies to stabilization alone. The $2,500 project was for a stabilized road built entirely of new materials to a width of 20 feet and a thickness of 6 inches. Bulletin No. 22 of the Calcium Chloride Association of Detroit, Mich., gives the following costs for stabilization, which is the cost of adding the necessary binder soil and calcium chloride to an ordinary gravel road and mixing the existing gravel with these materials: In Indiana, 130 miles of road, 18 feet in width, averaged $500 a mile. In Minnesota, costs have averaged $562 per mile on surfaces 22 and 30 feet in width. In Michigan, costs for 18-foot surfaces have been as low as $300 per mile. The stabilized depth is not given, but is known to be 3 inches for Michigan.

Detailed accounts for several stabilization projects in the State of Michigan are given in an article by W. R. Collings and L. C. Stewart, of the Dow Chemical Company, Midland, Mich., published in "Engineering News-Record" of June 21, 1934. As given in the article stabilization costs for the several projects varied from $200 to $400 per mile for stabilization alone, i.e. not including the cost of new aggregate. The largest item is the buying, hauling, and preparation of the clay binder prior to mixing, which makes up one-third to one-half of the stabilization cost. The following table gives the amount of traffic, annual maintenance charges, and savings resulting from stabilization for the several projects considered.

Traffic count, vehicles per day	Maintenance cost before stabilization	Minimum estimated saving after stabilization	Cost of calcium chloride after stabilization	Annual savings per mile
250— 500	$250 to $500	$125 to $250	$125 to $175	$ 0 to $125
500—1,000	400 to 800	200 to 400	150 to 225	50 to 250
1,000—1,500	600 to 1,000	300 to 500	200 to 250	100 to 300

Referring to columns 2 and 3, it is seen that stabilization is estimated to reduce maintenance charges by at least 50 per cent. Calcium chloride costs $25 per ton spread on the road. The maintenance savings accruing from stabilization would equal the cost of the improvement after two to three years, without any allowance being made for the enhanced value of the road.

Where sodium chloride or other chemicals are used instead of calcium chloride the data given in column 4 would vary somewhat, depending upon the laid-down tonnage costs of the chemical used, but the other cost data would remain the same since the general materials' specifications are of a similar nature for all gravel roads stabilized with moisture-retaining chemicals, and the construction techniques are virtually identical.

With an estimated reduction of 50 per cent in the loss of surface material due to wear or other causes, it is reasonable to assume that the stabilized road should last twice as long as the ordinary road under the same conditions before resurfacing becomes necessary, and certainly should outlast the time when the accrued savings in maintenance would equal the cost of the improvement. Since the larger item in the cost is that of getting and preparing the binder, the availability of a suitable binder soil seems to be the determining factor in most cases when deciding the economic soundness of stabilizing an ordinary gravel road. The same applies to an unimproved road planned to be gravelled, or a worn-out road requiring resurfacing, provided there is enough traffic so that accrued maintenance savings may balance the cost of stabilization within a reasonably small number of years. In certain cases, such as in thickly built-up districts, the advantages resulting from a dustless, smooth, well compacted surface outweighs the cost of stabilization.

CONSTRUCTION OF STABILIZED ROADS

Before construction work proper is undertaken, a survey should be made of available materials along or close to the route of the proposed improvement, with sampling and testing of the most likely suitable ones. This information at hand, hauling distances and required quantities of materials are determined, and an accurate estimate made of the cost of the project. This preliminary examination applies particularly to the clays, since the availability of suitable binder largely controls the cost of road stabilization. Other materials, such as gravel, sand, or quarry stone, have probably been used at one time or other in surfacing or patching local roads, so that their location and character are generally fairly well known. The condition of the clay also influences the cost of stabilization; for instance, a damp, highly plastic clay requires more handling to bring it to a suitable state for mixing than does a dry sandy clay. A plastic clay will be much easier to prepare for mixing if dug in the fall, spread on the ground and allowed to weather through the winter. If new gravel is required for the stabilization project, a good plan is to spread the clay over the gravel bank in the fall. When the excavating of gravel is started in the spring, digging and mixing can be accomplished in one operation, as the clay will be in such a state as to pulverize and mix easily with the gravel by a few strokes of the power shovel. In clay land, a suitable binder can be obtained right from the road sub-grade, shoulders, or ditches. In such cases, gravel is often scarce, and the cost of stabilizing the road depends largely on the coarse aggregate, unless there is enough aggregate left in the existing road surface for the proposed improvement.

ROUTINE TESTS

As already stated on page 3, designs of stabilized soil mixtures are based on the grading and plastic properties of the materials. These are determined by simple laboratory tests, and from the results of the tests computations are made of the quantities or proportions of each material required to give to the mixture the desired properties. The laboratory procedure for testing aggregates and binders to be used in stabilized mixtures is given in detail in "Public Roads" of February 1935, and other current literature on the subject, and is only briefly described here.

The sample as received is dried, quartered if too large, and the weight of the portion retained for setting is recorded. For a gravel sample, about 3 kilograms, and for a clay sample, 1 kilogram is sufficient. The sample is screened through the 1 inch, ¾ inch, No. 4, and No. 10 sieves, grinding each portion if necessary to break up lumps and loosen any fine material adhering to the larger stones. The amount retained on each screen is weighed. The material passing No. 10 sieve is divided into two, and each part carefully weighed. One is set aside for physical tests and the other is washed on No. 200 sieve, and the material retained on the sieve is dried in an oven to constant weight and screened through the No. 40 sieve, and the weight of the portions passing and retained on the sieve is recorded.

The amount washed off through No. 200 sieve (silt and clay) is calculated by difference. Converting weights into percentages gives the following:

Gravel	Retained on 1-inch sieve	per cent
	Passing 1-inch sieve; retained on ¾-inch sieve	per cent
	Passing ¾-inch sieve; retained on No. 4 sieve	per cent
	Passing No. 4 sieve; retained on No. 10 sieve	per cent
Coarse sand.	Passing No. 10 sieve; retained on No. 40 sieve	per cent
Fine sand.	Passing No. 40 sieve; retained on No. 200 sieve	per cent
Silt and clay.	Passing No. 200 sieve	per cent

From this, cumulative percentage weights, such as given on page 5, can be easily obtained.

The determination of the relative proportions of silt and clay in the material passing the 200-mesh sieve, although not necessary in routine testing, is highly desirable in testing a clay binder. This is conveniently done by a hydrometer analysis. For this purpose 50 grammes of the material passing No. 10 sieve is needed in the case of a binder sample, and 100 grammes if the portion passing this sieve is higher in sand.[1]

At the conclusion of the hydrometer analysis the material is washed on No. 200 sieve. The portion retained on the sieve is dried, screened through No. 40 sieve, and the weight of the parts passing and retained on this sieve is recorded. Weights are then converted into percentages as indicated above, with separate percentages for silt and clay, as determined by the hydrometer analysis.

The physical tests to be made on the part of the sample set aside for that purpose include the liquid limit test and the plastic limit test.

The liquid limit is defined as the lowest moisture content, expressed as a percentage of the weight of the oven-dried soil, at which the soil just begins to be fluid.

The plastic limit is defined as the lowest moisture content, expressed as a percentage of the weight of the oven-dried soil, at which the soil can be rolled into "threads" ⅛ inch in diameter without the threads crumbling.

The numerical difference between the liquid and the plastic limits is defined as the plasticity index. As the name implies the plasticity index is an indication of the plastic or cohesive properties of a soil. The higher the index number, that is, the greater the difference between the liquid and the plastic limits, the more plastic is the soil.

