Behavior of Hot Asphaltic Concrete Under Steel-Wheel Rollers

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Maximum compaction of hot asphalt concrete is obtained under steel-wheel rollers when the roller weight and number of passes are optimum for the roller diameter and load bearing capacity of the mix. When more than the optimum roller effort is used, low densities or checked surfaces result.

Some mixes behave in an abnormal manner by shoving excessively under rollers they should tolerate. According to ordinary design tests, these abnormal mixes may be quite stable. Sometimes these mixes are referred to as "slow setting."

The paper proposes a mechanism by which mixes can be unstable at high temperatures during rolling and still be quite stable by normal design criteria. The difference is attributed to a transient high "pore pressure" caused by unabsorbed asphalt.

The condition can be corrected by changes in the mix design, filler content, or aggregate dryness. The character of the asphalt does not appear to be of great importance Several examples of field problems corrected by application of some of these principles are given.

●MODERN HIGHWAY ENGINEERS use every device available to assist them in designing high quality, asphalt concrete pavements. They are assured that their designs and specifications are met by means of inspections made during and at the end of construction. In nearly all cases, these practices result in high quality surfaces because minor difficulties or unusual behavior of the mix under the steel-wheel rollers are resolved by field engineers and construction crews as soon as detected. Changes in mix design, temperature, layer thickness, or rolling procedure are routinely made to obtain the desired density, toughness, or appearance of the finished pavement.

Occasionally, however, an abnormal situation arises when these normal measures do not correct the difficulty as expected, although no obvious errors in mix composition or procedure were made. As a result, the finished pavement may have a low density, be tender, and easily marred by high pressures or power steering turns, or have a checked (fissured) surface. When these situations arise, both the mix and asphalt used are often called "slow setting." This term can be misleading because it implies the presence of questionable hardening qualities in the asphalt binder that have not been clearly demonstrated. Actually, all of the reports of abnormal behavior that have been received and the several instances that have been observed in the field resolve into failures of the mix to compact properly under steel-wheel rollers.

To understand this problem, a study was undertaken in the research laboratory. Under controlled conditions, many of the variables of asphalt concrete design and compaction were studied in laboratory and full-scale tests (1, 2). It was found that the porosity of the aggregate, the water content of the aggregate, the type and amount of fines, the aggregate gradation and the roller characteristics are all important in determining how well a mix compacts. Other factors might also contribute, but they have not been identified in the recent work.

The understanding gained in the laboratory has been applied to field problems with success. This paper describes the concept of the compaction mechanism, the data that were obtained and the conclusions that were reached. Several field studies have verified the principles postulated.

MECHANISM OF HOT ASPHALT CONCRETE COMPACTION

Steel-wheel rolling of hot asphalt concrete is a means of applying pressure and kneading action to a mix so that compaction will occur. When high roller pressures are used, shear deformations tend to occur in front and behind each wheel. Shear deformations in the mix under these conditions cause an expansion of the mix which results in decompaction. The intimate particle contact lost by the shearing action is not restored until pressure is again applied to the decompacted zone.

The conditions existing in a dymanic situation under a moving roller are shown in Figure 1. Most of the decompaction occurs in front of the roller, although a minor amount occurs in the rear. This action gives the appearance of a low wave traveling along, not unlike the bow wave in front of a moving boat. This wave is a symptom of a zone of decompaction preceding each pass of the roller.

Eventually, after enough passes have been made, an equilibrium is established in which the recompaction and decompaction are balanced. As discussed later, the state of compaction at equilibrium is dependent on the load-bearing capacity of the mix, as well as the roller weight and diameter. A small roller sinks deeper into a mix causing more extensive decompaction than does a larger roller of the same weight. This results in the larger bow waves observed with small rollers.

Because of the roller curvature, horizontal stresses are visualized in a mix under tension—like splitting wood with a wedge. If the resultant tensile strains are large enough, the mix surface pulls apart, causing fissures of checking to appear after rolling. These horizontal forces are larger with the sharper curvature of small rollers. This agrees with the field observation that checking is more severe with small-diameter rollers.

