Technical Report Documentation Page

1. REPORT No.

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE

Ideas and Current Problems in Pavement Design

5. REPORT DATE

July 24, 1957

6. PERFORMING ORGANIZATION

7. AUTHOR(S)

F.N. Hveem

8. PERFORMING ORGANIZATION REPORT No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

State of California
Department of Public Works
Division of Highways

10. WORK UNIT No.

11. CONTRACT OR GRANT No.

13. TYPE OF REPORT & PERIOD COVERED

12. SPONSORING AGENCY NAME AND ADDRESS

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Presented at the Seminar in Asphalt Paving Technology University of California Berkeley July 24, 1957

16. ABSTRACT

In arranging for this program, Professor Monismith said that he would like to have me present ideas on pavement design and discuss current problems. In trying to think of what I should say, I naturally tried to come forth with an idea or two, but I am afraid that the ideas have become somewhat overwhelmed and obscured by the problems. So it seemed that I might turn the title around a little and first describe the problems as they seem to be much more numerous than are ideas at the present time. Ideas for pavement design can only be exercised within a rather "narrow corral," that is to say there are fences and barriers in all directions. First, you are confined to a very limited number of materials. Another barrier limits you to types of construction and use of construction equipment that is capable of high rates of production. Thirdly, the entire project must be carried through from beginning to end in the shortest possible time.

Current problems in pavement design are probably the same problems that have always existed and basically seem to have three parts:

a. The demands of traffic.
b. The limitations of the existing soil and foundation.
c. The cost of the pavement.

Remove any one of these as an important consideration and the problem becomes relatively simple. Naturally, the magnitude or importance of each varies with the time and place.

17. KEYWORDS

18. No. OF PAGES:

35

19. DRI WEBSITE LINK

http://www.dot.ca.gov/hq/research/researchreports/1956-1958/57-05.pdf

20. FILE NAME

57-05.pdf

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

IDEAS AND CURRENT PROBLEMS in PAVEMENT DESIGN

By

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Materials and Research Engineer

Presented at the Seminar in Asphalt Paving Technology
University of California
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F. N. Hveem*

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The word stone is synonymous with permanence and endurance and the properties of soils and rock particles do not change very much so that for all practical purposes the engineer today must build roads over the same materials that made up the earth's surface in the days of Nabopolassar or Appius Claudius. Also there has been surprisingly little change in the type of materials used to form pavements and bases as the Babylonians used asphalt as a cementing agent and the Romans had hydraulic cements not vastly inferior to those in use today. The thing which has changed greatly of course is the traffic and this change has been in the total number of vehicles, axle loads, contact pressures and speed. On the favorable side, we no longer have to be concerned with steel tired vehicles and the deep grooves worn by chariot wheels in the pavement stone on the streets in Pompeii indicate that this factor could constitute a serious problem. However, there are problems enough and the principal one is the increase in the number and weight of vehicle wheel loads on both highways and airports.

The high speeds characteristic of modern traffic make pavement smoothness of greater importance than formerly and this problem has become especially acute within the last year or so with respect to the effect on military planes that must land and take off at high speeds. The bouncing or "porpoising" at high landing and take off speeds subjects both the plane mechanism and the pilot to very severe stresses. Good engineering demands that highway pavements should also be as smooth as possible, both out of consideration for the vehicle and the driver and in order to minimize the effects of surging loads on the pavement.

In its simplest terms, the problem facing a highway engineer or pavement designer today is how to meet the ever increasing demands of traffic while being limited to the same old materials. It is perhaps a comment on the relatively static nature of progress in pavement design to note that the $20,000,000 test road in Illinois contains no novel type or variety of pavement that has not been in use for at least 20 years. Most of the construction that will be tried on this most "modern" and greatest of test tracks is no different than that in use 50 or 75 years ago.

Cost considerations are, of course, one of the major deterrents to the use of anything but sand, gravel or crushed stone with or without the two common cementing agents of portland cement or asphalt. But certainly it is time that we were giving more attention to new concepts; if not in the basic materials at least to the design and structural arrangements.

Highways today are the result of the cooperative efforts of a virtually unlimited number of people. First, all roads are built to satisfy public demand and the actual work is divided among many individuals in the relatively large highway departments; whether city, county, state or federal. It must also be recognized that this division of responsibility and its accompanying division of interest has some interesting and important effects on the final outcome. The fact that engineers plan the roads and contractors build them has its effect upon types and methods. The fact that within the engineering organizations different individuals specialize in planning, design, construction and maintenance, (to say nothing of the higher sciences involved in materials evaluation) means that each engineer consciously or unconsciously feels a more or less limited responsibility. If a single individual had the authority, the ability and the time to develop the plans, prepare the design, carry out the construction and still be responsible for the overall economy and performance, it is quite probable that certain phases of pavement construction might be handled a little differently, assuming, of course, that he knew enough about all of the problems to select the best compromise.

While it is true that highways and pavements are built of materials, it is, of course, not true that all materials are equally suitable. This naturally leads to the question of what are the essential properties and before one can select properties of materials for a particular purpose it is necessary to know what properties the final structure or facility should possess. One can, of course, stipulate that paving materials must be durable and that they should be economical, et cetera, but these generalities do not mean very much except in a specific context and in relation to other things. For example, water is a fairly durable substance - at least it has been around for a long time and is hard to get rid of. It is also cheap enough and generally available except in Southern California. Diamonds, too, are durable - and scarce but in spite of high cost are found to be economical for some purposes. So we have to narrow these things down to the question of the conditions under which we operate. Paving materials must be reasonably durable under the effects of traffic and under variations in climatic exposure. It seems unlikely that any material will ever take the place of stone fragments for pavement construction but there could well be some improvement in the cementing agents used.

Among other peculiarities, engineers are people who rely much on formulas and the pavement design field has not been neglected. In 1945, the Highway Research Board published a list of some 22 formulas, none of which have been found to be completely satisfactory. In 1948, we tried our hand at this popular pastime and added one more formula which was adopted by the California Highway Department in 1949. I believe that this was the first attempt to include the effects of load repetition and to introduce factors allowing for the strength of the various types of pavement. The formula has worked well but accumulating experience indicates that adjustments are necessary to bring the design into better accord with actual performance. The existing formula appears to be quite satisfactory for the intermediate ranges of traffic but has tended to give very little margin of safety for roads carrying the heaviest axle loads and the old method of calculating equivalent wheel load has led to some extravagant thicknesses for lightly traveled frontage roads, etc. Essentially then, the improvements that seem to be indicated involve a different evaluation of traffic and a reduction in the allowance for the slab strength of pavements in order to provide a greater factor of safety.

Essentially, this and the original formula are based on the theory that the principal mechanism of pavement performance rests on the surcharge effect which means that the weight of the pavement slab and its slab strength or diaphragm effect both tend to restrain the upward movement of the subgrade around the area immediately beneath the wheel load. In line with this concept, the unit weight of the pavement and base structure is an important consideration, and the slab strength or tensile strength of the structure must also be evaluated.(1)

It may be worthwhile at this point to go back a bit and review the history of pavement "design" and note the conflicting ideas and confusion which has long existed over what constitutes a "poor" material or a "good" material. The Romans employed large blocks of stone surfaced with finer materials that were tightly cemented and in later years Telford was an advocate of similar heavy stone, but the modern ideas of road surfacing composition undoubtedly began with John Loudon McAdam. McAdam was strongly opposed to the incorporation of soil materials with the road stone but he differed from his predecessors in favoring a small maximum size of aggregate. In fact, he was very emphatic in his recommendation that no stone particle larger than about one inch should be included in the road surfacing. In spite of this intelligent understanding and strong admonitions on the part of McAdam, today his name is virtually synonymous with highway bases or surfaces containing large coarse stone.