The part of the sample set aside for the physical tests is separated on No. 40 sieve by alternate grinding in an iron mortar, and screening. The grinding is to break up lumps or separate any fines adhering to larger grains. Care should be taken to have enough material in the mortar so as not to risk crushing any particles. The weight of the part retained on the sieve is recorded. About 30 grammes of the thoroughly mixed portion passing the No. 40 sieve is taken, placed in a small poreclain evaporating dish and thoroughly mixed with water by means of a spatula. The mass is then smoothed into a layer ⅜-inch thick at the centre. A groove is made with a special tool dividing the soil into halves. The groove must penetrate the full ⅜ inch so that the dish is clearly visible at the bottom of the groove. The dish is then given ten light blows with the palm of the hand, or with a device specially made for this purpose. Good accuracy can be obtained

[1] For description of the hydrometer analysis, see reference cited above.

with the hand after a little practice on soils of known test values. If the two halves of the mass just come in contact at the end of ten blows, the moisture content is equal to the liquid limit. If not in contact after ten blows the soil is too dry; water must be added and the mass remixed. If the two halves come in contact before the ten blows have been struck, the soil is too wet and the test should be made with a new sample. The risk of wetting the soil too much and of having to start again with a new sample may be avoided by adding water to the soil in small increments. When the liquid limit has been reached, the percentage of moisture in the soil is determined by putting a small portion of the soil in a weighing bottle and drying it in an oven to constant weight. The weight is recorded both before and after drying.

For the plastic limit test about 20 grammes of the thoroughly mixed part of the sample passing the No. 40 sieve is taken and mixed with water in an evaporating dish until the mass becomes plastic enough to be shaped into a ball. The mass is then rolled into a thread with the fingers on a glass plate. When the diameter of the thread is reduced to ⅛ inch, the soil is kneaded together and rolled again into a thread ⅛ inch in diameter. The operation is repeated until the thread begins to crumble. The crumbled soil is then put into a weighing bottle and dried in an oven to constant weight and the weight recorded both before and after drying. This gives the plastic limit, or the percentage of water below which the material ceases to be plastic.

A quicker method of determining the liquid limit and the plastic limit consists in measuring directly from a burette the quantities of water used. This eliminates the oven-drying of the sample and the use of a sensitive balance.

For the liquid limit, a sample weighing 33·3 grammes is mixed with distilled water from a burette until the mass appears to be slightly below the liquid limit. From then on, the procedure is the same as already described. When the liquid limit is reached its value is equal to three times the number of cubic centimetres of water used. Similarly, in using 33·3 grammes of the soil sample for the plastic limit, and adding water from a burette, the percentage of water corresponding to the plastic limit is equal to three times the number of cubic centimetres of water used.

To obtain accurate results with this method each test should not last more than four minutes and should not be made where there is a breeze blowing, as any drying occurring during the test will raise the test results above the true values.

The plasticity index is then equal to the liquid limit minus the plastic limit.

$PI=LL-PL$

The meaning of the terms liquid limit and plastic limit may be made clearer by quoting the following from "Public Roads" of May, 1936.

High liquid limits may be caused by capillary moisture, cohesive films, or a combination of both. Cohesionless mica flakes, spongy diatomaceous earth, and colloidal clay could all have a liquid limit, say, of 200. When such is the case the liquid limit of various mixtures of these materials would also be 200.

This is not true for the plastic limits. In cohesionless materials there is no plastic limit, which means, at least theoretically, that the plastic limit is equal to the liquid limit.

If the colloidal clay is added to the diatoms in increasing amounts, the plastic limits of the mixtures will decrease until the minimum of possibly 35 is reached, the plastic limit of the pure colloidal clay. Thus for equal liquid limits, the lower the plastic limit the greater is the indication of the presence of cohesive films and of plastic clays which furnish cohesion.

Plasticity indexes exceeding 15 indicate soils not suitable for soil road construction.

The presence of the undesirable micaceous substances and diatomaceous, peaty, or other organic substances is indicated by liquid limits greater than those indicated by the expression:

$$LL=1{\cdot}6\ PI+14$$

The more the liquid limits exceed such values, the less satisfactory the soil binder is apt to be because of detrimental sponginess and capillarity. Elimination of such properties in detrimental amount from the final road mixture may be accomplished by keeping the liquid limits below 35.

STABILIZATION OF GRAVEL ROADS

The methods of construction here described apply particularly to stabilized gravel roads, as nearly all stabilization projects in this country at present involve the use of gravel as coarse aggregate. Where crushed aggregate is used, the construction practice is much the same as with gravel. Finer aggregate and fine-grained soils will be considered later.

Preparation of the sub-grade is one of the most important construction features. Spots where soft or spongy conditions persist in the sub-grade after finishing should be investigated and remedies applied. Where the water table lies close to the surface, the sub-grade should be built high enough to cnsure firmness at all times. The vital importance of drainage for roads stabilized with clay binder and moisture film has already been pointed out. If preliminary testing of the sub-grade soil shows that it is suitable for use as binder, enough of it should be bladed in windrows on the sides of the road and allowed to dry until ready for use. This can be most easily done while the sub-grade is being brought to shape. Differences in binding properties of the subsoil are likely to occur within short distances and as these cannot be detected by visual inspection alone, the soil should be sampled and tested at frequent intervals along the road.

Old gravel or stone roads make good, firm bases and should not be scarified but bladed just enough to smooth out any irregularities in the surface. If the existing gravel or stone road is not too badly worn and holds enough coarse aggregate, it should be scarified to such a depth as will loosen the required amount for stabilizing purposes. Stabilized surfaces should not be built on old bituminous roads, as the bituminous mat cuts off any moisture coming from underneath to supply the stabilized layer and keep it in damp condition. Such roads ravel easily under traffic in periods of dry weather, because their cohesion is much weakened from lack of moisture. If the old bituminous surface cannot be made serviceable any longer by ordinary maintenance it is better to break it up by scarifying and to stabilize the old aggregate by adding binder soil.

The different construction methods of stabilized roads can be divided in two general types: road mix method and plant mix method. In the road mix method, the different materials are mixed together on the road sub-grade by various devices, such as harrows, bladers, or machines designed specially for the purpose. In the plant mix, the different ingredients are fed into a portable mixer in much the same way as cement concrete is mixed. In fact portable concrete mixers have been successfully used for mixing materials for stabilized roads. Mixing can also be done in more elaborate stationary plants installed at convenient points and the mix hauled by trucks to the job ready for placing and compacting. In some of these plants equipped with pug-mill mixers the clay binder can be fed in a damp condition, whereas in other mixing methods the binder has to be pulverized fine enough for mixing and mixed dry with the other constituents. Other advantages of these stationary plants have already been mentioned on page 9. In certain cases the road mix method is the only practical one, as for instance where the old aggregate from an existing gravel road is used in the stabilized mix.

Road Mixed Materials

If the existing road holds enough gravel for a stabilized layer of the required width and depth, usually 20 feet wide and 3 inches deep, the surface is scarified to such a depth as will loosen the necessary amount of coarse aggregate, and the loosened material is windrowed to the centre. If there is not enough gravel left in the existing road, all loose material is windrowed to the centre and enough new gravel is added to the windrow to bring the total to the required amount. This is determined by measuring the windrow. An unimproved road or worn-out road will need new gravel to the full amount required for the stabilized course. If any sand is needed it is brought in with the gravel and windrowed in the centre. All amounts, whether of gravel, sand, or binder soil, are presumed to have been previously determined by test in the laboratory. For instance, the existing road surface may have enough gravel for stabilization, but the latter is deficient in sand, as shown by laboratory examination. Sufficient sand will then have to be brought in to make up for what is lacking, unless the binder soil be sandy enough to fill the deficiency.

Binder soil is then delivered and windrowed on each side of the road in sufficient quantity to give to the mix the desired plasticity, and allowed to dry. If the roal subsoil is suitable for use as binder, it should be bladed from the shoulders or ditches, windrowed on both sides of the road, and left there to dry. Drying of the binder may be accelerated and pulverizing facilitated by mixing a little gravel with it.