FACTORS INFLUENCING COMPACTION

There appears to be an optimum load-bearing capacity (or stability) which permits a maximum compaction to occur under a particular roller weight and size. To illustrate this point by extremes, a mix can be so stable (as occurs at ambient temperatures under traffic) that negligible compaction takes place. On the other extreme, the mix can have such a low stability that the roller sinks deeply into the mix.

A relative measure of this stability or bearing capacity of a mix is the familiar Coulomb equation (3), which expresses the stress, necessary to cause shear failure in a mix

$$S = C + \sigma \operatorname{Tan} \phi$$

in which C is the cohesion, σ is the confining pressure, and ϕ is the angle of internal friction of the mix.

Hot-mix plant operators have little control of ϕ because it is a consequence of the specified mix design. They do, however, have considerable control over the cohesion. They can vary this by changing the mixing temperature, the asphalt type or grade, or by changing the amount and kind of filler used. The effects of these factors are discussed in more detail later.

The contribution of cohesion to the high-

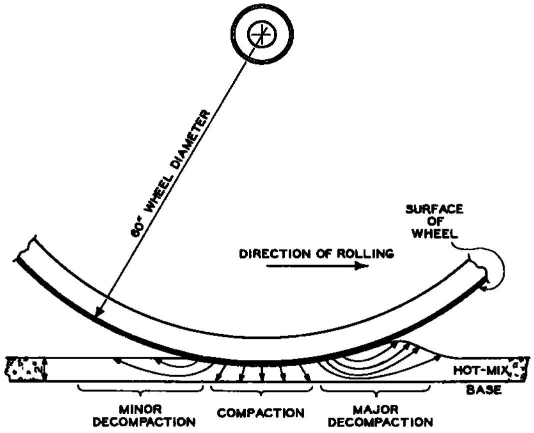

Figure 1. Behavior of hot-mix during rolling.

temperature stability of a mix can be estimated from McLeod's (3) work, which shows that doubling the cohesion doubles the bearing capacity of thin layers of asphalt concrete on a solid base under normal loading conditions. It seems reasonable, therefore, that this effect will hold at higher temperatures. If this is the case, higher cohesion will reduce decompaction in front of the roller, as well as checking in the surface directly under the roller. However, if the cohesion increases, as it does when put into service under traffic, it will eventually become large enough to prevent compaction. There appears to be an optimum mix cohesion to obtain a maximum compaction under a given set of rolling conditions.

Even more favorable conditions will exist if the cohesion is shear dependent (breaks down with shear), in which case compaction can occur easily directly under the roller because the local high shear rates reduce cohesion. In front of the roller the shear rates are lower (less shear breakdown) and the resultant higher cohesion is more effective in preventing decompaction. This ideal situation would have a low stability directly under the roller and high stability (confining forces) adacent to the roller. How this can occur is discussed in the next section.

FACTORS INFLUENCING COHESION

During rolling the cohesive properties of an asphalt concrete are dependent on the flow properties of the asphalt and filler mixture (binder). Three characteristics considered important in modifying the rheology of the binder are: (a) filler content and particle size distribution, (b) rolling temperature, and (c) nature of asphalt. Nijboer (4) studies the influence of the properties of the binder on the cohesion of a mix by means of triaxial and other laboratory experiments. He refers to cohesion as the initial resistance. Extrapolation of Nijboer's data to higher temperatures gives an indication of the relative effect of the different factors under rolling conditions. When the asphalt content is 6 percent and the mix filler content varies from 2 to 5 percent, Figure 2 shows the tenfold increment in cohesion. Reducing the average filler particle size from 100 to 10 microns doubles the cohesion, according to Figure 3. The effect of reducing the rolling temperature from 300 F to 200 F is shown in Figure 4 and results in a fourfold increase in cohesion. Figure 4 also shows that the nature of the asphalt has an effect on cohesion that might reach a factor of three.

The increase in cohesion at mix temperatures obtainable by changing from a 200-300 to a 40-50 penetration grade asphalt can be estimated from temperature viscosity curves. This is equivalent to about a 30 F difference in mix temperature (drop from 280 F to 250 F). This indicates that less than a twofold increase in cohesion can be expected by changing the grade of asphalt a maximum amount.