In the early days of scientific road construction in this country, Doctor C. M. Strahan of the University of Georgia[4] discovered that some of the local red clays formed excellent cementing materials when mixed with the local gravel. He emphasized the idea that he was constructing "road slabs" of natural materials. This concept of a road slab has a strong appeal to engineers accustomed to thinking in terms of structural design. It came to be the fashion to introduce what was called "binder soil" and all through the years up to 1940 it was fairly universal practice to mix soil binders with gravel in order to produce a tightly bound base. During the earlier years when most of the road improvement consisted of substituting gravel surfaces for mud; a tightly bound up gravel was much more satisfactory and pleasant to drive over than a layer of loose material. However, this introduction of "scientific road building" led to some widespread and expensive failures. With the advent of dustless road surfaces it was an evolutionary step to place bituminous surfaces on these old gravel roads and it was a natural thought on the part of most engineers that if the gravel had been adequate to carry traffic directly it should logically form an excellent base when protected by a new bituminous surface.[2] This would be called a "common sense" conclusion. Like many other assumptions, this one has proved to be very much in error. In 1937, the Bureau of Public Roads felt that granular base failures had become so acute on a nation wide basis that they sent a team of lecturers through all the states to expound on some of the principles of road construction. C. A. Hogentogler, at that time, made the statement that in the southeastern Atlantic coast states alone the cost of repairs and reconstruction totaled not less than $4,000,000.00 caused solely by too much clay in the gravel bases. $4,000,000.00 was a lot more money in those days than today and unfortunately the failures were not confined to the Eastern Seaboard. It would be impossible to say what the cost has been but the total for the United States alone must be enormous.

The long established habit of introducing binder materials to cement up gravel road surfaces carried over into the construction of gravel bases. For example, even the enlightened State of California had a type of base construction of which they were rather proud known as slurry base. Here the gravel and soil binder was carefully proportioned and mixed in a central plant and hauled to the road where it was spread and flush rolled. Construction engineers were wont to brag about these bases as they represented a sort of mud concrete, and when exposed to the wind and sun baked hard and almost seemed to need no surfacing "as anyone could see that they were as hard as concrete." The crop of failures that developed in this state kept the Maintenance Department busy for many years.

I think it well to emphasize, however, that the widespread practice of adding soil fines to good gravel or crushed stone was not necessarily a case where "no one knew any better."

A friend of mine who was with the Army Engineers during World War I was assigned the job of keeping some of the French roads open for military traffic. Road maintenance in France, as in most of Europe, was handled by hand patching of the holes with broken stone and the stone was broken by hand and tamped into the road by hand. When the American engineer proposed to speed up maintenance by blading in materials from the roadside the very thought was met with horror on the part of the French road engineer who had learned through many years that clay or mud must be excluded from the road metal.

If engineers had been concentrating upon the real properties of materials rather than upon appearances they would have discovered long ago that granular bases or gravel road surfaces derive their ability to support loads from the friction between the particles, and as wet clay is a very effective lubricant it should not have been too difficult to figure out that clay would destroy the stability. Even though wet clay does supply some cohesion, the cohesive forces are relatively low compared to the resistance developed by interparticle friction. These properties can only be evaluated by test but experience has shown that even test results can be misleading if they are measuring the wrong property or over-emphasizing a property. With the adoption of the California Bearing Value Test in 1930 many of these erroneous notions appeared to be confirmed because the test is quite responsive to cohesive properties, and its use led to undue emphasis upon the values of soil binders. This test was also responsible for the rejection of many sources of clean granular materials which have actually given an excellent performance in bases or subbases. However, clean granular materials that lack cohesion have one serious drawback - they present difficult problems for construction operations, and it is usually necessary to employ some special technique in order to traverse such materials with construction equipment. It has been demonstrated in many areas that clean sands and gravels can be used and that pavements can be constructed over them. Nevertheless, contractors nearly always object to working on such materials and this viewpoint wins the ready sympathy of the average construction engineer. As a result, there is an almost universal tendency to employ gradations or add fine materials which will cement up on the road under watering and rolling operations. Such combinations are the least troublesome to handle and they give the best appearance and are the least annoying to travel over <u>during construction operations</u>.

This brings up a very pertinent point which should be more widely recognized; namely that the reputation of most materials and methods derives almost entirely from perforance during construction. In other words, if the construction men like it, it is good. But if it causes them trouble, it is not good - it is terrible - it is worthless! Therefore, to a large extent, reputations of materials and methods are based on convenience and ease of handling and not upon ultimate quality and performance. While it may seem that this question of ideas and viewpoints of individual engineers is a little outside a discussion of pavement design practices, nevertheless, most young engineers, even though college graduates, continue their education and gain "experience" by absorbing opinions and copying attitudes from the older men in the particular field. The problem is further confused by terminology, and an example which came to my attention recently indicates the cross purposes and confusion that may exist. On a large test road project, it was proposed to use a layer of coarse sand as a subbase. Stabilometer tests indicated that the sand had a relatively high R-value, not far below that of the crushed stone base. It was concluded that it would be desirable to have a sand of lower quality in order that the experimental road would have a clearly defined three layered system. Tests by the CBR method on the pit run sand showed that the "Bearing Ratio" would be markedly increased by adding clay or would be lowered by removing the clay in the pit material. As a result the sand was washed, whereupon it presented a serious construction problem. Even though thoroughly rolled and compacted to 100% of standard AASHO density, it would still be rutted and displaced by the passage of a single vehicle. During a conference to decide upon ways and means of proceeding, the construction engineers argued that the sand should be "stabilized" by the addition of a soil binder so that they could work on it; whereas, R-value tests made with the Stabilometer show that the stability of most granular materials would be reduced by adding such a binder, while at the same time, as mentioned above, CBR values would be markedly increased. Thus the addition of clay increases one property and diminishes another, and it becomes a very pertinent question to decide what is important and what is less essential. If left to their own devices, construction engineers would invariably add some sort of soil material to cement up a gravel or clean sand so that it would stay in place under construction equipment, would hold stakes for side forms, et cetera. As stated above experience has shown that such mixtures, when properly compacted and dried out even moderately from direct exposure to the wind and sun, present a very favorable appearance and the construction engineer may be excused for thinking that he has constructed a superior base, and there would, of course, be nothing wrong if the cementing agent did not become plastic and revert to a lubricant when wet.

The above statements and reference to Chart, Fig. 1, indicate that appearances can be misleading and also the same may be said of test data. Note that the CBR test indicates that when a clean granular material is contaminated with clay the values increase whereas when the same mixtures are tested in the Stabilometer the stability decreases. The purpose for performing any test is to predict the value of the material in actual performance. Obviously, such contradictory test values cannot both correlate with performance and it is equally obvious that the two tests are not measuring the same thing. In short, there are many properties of individual materials and their combinations. Some of these properties are important for one thing and some for another. It is, of course, necessary to recognize construction problems and it is essential that it be feasible to build any engineering structure but construction convenience and preference should not be allowed to dominate the considerations of service performance and permanence. The designer should have in mind a list of the properties of materials which he might consider using and then he must know what properties are important or essential for a completed project.