When sufficiently dry, the binder is spread, pulverized by various devices, such as harrows, special rollers, or bladers, or a combination of these, and then bladed back into windrows on each side of the road. The pulverizing of the binder soil is judged sufficient when all will pass a 1-inch screen and 80 per cent will pass a $\frac{1}{4}$-inch screen. When no new gravel is required for the stabilization project, a saving in time and work may be effected if the clay binder is spread over the existing gravel road, allowed to dry, and pulverized with suitable equipment and by traffic. The road surface is then scarified to such a depth as will loosen the required amount of gravel for the stabilized layer. The amount of work necessary to prepare the binder for mixing will be found to vary much with various clay binders. For instance, some sandy clays crumble easily when dry, whereas freshly excavated, highly plastic clays need a great deal of handling to pulverize them fine enough for mixing.

After the binder has been prepared for mixing and windrowed on the sides of the road, the gravel windrow from the centre is spread over the prepared sub-grade, the binder from the side windrows is spread uniformly over the gravel together with the required amount of water-retentive chemical, salt, or calcium chloride. Salt is usually applied at the rate of 2 to 2·5 pounds per square yard for a 3-inch thickness of stabilized layer, or from 13 to 16 pounds per linear yard for a 20-foot road. Calcium chloride is applied at the rate of 1·5 pounds per square yard for a 3-inch thickness of stabilized layer, or 10 pounds per linear yard for a 20-foot road. If spreader boxes are used in spreading the different materials on the road, preparatory to mixing, a more uniform longitudinal distribution of the materials and a more uniform mix may be obtained.

The mass is then mixed by blading gradually to one side of the road, then to the other, and when thoroughly mixed, it is split into windrows on each side of the road. Instead of blading back and forth, mixing may be done by a sort of travelling plant, or mixing and spreading machine, of which there are several types on the market. Some of these pick up the material from windrows and run it through a continuous mixer. Others blade the spread material to a continuous pug-mill mixer made up of horizontal rotating shafts with blades attached. These machines operate on half the road at a time and leave the material spread and struck off, ready for sprinkling and compacting. On one of these machines, called the Jaeger triple pug-mill mixer, the strike-off screed is carried on long runners. This arrangement has the advantage of equalizing any irregularity of the surface.

Plant Mixed Materials

Materials may be mixed on the job in mixing machines, such as ordinary concrete mixers, or in portable plants installed at the gravel pit, or in stationary plants so situated as to facilitate the bringing in of the required materials and the delivery of the stabilized mixture. The binder soil has to be dried and pulverized before being fed to the mixer. Some stationary plants, however, are so equipped as to handle the binder in a damp condition, so that these plants are not dependent upon weather conditions for production. When using concrete pavers or similar portable mixers, quantities of materials for each batch are computed the same way as for concrete mixing, except that no water is added. Having the binder and gravel in windrows instead of piles saves much going back and forth to bring the materials to the mixer. In gravel pits where portable plants are installed for the production of aggregate, either crushed or uncrushed, the pulverized binder and the chemical may be fed in a continuous stream to the aggregate before it goes through the processing screens. After going through the screens the materials are thoroughly mixed. The finished mix may then be wetted or may be delivered dry on the job. A plant designed along these lines will function properly if the binder is dry enough for easy pulverizing, which depends upon weather conditions.

Equipment of Stationary Plant. The design and equipment of stationary plants for producing stabilized mixtures will vary with the availability of the materials and the condition of the binder, but even under not too favourable conditions these plants require comparatively little equipment and their installation is far from complicated. The most favourable case is when binder and aggregate are found together, for instance when the overburden on top of a gravel bank is a clayey soil having suitable plastic properties for use as a binder. Provided that the clayey soil is not too hard or sticky, it could be dug and fed directly to the mixer after having gone through a grizzly or screen to remove large stones or hard clods, thus doing away with drying and pulverizing equipment. If, on the other hand, the binder and the aggregate have to be obtained from two separate and distant sources, the first consideration is the location of the plant, whether near the binder or the gravel deposit. In general it is preferable to install the plant close to the binder source, as gravel is much easier to handle and probably less costly to transport than damp, sticky soil. Other factors, however, such as loading and transportation facilities of the materials, hauling or shipping of the finished mix influence the location of the plant.

The condition of the binder soil is next to be considered, more particularly its moisture content. With suitable pulverizing equipment, such as roll crushers or disintegrators, a certain degree of dampness of the binder soil is not objectionable, but freshly excavated clayey soil will probably hold too much water and will require some air-drying to lower its moisture content and bring it to a suitable state for pulverizing. For air-drying, the clay is piled up in the open by the excavating shovel. A prolonged period of rainy weather may raise the water content in the piles to such an extent as to force a temporary shut-down of the plant. If the demand for the stabilized mix is large enough to permit continuous operation of the plant during the road-building season, delays due to unfavourable weather conditions may be avoided by building a shelter over the piles. Air-drying and even pulverizing may be dispensed with in some cases, depending upon the condition of the binder soil in the bank.

From the stock pile the binder is taken by hoist to a hopper with screw conveyers and control gates to regulate the rate of flow at the discharge end of the hopper. From there the material is brought to the pulverizer over a conveyer belt. The gravel and the sand are loaded by crane from stock piles to hoppers. At the bottom of the hoppers control gates regulate the rate of flow over conveyer belts. Notwithstanding slight variations in the grading of the various constituents, a uniform finished mix may be obtained by adjusting the rate of flow accordingly. Salt or calcium chloride is dumped by hand into a small hopper with a feed control at the bottom. All materials are finally brought to the mixer over a conveyer belt. The mixer is of the pug-mill type and consists of a trough in which a rotating shaft is equipped with removable cutting and mixing blades. The blades are spirally inclined in the manner of a screw conveyer, so that the mixture is gradually led by the rotating device to the discharge end of the trough. The adjustable speed of the shaft and pitch of the blades control the rate of discharge and amount of mixing. It is important to have a sufficiently large mixer, since the capacity of the plant is largely governed by that of the mixer. A bucket elevator loads the finished product into a large storage hopper.

Production costs of stabilized material in stationary plants vary in different localities. The main cause of variation is the cost of materials, which probably runs from one-half to three-quarters of the total production costs. The remainder represents costs of power, labour, maintenance, and depreciation.

Several stationary plants have been installed in the State of Michigan, two of which were visited. The above description of plant equipment and machinery is made from information received on an examination of the plant of the Dow Chemical Company, Midland, Mich.[1]

At this particular plant gravel is obtained from a pit 75 miles distant and costs $1 a ton, which works out at 56 per cent of the production cost per ton of finished mix, and costs of all materials, gravel, sand, clay, and calcium chloride, represent 71 per cent of the total production costs.

Spreading and Compacting

The finished mix, whether road- or plant-mixed, is spread over the road, sprinkled to slightly above the plastic limit, and is compacted. The sub-grade should be well dampened prior to the spreading of the stabilized material over it, so as to ensure maximum bond between the two and prevent the base from drawing moisture from the stabilized layer. Some mechanical mixers, as already stated, spread the mix on the grade ready for sprinkling and compacting. It is important that the stabilized layer receive the proper amount of compaction throughout its full depth, and for this reason the stabilized surface should be built up gradually in thin layers, allowing enough time for compaction before spreading the next layer. Each layer should also be sprinkled prior to spreading the next layer to ensure proper bond between them and adequate amount of moisture throughout. The effectiveness of the equipment used for compacting will largely govern the method of building up the stabilized surface, the length of time required, and the maximum thickness of layer that can be compacted at one time. For best results, a layer of not more than three inches in thickness should be spread and compacted at any one time.