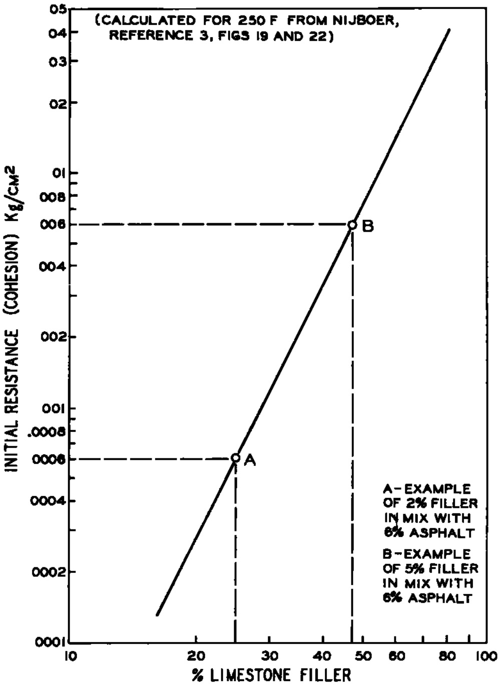

Figure 2. Effect of filler in binder on cohesion of mix.

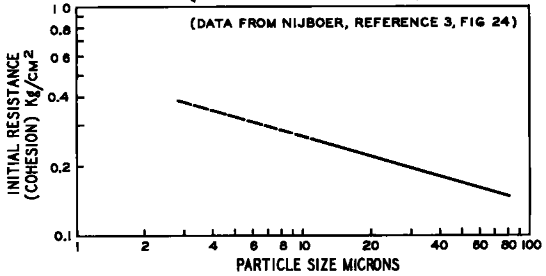

Figure 3. Effect of filler particle size on cohesion of mix.

If these extrapolations of Nijboer's data to higher temperatures are valid, clearly when the filler content is low raising it is the most effective way of increasing the hot mix cohesion.

The strain rate of a filled asphalt is not directly proportional to the stress at all levels (5). The rate of strain stays very low as the stress is increased until a point where shear breakdown occurs. Beyond this point, strain is proportional to stress in the customary manner. This is shown (Fig. 5) in illustrating experiments using the microviscometer (6). The breakdown point is proportional to the amount of filler included in the binder. All ordinary unfilled paving asphalts have very low, almost insignificant, shear breakpoints. Further work may show that quite different breakdown points are obtained using the same type and amounts of filler but with different asphalts.

NORMAL BEHAVIOR UNDER STEEL-WHEELED ROLLERS

A mix is considered to act normally when its behavior under a roller can be predicted from ordinary laboratory stabilily tests. This means that very stable mixes should tolerate heavy rollers or many passes before excessive decompaction occurs. Those with a low stability will tolerate only light rollers or a few passes.

For convenience, the behavior of these normal mixes is considered in two classes because they respond differently to severa variables. They are considered understressed when the mix is lightly stressed in the range where a greater compactive effort will increase the degree of compaction obtained. They are considered overstressed when an additional compactive effort causes a drop in the degree of compaction in a mix. The optimum amount is the transition point where maximum compaction is obtained between the under- and overstressed conditions.

UNDERSTRESSED

In the range where the stability of a mix is more than adequate to support the compactive effort imposed during rolling (or in a laboratory compactor where shear deformation is limited by the containing mold), increasing compactive efforts give higher densities (4). Figure 6 and Table 1 show this effect. The data, shown in solid

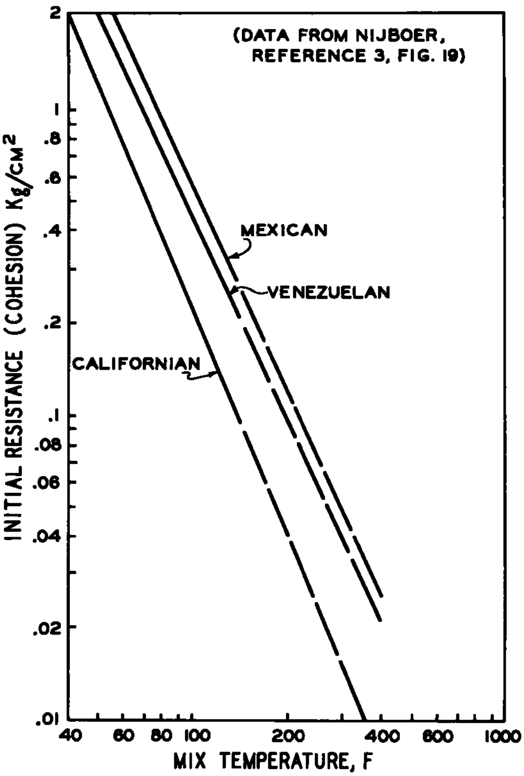

Figure 4. Effect of temperature and asphalt source on cohesion of mix.