In 1948, a design formula was suggested which attempted to provide numerical factors and relative values for the important properties or various elements that influence the structural design of pavements. The original formula is as follows:

$$T = K \frac{(P\sqrt{a}\log r)(P_h/P_v - 0.10)}{\sqrt[5]{c}}$$

Where T = Thickness of cover (Base and Pavement in inches)
K = .0175 for best correlation but without any factor of safety. For design purposes it is suggested that K = .02
P_h = transmitted horizontal pressure in the Stabilometer test (#/sq.in.)
P_v = applied vertical pressure in the Stabilometer test (typically 160#/sq.in.)
P = effective tire pressure (#/sq.in.)
a = effective tire area (sq.in.)
r = number of load repetitions
c = tensile strength of the cover material as measured by the Cohesiometer in gms. per sq. in. (approximately = Modulus of Rupture X 45.4)

The values assigned to the different factors were based upon the available evidence and primarily rested upon the data from a test track that had been subjected to a limited amount of traffic. The evidence supporting the varying relationships was by no means equally valid. For example, the data indicated clearly that the thickness needed to be increased with the repetition of load and suggested that it should vary directly in proportion to the log of the repetitions. It was clearly evident that the slab strength of the pavement was a factor as was also the total load and the tire pressure on the pavement. While there were not enough variables in the original data to clearly indicate the influence of all of these factors nevertheless, the formula has been used for several years with considerable success.

It was hoped that there would be an opportunity to test the validity against additional controlled data furnished by the WASHO test track. It was a considerable disappointment, however, to find that there were insufficient points to clearly establish the relationship between pavement thickness and repetition of load. However, so far as could be determined the performance on the WASHO test track was in good agreement with the predictions of the formula where the two-inch asphaltic pavement was employed. However, the sections covered with four inches of pavement performed much better than would have been predicted by the formula. This suggests, of course, that the allowance for slab strength of the heavier surface was too low. However, we were reluctant to make a change based on the limited evidence as there was considerable question whether this higher slab strength would be a permanent and dependable asset. Nevertheless, we did not question that the formula needed revision but the evidence from general state highway performance indicates the need for greater factors of safety rather than less. Hence, we now propose to reduce the design assumptions for the slab strength of the pavement components. These slab strengths have been based upon cohesiometer test values, and the effects of multi-layered systems were calculated from a formula which now appears to be of somewhat dubious value. In lieu of these calculations, we are proposing to substitute a table of cohesiometer values which will be arbitrarily assigned to the more common types and combinations of base and surface layers. (See Table I). It must be emphasized that the establishment of any such table can only rest upon assumptions of the values which can be achieved in actual construction. We do not assume that these relationships are necessarily correct or completely consistent, and they may be further revised at the completion of studies that are now under way.

In addition to introducing a greater factor of safety in the assumptions for pavement slab strength, it is evident that an adjustment is needed in the evaluation of traffic. Calculations for any engineering structure obviously require an estimate of the loads which the structure must sustain. In the case of pavements, the problem is complicated by the fact that traffic loads are dynamic and complex in their effects.

The gross load of the vehicle is an obvious factor but as it is transmitted to the pavement through the axles and wheels the individual wheel or axle load becomes a better unit, but the damage varies with the number of times the wheel loads pass over the road. It is also evident that the effects of wheel loads are influenced or modified by the size of tire, number of tires on the wheel, the inflation pressure and the space between the axles. In addition, trucks vary in load, number of axles and in speed, and the pavement designer is faced with the problem of resolving all of these variables into a single number to express the magnitude and summation of forces that the pavement must resist. In view of the difficulty and cost of determining the actual axle loads by weighing all or a sample of the truck traffic, we have adopted the expedient of deducing a traffic index number from the traffic census. This approach is based on statistical analysis that indicates the average axle load that is characteristic of each of the common types of commercial vehicles. By this means, the traffic index is computed from traffic census data by multiplying the number of vehicles in the different axle groups by a constant. Constants of this type have been used for a number of years by the California Division of Highways but need to be brought up to date from time to time as traffic patterns change. The following table gives the constants which are now proposed for use in the immediate future.

Axle Group	Constant
2 axle	330
3 axle	1070
4 axle	2460
5 axle	4620
6 axle	3040

Further studies of the behavior of pavements including those on test tracks suggest that the best correlation with the data indicates that the thickness is proportional to the $EWL^{0.11}$. The traffic index is a simple expression equal to $1.35\ (EWL)^{0.11}$. Therefore, the revised formula is as follows:

$$T = K\ \frac{(T.I.)\ (90-R)}{\sqrt[5]{c}}$$

T = Thickness of the pavement structure in inches
K = constant
T.I. = Traffic Index - $1.35\ EWL^{0.11}$.
R = Resistance Value of the underlying soil or layer
C = Unit Cohesiometer Value (to be taken from table of values)

Chart, Figure 2, shows some examples of the difference in pavement thickness which will result from the new formula compared to the old. It will be noted that these changes result from a different evaluation of traffic and a lesser allowance for the slab strength of pavement surface and base.

This formula will provide a greater factor of safety but it will not guarantee elimination of all sources of trouble. It is still necessary that the actual work meet at least the minimum qualities assumed in the design, and adding additional thickness of pavement is no guarantee of success unless the quality is positively and uniformly maintained.

After the designer has decided upon the type of materials and the thickness of layers necessary, it is then the job of the specification writers to define precisely and explicitly just what is required and expected of the contractor. While the successful bidder is, of course, agreeing to carry out the work as set forth in the plans and specifications, in actual practice the responsibility for seeing that this is done rests with the resident engineer. It is at this point that many problems arise. Up to the time when the contractor begins work the project has been largely a matter of conversation and paper work but once he begins to move and place materials the die is cast. There are certain limitations to the ability of contractors and construction equipment. There is a natural and proper tendency on the part of designers to aim at the most economical job. For example, they may select an adequate design consisting of a cement treated base surfaced with an asphaltic pavement but for reasons of economy the specifications may permit the contractor to employ road mixing of the base material. This step immediately introduces a considerable element of uncertainty as the control of road mixing operations is a very difficult matter. Results may vary with the type of equipment used, with the experience of the contractor's crew and the engineering inspector on the job. What may appear to be economy in construction may well turn out to lead to costly maintenance and repair to say nothing of the embarrassment in having a project show distress within a year or two after completion. Therefore, in the design of any structure, while it is necessary to understand the mechanics of materials and the principles involved, it is equally essential to recognize the limitations of the materials and construction methods.