The purpose of compaction is to force the particles of the mixture to adjust themselves to the smallest possible space, thus producing a mass of maximum density and cohesion. On account of the plastic state of the mix, a kneading action as well as a compressing action is necessary to obtain the desired result. For this reason ordinary smooth rollers such as are used for compressing paving mixtures are unsuitable, unless used in combination with other equipment. Sheepsfoot rollers, specially built rollers, multiple-wheeled pneumatic tire rollers, and dual-wheeled trucks, or a combination of these give good results. When surfacing with plant-mixed stabilized material, a good plan is to start nearer the plant and work gradually away from it. In this way hauling trucks travel back and forth over freshly

[1] A detailed description of this plant is given in an article entitled "Plant Mixing of Stabilized Soil Road-Surfacing Materials", by L. C. Stewart and S. J. White, of the Dow Chemical Company; reprinted from "Roads and Streets", November, 1935.

spread material and give it an initial compaction at the proper time, which is immediately after being laid. Whatever means are used in compacting, the stabilized mass reaches its final state of compaction only after being under traffic for some time. During the so-called seasoning period, the road surface requires special attention. It should be kept constantly moist and any defects likely to develop during that time should be remedied at once. Proper care of the road during the curing period has considerable bearing on its condition and maintenance costs after it has reached its state of final compaction and maximum density.

In some cases the material is compacted by traffic only. A thin layer is spread, sprinkled, and left for traffic to compact. When the amount of compaction is judged sufficient, another layer is built up in the same way, and so on until completion. The obvious disadvantage of the method is that it makes the period of construction and seasoning unduly long, with the danger that if a wet spell occurs in the initial stages of construction the thin stabilized layer may be cut up by traffic and some of the sub-grade material may become mixed with it. Any savings realized on the cost of compacting may be easily wiped off with unfavourable weather conditions and the particular care required during the longer seasoning period.

MAINTENANCE

Although a stabilized road, if properly built and cared for during the curing period, will need but little attention after, it does not mean that a road of this type may be built and forgotten. The maintenance work required during the curing period is really a part of the construction program. This work consists in keeping the surface constantly moist and maintaining it to true shape and crown by blading. Holes, ruts, or other deformations are likely to occur under traffic. If blading alone will not level off depressions, new material properly dampened should be added and rolled or tamped into place. Spots may occur on the surface showing an excess of coarse or fine material. These are generally the result of improper spreading or insufficient mixing during construction. Spots with excess of fines are easily detected after a rain and are blotted up by adding pea gravel or other aggregate not over $\frac{1}{2}$ inch in size and as free as possible from sand or other fines. Areas showing excess of coarse are covered over with a thin coat of soil mortar, which under traffic will be worked into the surface, provided there is enough moisture present.

The amount of maintenance work necessary after the road surface has passed the seasoning stage will depend upon traffic conditions. Light blading or honing every month is usually sufficient. This may be repeated oftener if the traffic reaches over 800 vehicles per day. All maintenance work should be done when the surface has been sufficiently softened by rain. At other times the road will be too hard and any attempt to blade the surface will do no good. After the spring thawing when the road is still damp, it should be given a thorough blading and new material added if needed. The new material if damp enough will bond with the old surface without scarification. A properly maintained stabilized road will be found to improve with age. Any loose material will gradually disappear, leaving a smooth, firm, dustless surface. If float material forms it should not be allowed to remain on the surface as it acts as an abrasive under traffic. If there is only a small amount, it is bladed off to the sides and left there until the following spring, when it will be incorporated back into the surface. When there is at least 50 cubic yards of float per mile, enough new material, binder, sand, and pea gravel or crushed stone, should be added to build up a thin stabilized layer over the original surface. Depending on the thickness of the layer, it may be left for traffic to compact, or else be mixed and compacted in the same manner as used in building up the road.

STABILIZATION OF SAND AND CLAY ROADS

The addition of clay to a sandy road soil, or sand to a clayey soil in order to give to the road surface more stability under all weather conditions has been a common practice for many years in areas where coarser granular material is not available. In Canada this type of surface is practically unknown, due to the abundance of gravel, boulders, or rock ledges from which road aggregates of the desired coarseness can be easily obtained. Isolated stretches of sand-clay road surfaces may be observed on some roads of secondary importance with a clay subsoil over which a sand layer has been spread and gradually mixed with the clay soil by traffic and maintenance equipment. A fairly large mileage of clay roads has been surfaced with sandy gravel or gravelly sand, and although no attempt was made to bind the granular material with some of the clay soil, maintenance manipulations or capillary moisture in time brought enough clay into the layer of granular material to constitute a gravel-sand-clay mixture. On account of the comparatively large proportion of coarse aggregate (retained on the No. 10 sieve) these surfaces may be considered as an intermediate type between true sand-clay and gravel roads.

In some of the southern States sand-clay road surfaces have been built for many years, and there is now a considerable mileage of such roads, many of which have been surface-treated to make them more resistant to the abrasive action of modern motor traffic. The first experimental work based on a scientific study of soil properties for the purpose of improving the stability of soil road surfaces was done on mixtures of sand and clay. It was in 1906, in the State of Georgia, that study was made of road surfaces built of sand and clay mixtures with regard to the effect of their grading, as determined by sieve analysis, on the stability and performance of the roads in service. More recently, with an increased knowledge of soils as a result of a more exhaustive study of their properties and behaviour with different moisture contents, principles developed in the stabilization of road surfaces with the use of coarse aggregate have been applied to sand-clay roads with the proportioning of the ingredients based on their grading and the resultant plasticity of the mix.

Although good all-weather stability is obtained these roads do not have the ability to resist the abrasion force of traffic to the same degree as do those made of coarser aggregate. As already pointed out, the hardness and durability of these roads increase with the addition of coarse aggregate and continue to increase by further addition until the gravel type of surface is reached. As in the case of stabilized gravel roads, the traffic-carrying capacity of sand-clay roads is greatly increased with suitable surface treatment. In some States the greater mileage of sand-clay stabilization projects call for base-courses, which immediately after compaction are given a bituminous surface treatment or are topped with a thin layer of bituminous retread as a wearing course.

In one part of the State of Michigan where the subsoil is fine sand, 95 per cent of which passes No. 40 sieve, good results have been obtained with this sand in building a 5-inch stabilized sand-clay base course topped with a 2-inch stabilized gravel layer as a wearing course. It is claimed that stable sand-clay mixtures serve as well for base course as do most gravels.

Stabilized sand-clay mixtures are also built for playgrounds, tennis courts, and similar surfaces.

Good results will be obtained with sand-clay or other similar mixtures in which the fine aggregate consists of stone or slag screenings if the grading of the mix conforms to the following requirements:

	Per cent
Passing $\frac{3}{8}$-inch sieve	90–100
Passing No. 4 sieve	75–100
Passing No. 10 sieve	55–100
Passing No. 40 sieve	35– 70
Passing No. 100 sieve	25– 45
Passing No. 200 sieve	20– 35

The fraction passing No. 40 sieve should have a plasticity index between 3 and 9 and a liquid limit not exceeding 35. The fraction passing No. 200 sieve should be less than two-thirds of the fraction passing No. 40 sieve. The mixtures with the higher proportion of material retained on the coarser sieves are the more desirable. Coarseness is not so essential for sub-grades or base courses, although in mixes for sub-grades or base courses the fine passing No. 200 sieve should be less than one-half the fraction passing No. 40 sieve, and should have a corresponding lower plasticity index than that recommended for a surface course.

Stabilized sand-clay or other similar roads built up of fine aggregate and binder occupy an intermediate position between natural soil and gravel roads as regards durability and traffic-carrying capacity, but cost as much as gravel roads because of the greater thickness of layer required to ensure proper stability; a minimum thickness of 6 to 8 inches of compacted layer is recommended, which requires between 3,000 and 4,000 cubic yards of loose material per mile for a 20-foot road. The cost of these roads, however, does not appear unduly high when it is considered that they are built in areas where there is no coarser aggregate available. The cost of traffic-bound roads depends largely on that of materials delivered on the job, and the service rendered for the money expended decides in the final analysis whether to use local materials or to bring in better but more costly materials. In building sand-clay roads local materials are utilized to the fullest extent possible to reduce hauling distances and construction costs. In fact these roads are ordinarily built on sand or clay soils so that one of the ingredients for the stabilized mixture can be obtained right from the sub-grade. Under conditions such as exist in some of the States the cost of sand-clay roads is fully justified by the service that they render, but these roads will probably never develop to any extent in this country, as there are but few areas where such roads would give better results for the cost than roads built of coarser aggregate. In Prince Edward Island and in the low lands bordering the St. Lawrence River in Quebec, where clay and sand are abundant and coarser material scarce, the economic advantages of stabilized sand-clay roads would be worth investigating.