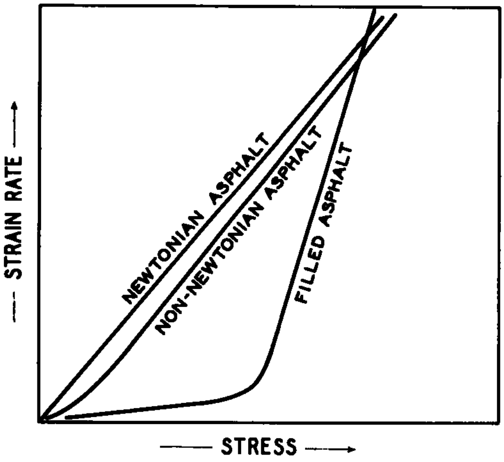

Figure 5. Filled asphalt strain rate drops rapidly with stress.

TABLE 1

EFFECT OF NUMBER OF PASSES[1] ON CORE DENSITY

	Core Density (pcf)			
Core	1 Roller Pass	2 Roller Passes	4 Roller Passes	5 Roller Passes
A	129 77	130.88	132.68	134.42
B	130.88	131.15	133.91	133.08
Avg.	130.32	131.01	133.29	133.75

[1] Asphalt A, Table 3, used in these experiments

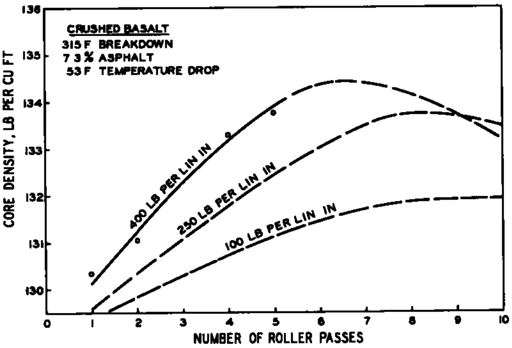

Figure 6. Core density vs number of roller passes for different wheel pressures.

lines, were developed using full-scale equipment described in Ref. (2). The dotted lines and extensions are estimates based on limited experiments and on field experience. Figure 6 shows that by increasing either the number of roller passes or the roller weight, up to a certain point, higher densities are obtained. This finding is consistent with Nijboer's studies (4), which appear to be limited to the understressed class.

Under these conditions the temperatues of rolling have a pronounced effect upon increasing the density obtained during rolling. However, as shown in Figure 7 and Table 2, the effect varies, depending on the temperature range and compactive effort. As the temperature increases, cohesion drops; and the stability of the mix decreases slightly, thus permitting more compaction to occur under the roller. The remaining stability is still high enough to support the roller without excessive decompaction.

Nijboer (4) shows that in these understressed conditions an increased compaction for a given roller weight can be obtained by reducing the roller diameter. This will produce the increased deformation required under these conditions. However, as previously discussed, smaller rollers increase the checking and the amount of decompaction in front of the roller at the same time.

In this situation, where the cohesion of the mix is not a major factor, the source of the asphalt appears to have little effect. This point is confirmed by the results of full-scale experiments summarized in Figure 8 and Table 2 which relate density obtained to rolling temperature when asphalts of different types are used. Table 3 lists the properties of asphalts used.

Normal Behavior When Overstressed and Stressed at Optimum During Rolling

As shown in Figure 6, increasing the number of passes of a low-pressure roller will increase the density up to a limited value. No amount of further rolling will increase it more. The plateau at which this maximum density occurs depends on the roller pressure and diameter, the mix properties and temperature, and the thickness of the layer of asphalt concrete being rolled.