Since very ancient times, men have constructed durable and satisfactory engineering structures. The thing that distinguishes modern practices from the ancient is the gradual shift from the status of an art to that of a science. While in the long run the scientific method may be expected to win out and achieve a higher degree of success than can be expected from skill and personal experience alone, nevertheless a certain humility is becoming to those advocating scientific methods. There is a good deal of evidence to prove that theoretical concepts have turned out very badly and have led to some costly repairs, especially in the highway field. Emphasis on strength of concrete and concern over stresses and strains have done little to improve the performance of portland cement concrete pavements. Emphasis on the theory of elasticity while ignoring the equally valid theory of plasticity and the rheological properties of materials has tended to leave many blind spots in engineering concepts. As a result of academic training and general conditioning, engineers instinctively think in terms of "strength" and will all too easily accept any measurement which is alleged to reflect the strength of an individual member or of a structure. Figures representing the breaking strength of a steel cable or the load required to crush a concrete cylinder are regarded all too complacently as significant indices of strength and the average engineer feels better about such things if they are expressed in pounds per square inch. Nevertheless, materials have properties that are not adequately reflected by simple tests of this type. The load carrying capacity of pavements may be markedly influenced by viscous elements and the performance be markedly affected by speed of traffic and temperature. Traffic loads are moving loads and the concepts of structural design based upon relatively sustained or static conditions are not realistically applicable to pavement problems.

For example, engineers who have a background or training in structural design are prone to think of a pavement section as a sort of beam and with the first evidence of weakness or inadequacy the natural trend is to increase the thickness or strength of the beam. This concept is not necessarily completely wrong but it is necessary to recognize that in the case of pavement the actual beam may be many feet in depth. Deflection tests, for example, have shown that soils are compressed and rebound with each passing load up to a depth of 20 feet or more. In this scale then the average pavement is only a thin layer or a more or less brittle crust on the upper surface of the "beam." Any pavement slab having less than the strength of a bridge deck is unable to sustain loads except through the assistance of the supporting layers beneath. If the underlying soil yields under the loads then the pavement slab may be bent or stressed beyond its capacity and even though not broken with a single load may develop fatigue failures under repetition of load. Obviously, however, the pressures generated by wheel loads are dissipated with depth. This is not quite the same as saying that the pavement or base "spreads" the load as there appears to be an actual tendency to focus or concentrate the load at certain depths or zones beneath the pavement surface. The amount of pressure existing at different levels beneath the pavement surface will vary with the total wheel load, with the tire area, the slab strength of the pavement, and with the depth. Figure 3a shows typical lines of failure in a concrete cylinder broken under direct compression. Figure 3b shows similar cone shaped surfaces of failure in a plaster of Paris specimen. Figure 3c is a specimen of soil. Figure 4a is a photograph showing this cone shaped element developed in a mass of cohesionless sand. Figure 4b illustrates the type of movement that takes place in a bituminous pavement, in a gravel base or a soil under a sufficiently heavy load to cause deformation. In other words, the effect of applying a load over a limited area on a bed of granular material is to force a cone shaped mass of the material downward displacing the adjacent material laterally and upward.

It has been observed, for example, that timber piles offer about the same resistance to driving whether blunt or pointed, the reason being that the blunt pile acquires a sort of point from the soil material itself. In the more stable soils and granular materials, the shape of this cone approximates 45 degrees. However, the shape of this element varies with the quality of the material, becoming flatter and more shallow in the more plastic lubricated soils. This flattening of the cone continues as the soils become less stable until it disappears entirely when a liquid state is reached.

It has long been known that there is a falling off in unit pressure with depth beneath the surface and these curves have been plotted many times from plate bearing tests. If the depth beneath the surface is plotted in proportion to the radius of the area under load, very similar curves may be developed irrespective of the actual load area. There is a good deal of data to show therefore that pressures at some point beneath the surface under vehicle wheel loads may be greater than at the surface of the pavement and the existence of this cone shaped mass seems to offer a ready explanation for this concentration of load. For example, Dr. Krynine showed that pressures had been measured as high as 230 percent of the surface pressure, Fig. 5.(3) Figure 6 is a sketch showing three different load areas representing a typical touring car, truck and airplane and the corresponding cone at a 45 degree angle illustrating the variation in depth below the surface at which the point of maximum pressure will occur.

It is obvious, therefore, that the need for internal stability or resistance to deformation is greatest at the "point of the cone" which varies in depth according to the load area. What is less well realized is that the need for stability diminishes above this point until we reach the actual surface of the road, at which point a thin layer of liquid will support the wheel loads. Figure 7 is a graph showing the minimum stability that would be required at different depths below the surface. These diagrams have only limited practical value as there would be little justification for actually constructing a pavement in a large number of thin layers beginning with a low stability layer two or three feet below the surface, gradually improving the quality up to the critical zone and then reducing the stability up to the actual surface of the pavement. Nevertheless, such a distribution of stability or resistance values should enable a pavement to withstand traffic loads provided all wheels were approximately the same size and carrying very similar loads. This picture of the non-uniform distribution of pressure does explain why stability is of little importance in very thin asphalt surface treatments and why heavy asphalt pavements must be more stable than thin ones, and most important of all it illustrates what has been observed in actual practice that the quality or stability of a base course must often be higher than that of the actual surfacing.

I have no illusions that I have explained all of the factors and relationships which bear upon the performance of a pavement structure. If I have, it has been inadvertent on my part. In any event, I hope that I may have demonstrated that the problem is complex and it seems apparent that an ultimate solution will only be reached by measuring real properties and not imaginary ones. It seems most likely that ultimate success will come through the use of the inductive method based on actual measurements and experiments and not upon the deductive approach based on mathematical concepts and assumed "principles."

ACKNOWLEDGMENTS

I wish to acknowledge the work and valuable contributions of George Sherman and Joseph R. Santos of the Pavement Section under the direction of Ernest Zube. Acknowledgment is also due to Mrs. Agnes Lyon and Margaret Lark who typed the manuscript, to Bill Yttrup and others who prepared the drawings and illustrations.

Table I

Average Unit Cohesiometer Values for Combinations of

PMS and Class "B" CTB Over Untreated Material

(Plant Mixed Surfacing over CTB Class "B"; Total Depth of Structural Section)

0									
1									
2	400	400	400						
3				400	400	400			
4							400	400	400
5									
6									
7									
8	640								
9	540			620					
10	470	660		530			590		
11	410	580		460	640		510		
12	370	510	680	410	560		460	620	
13	340	460	600	380	500	650	410	550	
14	310	410	540	340	450	580	380	490	630
15	290	380	490	320	410	530	350	450	570
16	280	350	450	300	380	480	330	410	520
17	260	330	410	280	360	440	310	380	480
18	250	310	390	270	340	410	290	360	440
19	240	300	360	260	320	390	270	340	410
20	230	280	340	250	300	370	260	320	390
21	220	270	330	240	290	350	250	310	270
22	210	260	310	230	270	330	240	290	350
23	210	250	300	220	260	310	230	280	330
24	200	240	280	220	250	300	230	270	320

PMS Over Untreated Material

(Plant Mixed Surfacing; Total Depth of Structural Section)