CONSTRUCTION

Construction methods of stabilized roads with fine aggregate do not differ much from those followed for gravel roads. The simplest case is where there is a natural deposit of sand and clay mixed in the right proportions close to the road planned to be improved. The excavated material is then ready for spreading on the road, sprinkling if necessary, and compacting. This eliminates the largest item of construction cost, which is preparing the binder and mixing it with the sand. Ordinarily, however, clay and sand have to be obtained from separate sources. As already stated, these roads are usually built where one of the required materials is available right on the road, hence the two different modes of procedure, according as to whether the road soil is sand or clay.

On clay roads, the surface is scarified to such a depth as will loosen the required amount of clay binder for the mix. The clay is dried and pulverized on the grade. This can be easily done in dry weather when the road surface is firm. When in a suitable state for mixing, the clay is bladed into windrows on each side of the road, the sand or stone screenings, whichever is available, spread uniformly on the grade. The clay from the windrows is then bladed back on the sand and the whole is dry mixed. After the first heavy rain, salt or calcium chloride is sprinkled on the mix, the whole is mixed while still in a wet condition and then shaped to final cross-section. Methods and devices for drying, pulverizing, and mixing are the same as already described for stabilized gravel roads.

On sand roads, clay is spread over the grade in such quantity as will provide sufficient binder for the full depth of the stabilized layer. It is then dried and pulverized, and this is often a difficult problem, depending upon the condition of the clay and of the road surface. Lumpy clay is very hard to break up by ordinary means on a loose sand grade, even with repeated manipulation. Clay that has been allowed to weather through winter is much easier to pulverize than freshly excavated clay. For that purpose the clay may be excavated in the fall, delivered to the side of the road after freezing has made the sand surface sufficiently firm. In the spring, when the clay has dried just enough for easy handling with bladers, it is spread on the road, sprinkled with salt or calcium chloride and wet-mixed with the sand from the grade by repeated bladings. After mixing, the wet mass must be partly dried for shaping and compacting and for this purpose it is bladed into a well rounded mound to the centre of the road to shed its moisture. The mix should be spread to shape as soon as it has dried enough, so that traffic may compact it while still in the moist state. When it is found impracticable to have weathered clay for preparing the mix and the latter still holds many clay lumps after repeated bladings, the layer may be spread on the grade and left to stand until the following spring. Further mixing then will break up any lumps left and give a thoroughly uniform mixture.

CONSTRUCTION WITH PERMANENT STABILIZERS

Most of the experiments with so-called insoluble or permanent stabilizers have been done on fine-grained road soils, particularly clay roads. These clay soil roads become very soft and unstable when wet, even to the point of being impassable for motor traffic. By adding coarser material in suitable proportion and mixing it intimately with the surface clay, an all-weather stability may be obtained, if measures are taken to ensure proper surface drainage at all times. Where coarser soils or aggregates are not easily available, various other means have been tried by different experimenters to increase the supporting power of the clay surface under adverse weather conditions. Laboratory tests on gumbo soils of Alberta have shown that lime treatment produces beneficial effects in reducing the stickiness and increasing the stability of these soils.[1] Lime has also been used in treating sections of clay roads in the United States. Other chemical substances have been used, with the idea of destroying the colloidal properties of the soil and making the stability of the road independent of moisture changes. These admixtures improved conditions, but the results were not lasting, because the importance of intimate mixing, adequate compaction, and protective surface treatment was not then fully realized. The purpose of these admixtures of so-called permanent or insoluble stabilizers is not to impart hardness or toughness to the mass but to make it resistant to water absorption and thus keep constant its dry state stability. Some sort of surface treatment or covering is therefore necessary to protect the structure against the abrasive action of traffic. Much experimental work on clay soil stabilization has been done in the last seven years with Portland cement and bituminous materials.

The first experimental work of road soil stabilization with Portland cement was done in 1933-34 by the State of South Carolina, where several stretches of sandy clay roads were treated with cement as the stabilizer. Considerable improvement in the construction methods was deemed necessary before drawing definite conclusions. The experiments showed, however, that Portland cement stabilizes soil to an appreciable extent and all but destroys the harmful effect of colloidal soils. This early work gave results encouraging enough to warrant further investigation with this kind of stabilizer.

Since then, a great deal of research work on soil stabilization with cement has been carried on by the Portland Cement Association of Chicago. A definite laboratory procedure has been worked out, by means of which it can be ascertained whether any particular soil is economically amenable to treatment with cement, and how much cement is required for each soil to obtain satisfactory results. Costly experiments in the field are in this way avoided. Another important factor determined by laboratory tests is the optimum moisture content at which the soil-cement mixture will compact to its greatest density. This varies with different soils and has to be determined accurately in each case, as compaction to the predetermined density is an essential part of the field operations

[1] Phillips, J. G.: "Lime Treatment for Gumbo Roads"; Investigations in Ceramics and Road Materials, 1928-29, Mines Branch, Department of Mines, Ottawa, Canada.

in order to obtain proper stability. Several State highway departments have built a number of road sections with soil-cement mixtures for observation under service conditions and for devising efficient construction methods and field control procedure.

Briefly, the different construction steps are as follows:

The soil is scarified and pulverized to such depth as is necessary for the thickness of the stabilized layer, usually 6 inches of compacted mixture. The pulverizing is continued until 80 per cent of the soil, exclusive of gravel or stone, passes a 4-mesh sieve.

The cement is mixed with the dry raw soil in the proportion previously determined in the laboratory. The raw soil need not be perfectly dry for this operation. According to the construction handbook of the Portland Cement Association, "cement can be successfully spread and mixed whenever the moisture content of the raw soil does not exceed the optimum per cent of moisture of the soil-cement mixture by more than two".

The soil-cement mixture is moistened to its optimum moisture content or slightly above it, if allowance be made for evaporation during the processing, depending upon atmospheric conditions.

The moist layer of soil-cement mixture is compacted from the bottom up by means of sheepsfoot rollers. This is the only type of roller that will give uniform density throughout the whole depth of the layer. The surface is finished by rolling with a smooth roller.

The finished surface is covered with moist straw, hay, or earth for a period of seven days, to prevent evaporation during hydration. The cover is then removed and the road opened to traffic.

When a bituminous surface is desired it should not be laid until after the bare soil-cement road has been subjected to traffic for upwards of a year.

Tars, asphaltic oils, and bituminous emulsions have recently been used in experimental stabilization work on clay soils in different parts of the United States. In the last few years much research work has been done on stabilization of fine clay soil with emulsified asphalt, and experimental projects built according to the principles evolved from these studies are reported to be giving encouraging results. For this the soil should contain at least 20 per cent passing No. 200 sieve and 5 per cent of colloidal clay. As the amount of emulsified asphalt required is roughly proportional to that of the fines passing No. 200 sieve, granular material is added when the proportion of fines is much in excess of 20 per cent, say, over 30 per cent. On heavy clay soil a substantial saving in building cost is thus effected, provided that the granular material can be obtained at reasonable cost. For each soil there is an optimum amount of stabilizer that will give maximum stability and this amount should be accurately determined by preliminary testing, as an excess of stabilizer is no better than an insufficient amount. Soil tests, such as plasticity determination and granulometric analysis with sieves and hydrometer, are made in the same manner as already outlined for stabilization with clay binder and moisture film. Tests are also made for stability and water absorption on moulded specimens of the untreated soil and trial mixtures. The optimum amount of emulsified asphalt is determined from the results of these tests; it runs from 10 to 20 per cent of the portion passing No. 200 sieve, depending upon the characteristics of the soil. It is much less than the minimum required for binding paving mixtures. The ordinary quick-setting emulsion used in paving mixtures with fine aggregates is not entirely satisfactory for stabilization work.

Construction methods are somewhat the same as already described for gravel roads stabilized with clay binder and moisture film, except that mixing is done in the wet state. When granular material is added to the clay soil, however, it is mixed dry with it and moistened to slighly below the plastic limit prior to the application of the emulsion. The stabilized course is built up gradually in thin layers with an application of emulsion on each layer. For better and quicker distribution of the asphalt throughout the soil mass it is recommended that the emulsion be diluted in the ratio of 2 to 4 parts of water for 1 of emulsion. A surface treatment or thin wearing course is laid with emulsified asphalt and stone chips. Full stability is obtained only after the course has thoroughly dried, and thus the wearing course should not be laid until the stabilized base has dried to the bottom.

FUNCTION OF CHEMICAL ADMIXTURES

In road stabilization, chemical substances are used for various purposes. Moisture-retaining chemicals ensure against too great a variation in moisture content and cohesion in stabilized mixtures. Solutions of electrolytes reduce the thickness of moisture films on the soil particles and enable stabilized mixtures to compact to greater density. Some substances are used as primes and fillers, to increase the adhesion between the soil particles and chemical admixtures. Certain chemicals, so-called neutralizers, correct the acidity of soils and thus ensure against loss of stabilizing admixture caused by base exchange. Some substances, called insoluble or permanent stabilizers, prevent detrimental volume changes due to variation in moisture by destroying permanently the colloidal properties of the clay and provide the cohesive or binding power required for proper stability.

Deliquescent salts are suitable for use as moisture retainers. These salts have the property of absorbing moisture from the air and retarding evaporation due to the lower vapour tension of their solutions, as compared with pure water. Of the many salts possessing this property, calcium chloride has been most widely used because of its comparatively lower cost. Calcium chloride has long been used as a dust layer on waterbound road surfaces. Along the coast, sea water has also been used for this purpose. Its superiority over fresh water as a dust layer is due to the deliquescent properties of magnesium chloride held in solution. In treating road surfaces with calcium chloride for dust laying, it was observed that road sections surfaced with well-graded aggregate acquired a firmness and smoothness not attained by untreated sections surfaced with the same aggregate. This was attributed to the slightly moist condition maintained in the surface by the treatment, and led to the idea of using the same salt as moisture retainer in stabilizing road surfaces with clay binder and moisture film. On account of the better grading and closer texture of the stabilized surface, evaporation is slower and the beneficial effects of chloride treatment are more lasting than on ordinary roads. However, other chemicals which do not possess the property of hygroscopicity to such a marked degree have also come into use for road stabilization purposes.

All soluble salts have the property, when in solution, of reducing the vapour tension of water, and thus have a moisture-conserving action when used for purposes of road stabilization. Common salt in particular has been more generally used than others because of its lower price. It was used as admixture in the first stabilized road built in Canada, a short section of a gravel road near Elmsdale, Nova Scotia, stabilized with the admixture of clay and salt in 1931, under the direction of A. R. Chambers of New Glasgow, Nova Scotia. Since then the use of salt as a stabilizing admixture has spread rapidly in both the United States and Canada.

Both calcium and sodium chlorides make good moisture retainers for stabilized roads, although their action varies somewhat, owing to their different properties. The calcium salt is hygroscopic and dissolves in the water that it absorbs from the air, and it will stay liquid in the road surfaces under ordinary atmospheric conditions. When it rains, the small amount of water penetrating the stabilized layer carries the solution down a short distance below the surface, and as the road surface dries after the rain, capillary moisture from beneath concentrates the solution in the upper part of the layer, where it prevents further evaporation from the surface. Sodium chloride is only slightly hygroscopic and is less soluble than calcium chloride. Its lower cost, however, permits of its economic use in somewhat greater quantity. Its main function is to retain the moisture already present in the soil as an aid to compaction. As the road surface dries, the salt solution becomes gradually concentrated to the saturation point, so that small salt crystals form at the surface. This crystal growth fills the soil pores, minimizes detrimental shrinkage and acts as a protective covering to reduce further evaporation. In dry weather, as evaporation slowly proceeds, crystal growth within the soil adds to the strength and hardness of the stabilized layer.

Solutions of calcium chloride, sodium chloride, sodium hyposulphite, and other salts through their electrolytic action produce thinner moisture films than water alone, and thus make it possible to obtain higher density and greater cohesion of the soil by compaction, also less swelling and shrinkage. While the low vapour tension of salt solutions is considered the primary cause of water retention due to slow evaporation from the road surface, the electrolytic action of the solutions probably plays also an important part in retaining moisture. The closer texture of the soil due to the greater density attained by the use of electrolytes contributes also to retarding evaporation. A large number of chemical substances could be used as electrolysers, and experiments have been made with some of them, but apart from the two chlorides of sodium and calcium, their use has not passed the experimental stage, chiefly on account of their cost or of some other undesirable feature. It has long been known in the ceramic industry that common salt has a beneficial effect on certain clays.

Primes and fillers are used to give stronger adhesion between the mineral constituents of a soil and chemical admixtures, so that the latter may develop their beneficial effect to the fullest extent. Limestone dust and hydrated lime are the two more common materials used for this purpose with either chemical salts or bituminous materials as admixtures. Slag has also been used with as good results. Certain soaps greatly increase the adhesion between soil particles and bituminous materials, as judged by experiments conducted in several parts of the United States. While fillers, as suggested by the name, seem to perform a purely mechanical function, there is as well an electrochemical action taking place in some mineral mixtures. Prévost Hubbard[1] described in 1910 the effect of mixtures of rock powders on the bond of waterbound road surfaces. Granite, diabase, chert, slag, and clinker, in powder form, were separately mixed with lime or limestone dust and the cementing power of the mixture was found to be much higher than that of either constituent alone. The following table gives the results obtained in mixing different granites and limestones.

Cementing Value

(As determined by the method of the American Society of Ceramic Engineers)

Granite	Limestone	Mixture
3	27	110
9	22	56
7	26	38
7	26	53
6	20	82

Acidity in soils is an undesirable feature for purposes of stabilization, as such soils, if holding enough clay, show higher plasticity, swelling, and shrinkage than neutral or slightly alkaline soils of equivalent clay content; and if a moisture-retaining or stabilizing chemical is used a detrimental base exchange takes place, that is, the base of the salt is displaced, with a consequent loss of the beneficial effect that the salt was expected to furnish. Soil acidity may be due to organic matter, such as acid humus, to soluble inorganic salts such as phosphates or sulphates, or to an accumulation of silica resulting from the gradual leaching out of the bases from the soil-forming constituents. Detrimental properties of acid soils are corrected and base exchange is prevented by treating the soils with alkaline substances, so-called neutralizers, such as limestone dust, basic slag, or hydrated lime. Because of the difficulty of determining the exact amount required to neutralize the acid soil, the best way to ensure against detrimental exchange is to use an excess of neutralizer and make the soil alkaline. In the worst cases it will be sufficient to use one pound of high-calcium limestone dust per square yard per inch of thickness of the compacted stabilized layer. The same result will be obtained with a smaller amount of hydrated lime.

The function of insoluble or permanent stabilizers is to act as binders and furnish alone the required cohesion which is provided by clay particles and moisture film in waterbound stabilized surfaces. Roads treated with insoluble stabilizers are of course quite different from waterbound stabilized

[1] Prévost Hubbard: "Dust Preventives and Road Binders"; John Wiley & Sons, Inc., New York, 1910.

roads, since moisture plays no part in their stability. This form of stabilization is of particular value for fine clayey soils holding very little granular material. The stability of these soils is greatly affected by changes of moisture content, and the purpose of treating them with insoluble stabilizers is to maintain permanently in them the stability that they have in the dry, compacted state. The insoluble binder forms a film around the soil particles and destroys the colloidal properties responsible for changes of volume and stability of the soil with variations in moisture content. On account of the absence of granular material in the soil to resist the abrasive action of traffic, roads stabilized with insoluble binders are given a surface treatment or protective covering of gravel or stone chips mixed with a bituminous binder.