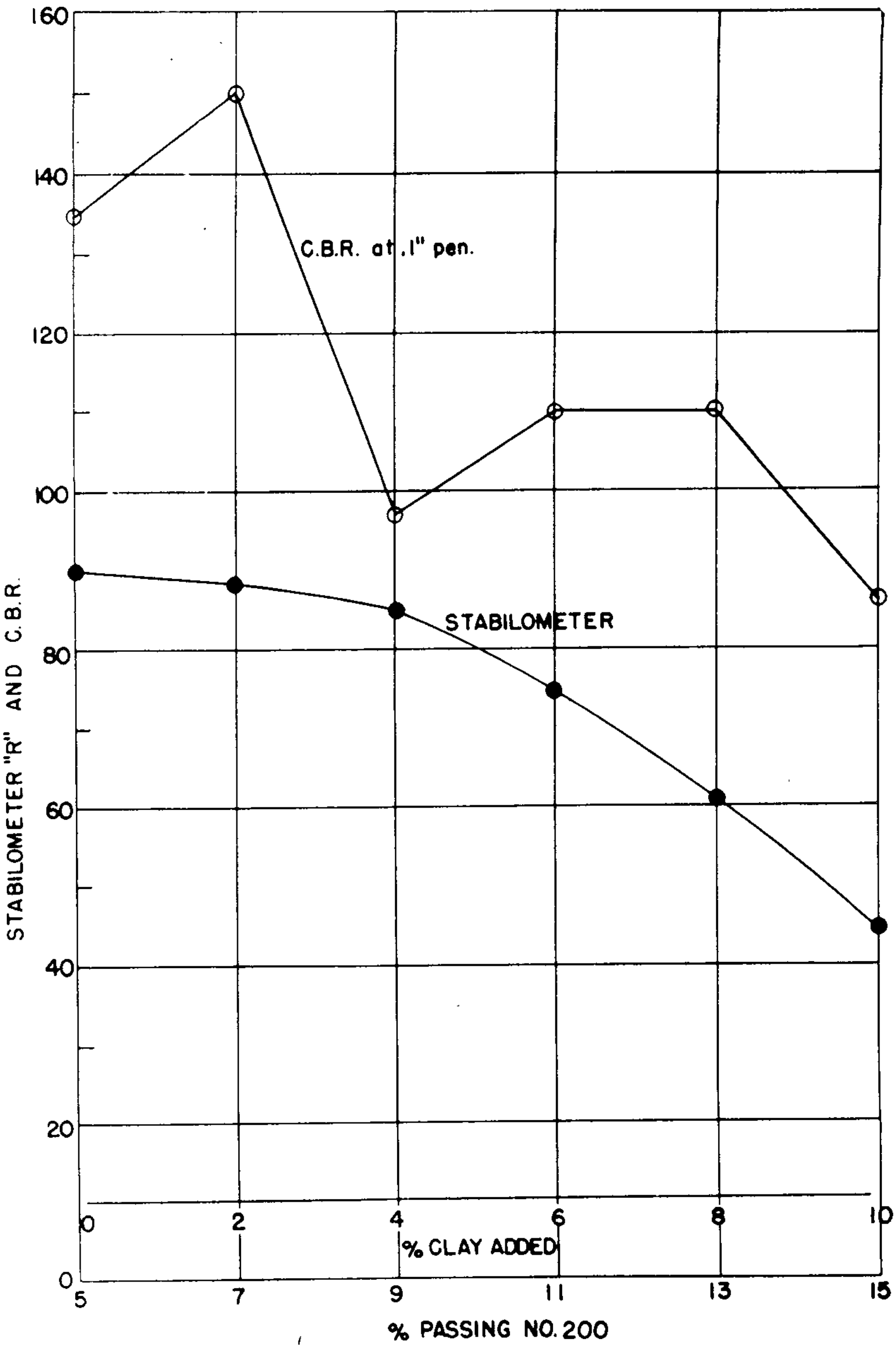
0						0
1						1
2	400					2
3	260	400				3
4	210	290	400			4
5	180	240	310	400		5
6	170	210	260	330	400	6
7	160	190	230	280	340	7
8	150	180	210	250	290	8
9	140	170	190	230	260	9
10	140	160	180	210	240	10
11	130	150	170	200	220	11
12	130	150	170	190	210	12
13	130	140	160	180	200	13
14	130	140	160	170	190	14
15	120	140	150	170	180	15
16	120	130	150	160	180	16
17	120	130	140	160	170	17
18	120	130	140	150	170	18
19	120	130	140	150	160	19
20	120	130	140	150	160	20
21	120	130	130	140	160	21
22	120	120	130	140	150	22
23	110	120	130	140	150	23
24	110	120	130	140	150	24
25	110	120	130	140	150	25
26	110	120	130	130	140	26
27	110	120	130	130	140	27
28	110	120	120	130	140	28
29	110	120	120	130	140	29
30	110	120	120	130	140	30

Table 1 (Cont'd.)

Average Unit Cohesiometer Values
Combinations of PMS and Class "A" CTB
Over Untreated Material

Plant Mixed Surfacing

Total Depth of Structural Section	CTB Class "A"			CTB Class "A"			CTB Class "A"			CTB Class "A"			CTB Class "A"		
8	1110														
9	900			1010											
10	750	1190		830			930								
11	640	990		710	1080		790			840					
12	570	850	1240	620	920		680	1010		740			810		
13	500	740	1060	550	800	1140	600	870		650	940		710		
14	460	660	920	500	710	990	540	770	1070	580	820		630	890	
15	420	590	820	450	640	880	490	690	940	530	730	1010	570	790	
16	390	540	740	420	580	790	450	620	840	480	660	900	520	710	950
17	360	490	670	390	530	710	420	570	750	440	600	810	480	650	860
18	340	460	610	360	490	650	390	520	690	420	550	730	440	590	780
19	320	430	560	340	460	600	370	480	630	390	510	670	410	550	710
20	300	400	520	320	430	550	340	450	580	360	480	620	390	510	650
21	290	380	490	310	400	520	330	430	540	350	450	580	370	480	610
22	280	360	460	290	380	480	310	400	510	330	420	540	350	450	570
23	260	340	430	280	360	460	300	380	480	310	400	500	330	420	530
24	250	330	410	270	340	430	290	360	450	300	380	480	320	400	500


160
140
120
100
80
60
40
20
0
STABILOMETER "R" AND C.B.R.
C.B.R. at .1" pen.
STABILOMETER
0
2
4
6
8
10
% CLAY ADDED
5
7
9
11
13
15
% PASSING NO. 200