Many different materials have been tried as permanent stabilizers on experimental sections of road in the United States since about 1923. "Public Roads" of February, 1935, mentions some of them, such as hydrated lime, stone dust, granulated slag, Portland cement, calcium chloride, sodium silicate, kerosene, tar and asphaltic oils, and even lubricating oils. Some of these materials were used in combination, for instance, sodium silicate was used in combination with calcium chloride, lime or limestone dust, to produce insoluble stabilizers. As pointed out in the same journal of May, 1936, "the results of early work were not particularly promising but they should not be considered as indicating the possibilities of such treatments, because the requirements of thorough distribution of admixture, high degree of compaction, and protective surface treatment now deemed necessary were not recognized in the earlier work".

Ferric chloride should make a good stabilizer, as it is an active coagulant of clays and is easily transformed under certain conditions into ferric hydroxide, which has strong binding properties.

No definite information is available as yet on the success attained with insoluble stabilizers, except with Portland cement and bituminous emulsions, which have given encouraging results in experimental work.

SILICATE ROADS

In the middle of the last century Frédéric Kuhlmann in France advocated the use of sodium silicate as a binding agent in the making of artificial stone. Sodium silicate has been used in the United States to a very limited extent as a dust layer on broken limestone roads early in 1900. In the last fifteen years sodium silicate has been used in France to increase the durability of waterbound broken stone roads under motor traffic, particularly in localities where road stones are of only fair quality.

Commercial sodium silicate, or water glass, is not a compound of a definite chemical formula, as the ratio of SiO_2 to Na_2O may vary within certain limits. According to chemical analyses and determination of physical characteristics made on different commercial silicates by P. Deslandres[1], "water glass" appears to be a heterogeneous compound which is formed of silica held in solution in one or more sodium silicates, together with a certain amount of free soda. Contrary to the general opinion

* "Etude et Recherches sur les Silicates de Soude Routiers", published in "Bulletin Technique de la Route Silicatée", February 15, 1929.

originally held on the action of sodium silicate, the improvement of the road by the silicate is not due to a chemical reaction, i.e. base exchange between the silicate and the calcium carbonate of the limestone aggregate, according to various investigators. In this connection Deslandres says: "There is really no chemical action between the sodium silicate and the limestone but a series of phenomena, mostly of a physical nature, bringing about transformation and decomposition of the initial sodium silicate and a separation of an important part of its silica in an insoluble and irreversible form".[1]

The advantages claimed for silicate roads over the ordinary water-bound roads are that they are more strongly bound, more impervious, and compacting to a greater density. Through surface impregnation of the aggregate with the silicate it also is rendered more resistant to abrasion.

Nearly all silicate projects in France applied to roads made of limestone aggregate. Best results were obtained with limestones falling within the following limits as regards physical characteristics:

Specific gravity: 2·00 to 2·70.
Porosity: 30 to 250 litres per cubic meter (3 to 25 per cent by volume).
French coefficient of wear (Deval): 2·5 to 8.
Crushing strength: 400 to 1,600 kg. per sq. cm. (5,690 to 22,760 lb. per sq. in.).

Stones softer than the above limits should be rejected. Harder stones may be used as coarse aggregate, provided that they are mixed with fine aggregate made up of softer stone. Limestones holding impurities of an argillaceous nature should be avoided. The limestones used for roads in France, at least those involved in silicate projects, are geologically classed as belonging to the Secondary and Tertiary eras, are softer and particularly much more porous than limestones used as road aggregate in Eastern Canada, none of which is geologically younger than late Palæozoic. Very few limestones occurring in Eastern Canada are porous enough to come within the above limits.

The improvement attained by the use of sodium silicate makes this type of road well adapted to localities where the road stone is of mediocre or even poor quality and the traffic is not important enough to warrant the expense of bringing in better aggregate. These roads are particularly suitable under conditions of moderate traffic. Their traffic-carrying capacity may be increased by surface treatment with a bituminous emulsion, provided precautions are taken to ensure proper bond, such as admixing a certain amount of silicate to the emulsion.

In contrast with artificial stone, in which sodium silicate acts as a permanent binder, the amount of silicate used in road work is so much smaller that its binding action is considered as more or less temporary. Its effect, however, is undoubtedly more lasting when the silicate road surface is protected by a bituminous mat.

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[1] "Nature et Qualités des Matériaux Entrant dans la Construction des Revêtements Silicatés", published in "Annales des Ponts et Chaussées", III, 1929.

SOIL STABILIZATION CONSIDERED IN RELATION TO ROAD IMPROVEMENT IN CANADA

In relation to its population Canada has one of the largest road mileages. There are over 400,000 miles of public roads in the country, or 200 feet per capita, exclusive of urban streets. In 1920 only 7 per cent of the total mileage had been improved in some form or other, and by 1935 this percentage had increased to about 23 per cent. Of the 96,400 miles improved at the end of 1935, 88 per cent were of gravel, while the harder types of surfacing or pavements accounted for only 6 per cent.

The ever-increasing amount of gravel absorbed in road improvement in the last fifteen or twenty years is largely due to changing conditions in road traffic. The rapid development of the motor vehicle has created a consistent demand for a type of road surface that could serve this form of traffic under all weather conditions. In order to cover the large mileage of roads needing improvement and to serve the greatest number of people, it was necessary to select some type of waterbound surfacing because of its low cost. Waterbound surfacing was also sufficient for the needs of traffic over most of the roads. In Eastern Canada gravel proved eminently adaptable to such a service, on account of its widespread occurrence, ease of handling, and wearing qualities. With improved methods of road construction, selection of hard gravels and proper grading of the constituents through crushing and screening, gravel roads can serve satisfactorily a traffic of 500 to 800 vehicles per day, when properly maintained. As traffic increases, however, maintenance charges go up, and above 500 vehicles per day a daily maintenance is necessary to keep the road in good and safe condition for fast-moving vehicles.

In order to obtain a more firmly bound surface, increase its resistance to disruption by traffic, and reduce maintenance charges, various types of binder are applied to the road, but do not produce lasting results, as their cohesive action is limited to too thin a layer at the surface. Good cohesion is obtained with artificial or so-called permanent binders, such as bituminous materials, but road surfaces thus treated are intermediate between waterbound surfaces and pavements as regards cost as well as wearing quality. Waterbound road binders, such as clay, limestone dust, and other materials give more lasting results when mixed with the road aggregate than when simply applied on the surface, and the more so with well graded aggregates. When such a mixture has been properly compacted with the optimum moisture content, it makes a surface that has all the characteristics of a stabilized road and is truly a stabilized road, except that there is no moisture-retaining chemical. Waterbound stabilized roads have a greater traffic-carrying capacity and cost less in upkeep than other traffic-bound types of road surfaces.

USE OF GRAVEL AND GLACIAL DRIFT

The stabilization of waterbound road surfaces with clay binder and moisture film seems well adapted to conditions in this country, particularly in Eastern Canada. Stabilized gravel roads in particular would prove more serviceable in proportion to their cost than other forms of improvement. Most of our roads do not carry enough traffic to warrant anything more expensive than a waterbound type of surface. The materials required, gravel, sand, and clay, can be found almost anywhere. Stabilization permits of a wider choice of materials in road improvement than is allowable in ordinary gravel road construction methods. Hard sandy gravel does not compact readily on a road built according to ordinary standards, but works well in a stabilized mixture. There are numerous deposits of such fine gravels throughout Eastern Canada. In fact it is more common than the kind of coarse gravel usually specified for road construction. Another common material, boulder clay, glacial drift or till, considered useless for road surfacing, may prove a useful ingredient in a stabilized road mixture. Glacial drift makes a good foundation or embankment material, as it compacts firmly. It is, however, unsuitable for road surfacing on account of its grading in size. It is a mixture of coarse stones and boulders with fine silty or clayey soil and holds a relatively small amount of granular material of suitable size for road surfacing. On the road it acts like fine-grained soils, that is, the condition of the road is greatly affected by weather changes. Its road-making properties could undoubtedly be much improved with proper treatment, and its possibilities as road-surfacing material in stabilized road construction would be worth investigating. Boulder clays, like gravels, are not all suitable for roads, but many of them, through proper processing, such as crushing and screening, could be made satisfactory for use in a stabilized wearing-course. On account of its closer texture, glacial drift has been less exposed to the disintegrating action of weathering and is fresher than most gravels. Due also to its large proportion of coarse stones, the average boulder clay, once passed through a crusher, holds a larger percentage of sharply angular material than do most crushed gravels. Its grading is also much improved by crushing, as the proportion of granular material of suitable size for road purposes is thereby greatly increased. Glacial drift may hold enough fines to come within the plasticity requirements, so that the admixture of a suitable binder clay may be dispensed with. In any case it would require less binder than gravel, as the grading of crushed boulder clay comes closer to the prescribed grading for maximum density and stability than that of stratified gravels, whether crushed or uncrushed. Deposits of glacial drift are harder to work than gravel deposits, because in its natural state glacial drift is not so loose as gravel and frequently requires the use of a pick, if worked by hand. The presence of large boulders in many deposits also interferes with development work. The excavating of boulder clay by mechanical means should not present more difficulty than would the working of plastic clay deposits. In working boulder clay for road-surfacing purposes it is necessary to pass it through a crusher in most if not all cases in order to obtain a satisfactory product. Drift deposits, although not so widespread in distribution as gravel deposits, cover much larger areas, and in many parts of Eastern Canada this material is more easily available than gravel; in fact drift deposits can be traced without interruption for miles along many of our roads.

The rapid development of the northern mining districts and the increasing demand for highway communication with the older parts of the country make it necessary to improve roads through many miles of unsettled or sparsely settled land, where it is impracticable to go far afield in the search of suitable surfacing material, and where stabilization would permit of a wider choice of materials occurring along or near the right of way. Glacial drift may play an important part in the improvement of these northern roads by the stabilization method.

INFLUENCE OF CLIMATIC CONDITIONS

Road stabilization would tend to minimize any harmful action caused to our roads by such climatic factors as changes of weather and temperature ranges. In this country low winter temperatures followed by the spring breakup put highways to a particularly severe test, and this applies to pavements and permanently bound as well as to waterbound road surfaces and bases. Waterbound surfaces are also adversely affected by prolonged wet weather or long spells of warm and dry weather. Excess of moisture in one case, lack of moisture in the other, both are the immediate causes for the unstability of the roads. Well graded, densely compacted mixtures, which are characteristic of stabilized road surfaces and bases, tend to maintain the moisture already present and to keep any additionl moisture from penetrating the stabilized layer. The admixture of soluble chemicals greatly enhances this property of moisture control. Soluble chemicals have also the property of lowering the freezing point of moisture held in soils, which may prove an effective means of frost-heaving control. This is of particular significance in Canada, where frost action is so intense. Encouraging results have already been obtained with common salt as a means of protecting roads, pavements, and other structures against detrimental frost action.

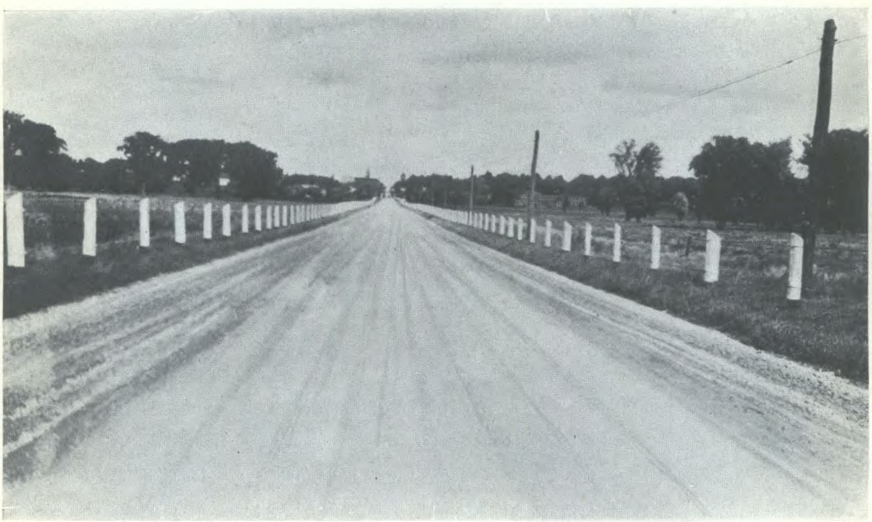
ROADS IMPROVED BY STAGES

Road stabilization makes it possible to improve roads progressively, according to traffic requirements: this is called stage construction. With the prevailing system of road improvement, when the amount of traffic reaches such a point that a gravel surface can no longer be economically maintained in a serviceable condition, paving becomes necessary. A bituminous surface treatment on an ordinary gravel base is too thin and flexible to take care of the impact of heavy traffic, with the result that displacement or settling takes place in the base and the bituminous surface becomes uneven. A well-compacted stabilized gravel layer has sufficient internal stability to resist deformation under traffic loads. If traffic on the stabilized surface is such as to cause undue wear, a thin bituminous surface treatment will give adequate protection against surface abrasion. When further increase in traffic makes it necessary to provide for a thicker protective covering, recourse may be had to a bituminous retread, or even to a regular paving mixture. In this way, for each successive improvement there is a substantial base already built up.

It may be repeated in conclusion that one of the great advantages of stabilized road construction is its easy adaptability to local conditions. Stabilized gravel-clay roads would probably be the most economical in Eastern Canada, on account of the widespread occurrence of the materials entering into their construction. Good judgment, rather than skill, is required in the choice of materials and construction procedure, so that local labour could be used as effectively as in other types of waterbound roads. As regards chemicals for use as moisture retainers and electrolysers, common salt and calcium chloride have been so far almost exclusively used in Eastern Canada, because they are obtainable at lower cost than other chemicals and have proved suitable for the purpose. Sodium chloride is available in all provinces, either in the form of rock salt, evaporated salt, natural brine, or sea water. A number of rock salt deposits are now worked for the production of different grades of salt. Calcium chloride is also now produced by one manufacturing concern in Ontario. Limestone dust and hydrated lime are the cheapest kinds of neutralizers available for the pretreatment of acid soils, and are produced in many parts of Canada. In limestone quarries, limestone dust is often a waste product. It is sometimes used as both filler and binder in stabilized mixtures, particularly where suitable clay binders are scarce. Sodium sulphate is claimed to have good dust-laying properties and may prove beneficial as an admixture in stabilized roads. It forms large deposits in certain parts of Western Canada, where its use for road purposes would probably be more economical than that of other chemicals and would be of great benefit to the local industry.

PLATE I

A. Illustrating smoothness of stabilized road surfaces: sodium chloride treated road at Schomberg, Ont.



B. Illustrating smoothness of stabilized road surfaces: calcium chloride treated road near Wingham, Ont.

PLATE II

A. Whitish appearance of sodium chloride treated road in dry weather, east of Port Carling, Ont.

B. Illustrating hardness of sodium chloride treated road: tractor marks do not penetrate surface, Brechin, Ont.

A. Close-up view of stabilized road surface: sodium chloride treated road at Cookstown, Ont.

B. Close-up view of stabilized road surface: calcium chloride treated road between Huntsville and Dwight, Ont.

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