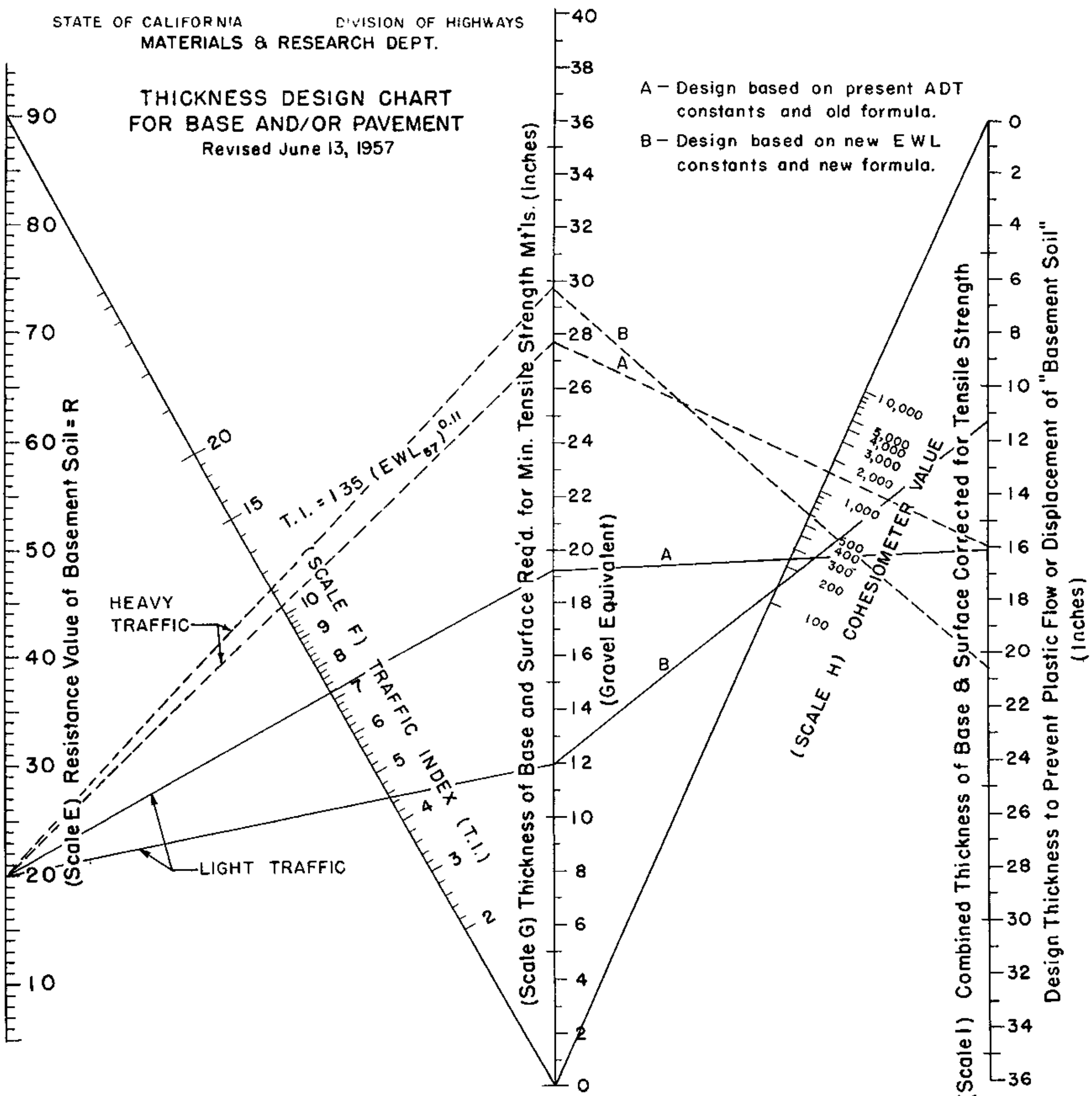
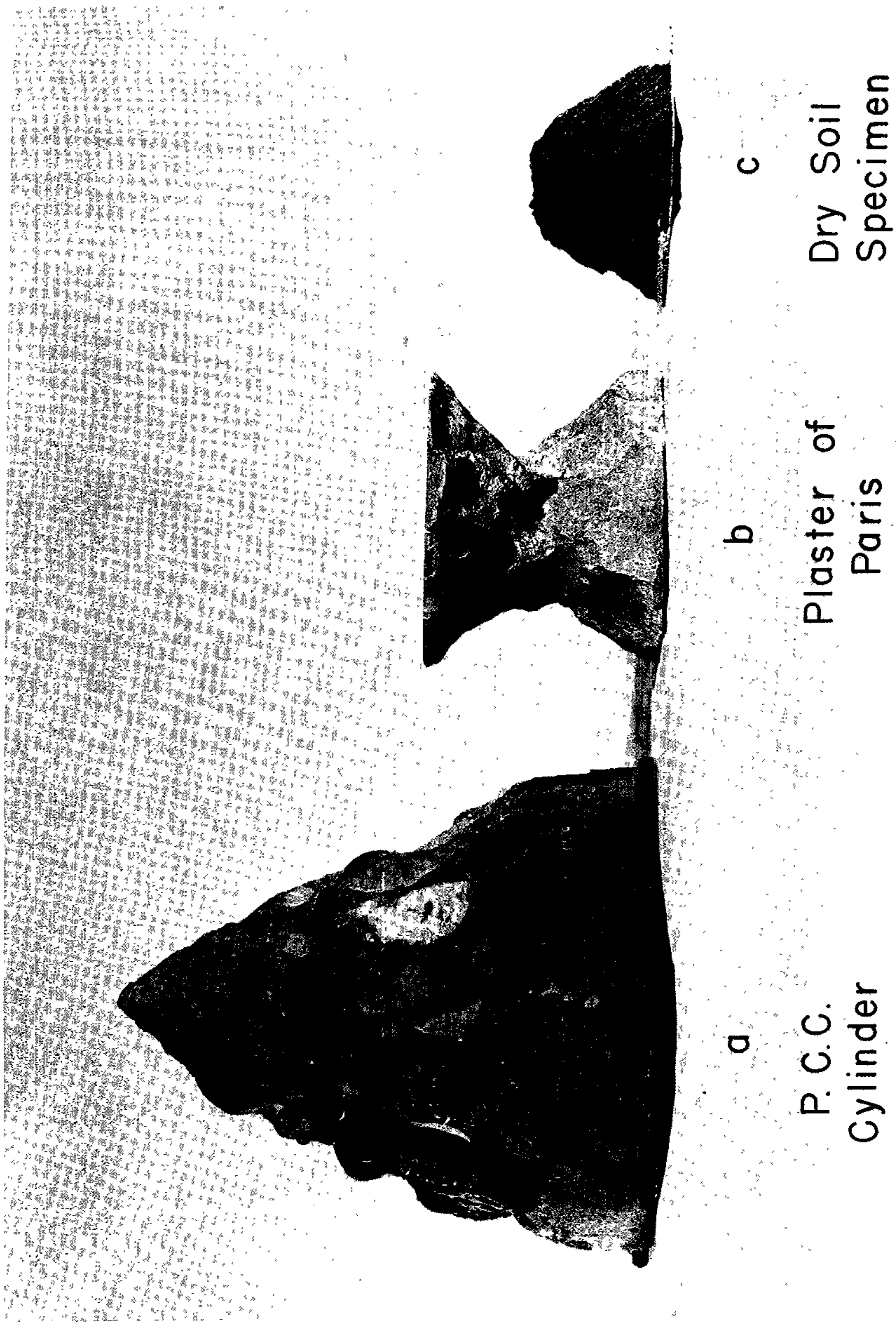
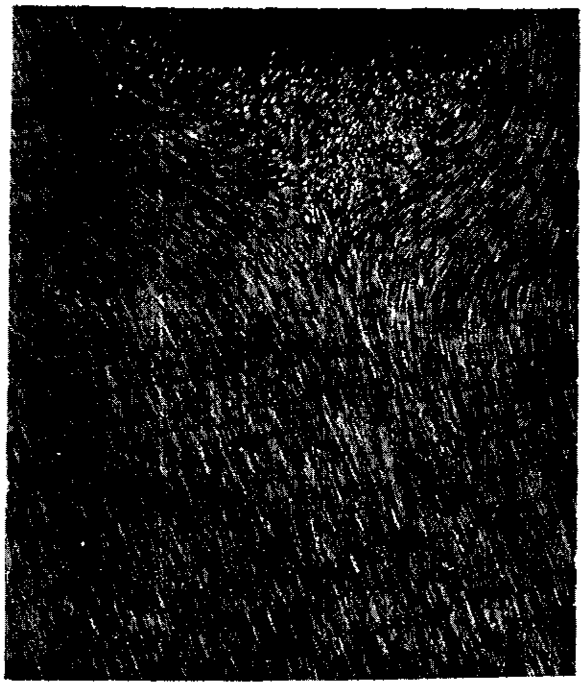
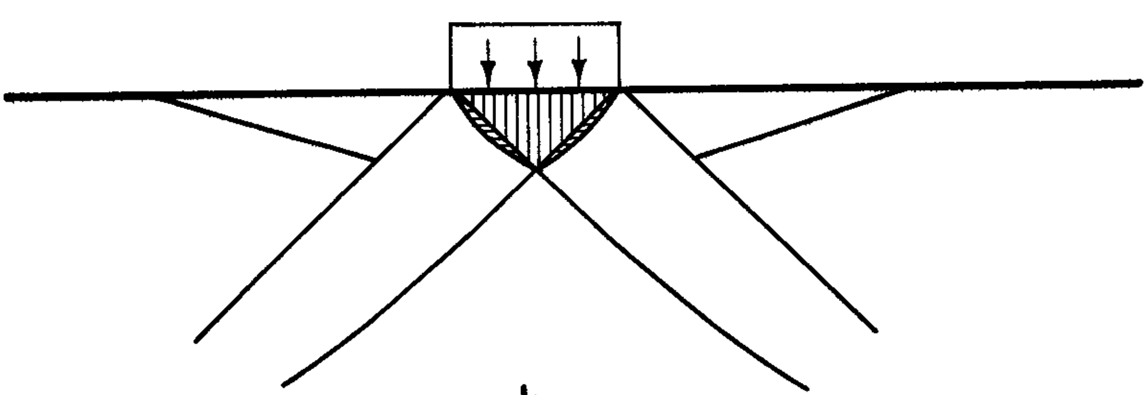

STATE OF CALIFORNIA
DIVISION OF HIGHWAYS
MATERIALS & RESEARCH DEPT.
THICKNESS DESIGN CHART
FOR BASE AND/OR PAVEMENT
Revised June 13, 1957
A — Design based on present ADT constants and old formula.
B — Design based on new EWL constants and new formula.
(Scale E) Resistance Value of Basement Soil = R
(Scale F) TRAFFIC INDEX (T.I.)
T.I. = 1.35 (EWL57)0.11
HEAVY TRAFFIC
LIGHT TRAFFIC
(Scale G) Thickness of Base and Surface Req'd. for Min. Tensile Strength Mt'ls. (Inches)
(Gravel Equivalent)
(SCALE H) COHESIOMETER VALUE
(Scale I) Combined Thickness of Base & Surface Corrected for Tensile Strength
Design Thickness to Prevent Plastic Flow or Displacement of "Basement Soil" (Inches)

Figure 3

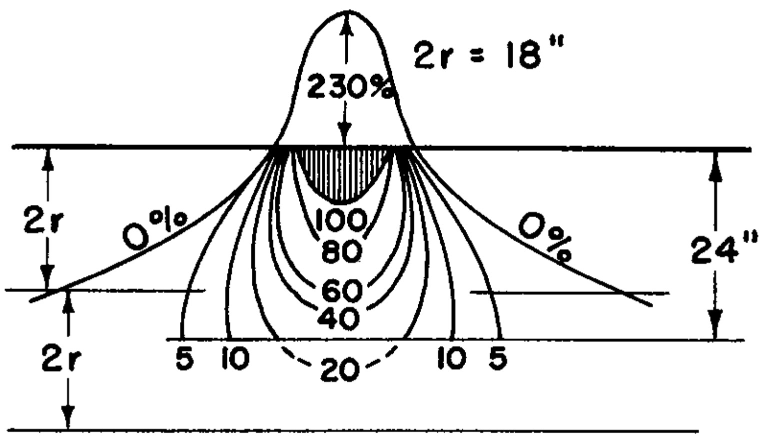




a

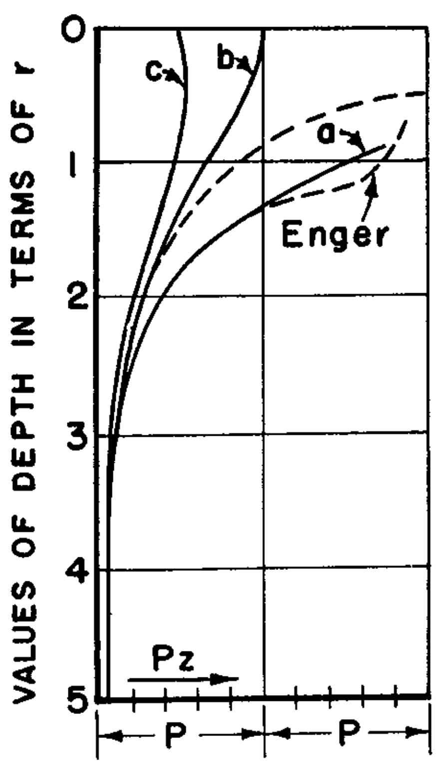


b



KÖGLER AND SCHEIDIG'S EXPERIMENTAL ISOBARS

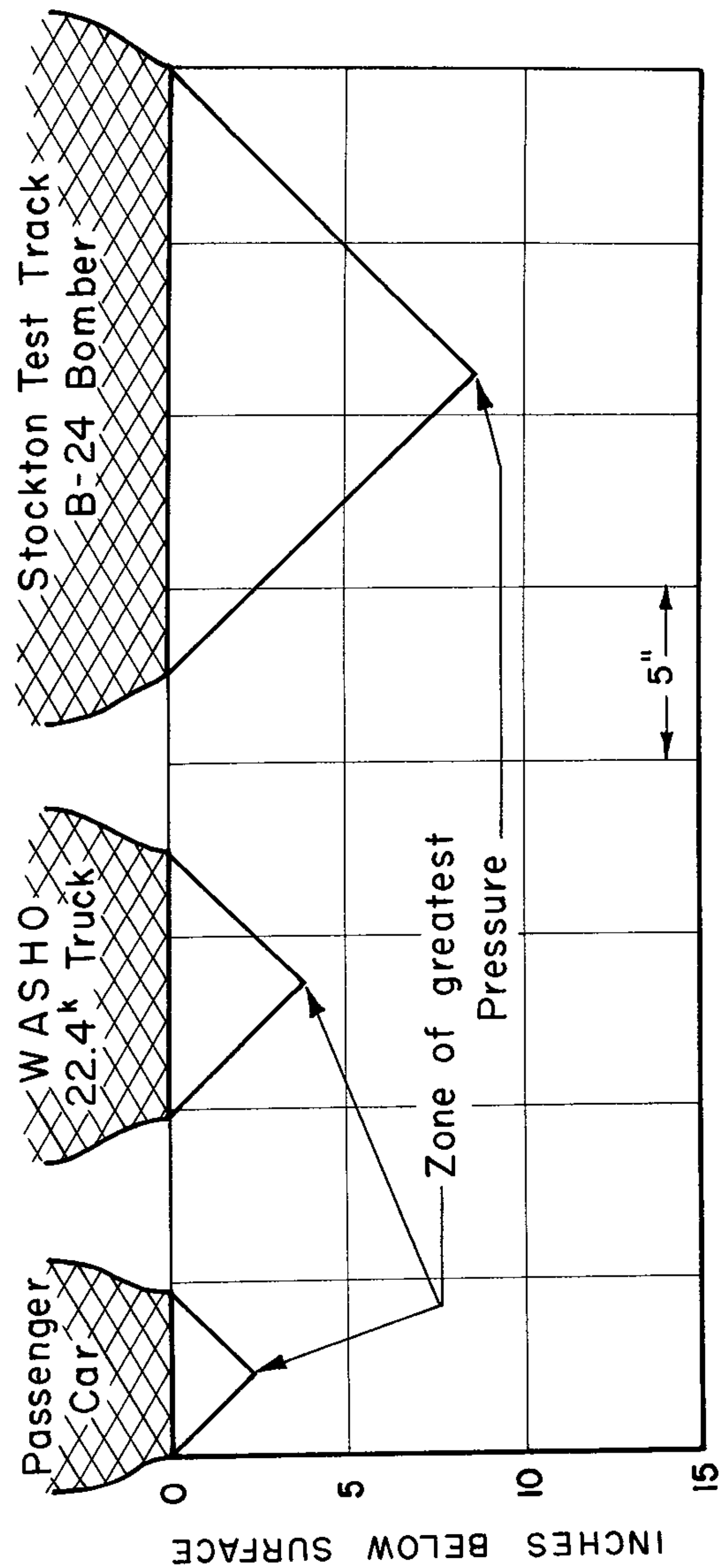
a

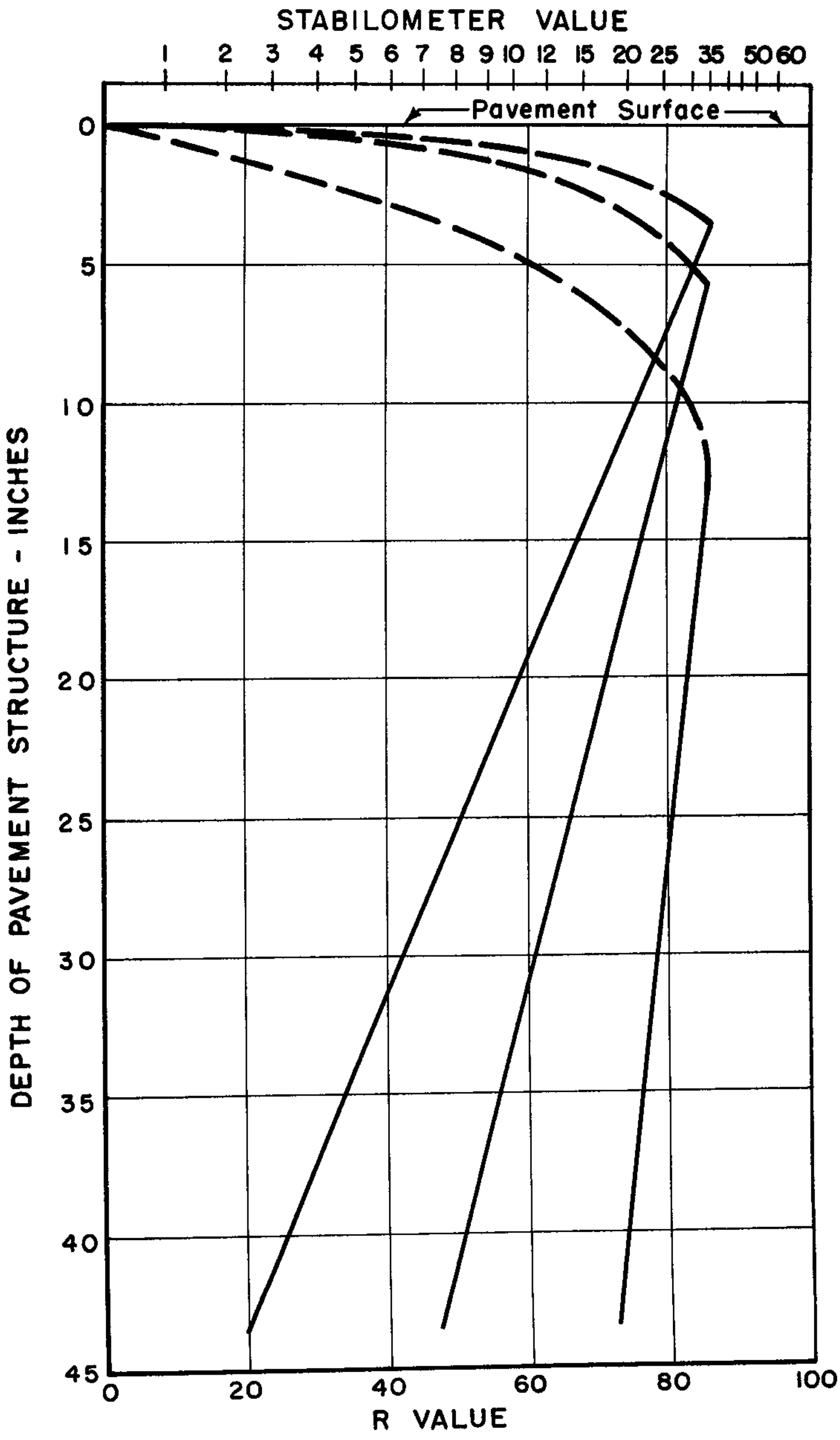


DECREASE OF PRESSURE WITH THE DEPTH

b

DEPTH OF MAXIMUM PRESSURE UNDER VARIOUS TIRES




STABILOMETER VALUE
1 2 3 4 5 6 7 8 9 10 12 15 20 25 35 50 60
Pavement Surface
DEPTH OF PAVEMENT STRUCTURE - INCHES
0
5
10
15
20
25
30
35
40
45
0 20 40 60 80 100
R VALUE

REFERENCES

1. F. N. Hveem and R. M. Carmany, "The Factors Underlying the Rational Design of Pavements," Proceedings, Highway Research Board, Vol. 28, pp. 101-136 (1948).

2. "Notes on Design and Construction of Bituminous Pavement Surfaces," published by Milton Hersey Co. Limited, Montreal, Canada, pp. 60 and 61.

3. D. P. Krynine, "Soil Mechanics," pp. 113-120.

4. C. M. Strahan, Proceedings of Third Annual Meeting, Highway Research Board, (1923) page 81. "Sand-Clay Road Investigations," Proceedings of Fourth Annual Meeting, Highway Research Board, (1924) page 41.

STATE OF CALIFORNIA DIVISION OF HIGHWAYS
MATERIALS & RESEARCH DEPT.

THICKNESS DESIGN CHART FOR BASE AND/OR PAVEMENT

Revised June 13, 1957

PROCEDURE

With a straightedge intersect Scale E at the value for R (as determined by the Stabilometer on specimens with H/D = 0.6) and Scale F at the traffic index for the total traffic load for the design life of the highway. The intersection of this line with Scale G is the thickness of gravel required to support the load (neglecting abrasion, etc). From this point intersect Scale H at the cohesiometer value of the cover. This line will intersect Scale I at the thickness of base and surface required to resist plastic flow of the basement soil.

The cohesiometer value to be used should be determined from the appropriate table in the Planning or Materials Manual.