As the roller pressure is increased beyond a critical point for a given mix, the density of the mix is no longer unaffected by an excess of passes. It begins to drop. As Figure 6 shows, only a few passes of the highest pressure rollers can be tolerated.

This drop in density with excess rolling appears to be caused by the formation of surface checks or fissures. It can occur on a cold mix with a heavy roller if enough passes are made. The concept on how this occurs is as follows: As the mix becomes

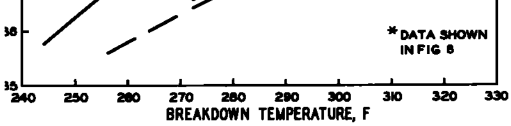

Figure 7. Normal behavior: Density increases with breakdown temperature and roller pressure.

more stable under compaction or by cooling the roller does not sink into the mix so much and its full weight is concentrated in a narrow band. Thus, the horizontal components of force causing tensile stresses are concentrated and the mix fails under high local tension. An example of this decompaction at the surface is shown in Figure 9. This shows the varying densities in a core sliced into thin horizontal sections with a diamond saw. The density is lowest at the surface.

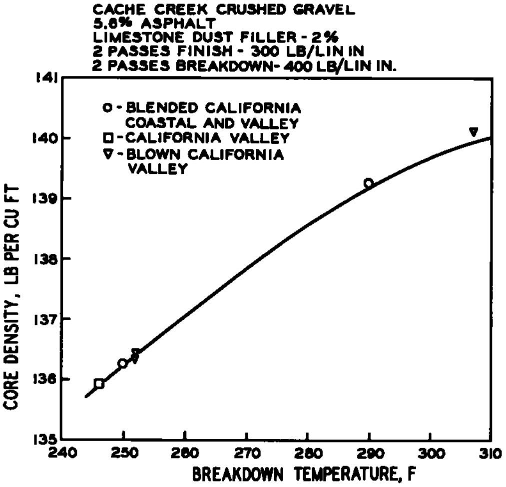

Figure 8. Normal behavior: Density increases with breakdown temperature regardless of asphalt source.

TABLE 2
CORE DENSITY AND BREAKDOWN TEMPERATURE[1]

	Core Density (pcf)						
	Asphalt A[2]		Asphalt B[3]		Asphalt C[4]		
Core	250F[5]	290F[5]	246F[5]	303F[5]	252F[5]	252F[5]	307F[5]
A	136.48	139.48	135.65	140.08	137.34	135.46	139.68
B	136.39	138.81	135.84	139.33	136.79	134.89	139.89
C	135.94	139.55	136.44	139.05	136.06	135.78	140.76
D	135.99	-	134.38	-	135.00	136.82	-
E	136.78	-	136.25	-	136.37	138.70	-
F	136.93	-	136.86	-	136.07	136.87	-
Avg.	136.41	139.28	135.90	139.48	136.27	136.42	140.11

[1] Data for Figs. 7 and 8.
[2] Blended California coastal and valley asphalt.
[3] California valley asphalt.
[4] Blown California valley asphalt.
[5] Breakdown temperature, in °F.

Increasing roller pressure up to a point will raise the density obtained for a given mix. However, as schematically shown in Figure 10, a maximum value will be obtained where the decompaction resulting from the increased weight offsets the compaction expected from higher pressure. Eventually, with a further increase in pressure, the density actually drops. Each mix then has an optimum roller pressure which gives a maximum density to the mix.

Figure 11 shows the relation between the stability of a mix and its optimum roller weight. It indicates that more stable mixes tolerate heavier rollers. This relation is clear if the reader will recall from his own experience, the very low roller weights or low mix temperatures required to roll unstable mixes made with uncrushed gravel. Recall also the high pressures required to compact well graded, crushed, aggregate systems having high stabilities. The stability of a normal mix, as measured by normal mix design tests, is related to the optimum roller weight that will give the mix a maximum density using a fixed number of passes. The ranges shown are estimated from field observations and intended to be illustrative only.

It should be kept in mind that the values shown will be quite different for rollers with different diameter wheels. With large wheel diameters, higher pressures can be used and higher densities obtained before excessive shear deformation occurs. Wheels with small diameters cause excessive shear failure at rather low loadings and will

TABLE 3

PROPERTIES OF ASPHALTS USED IN FULL-SCALE EXPERIMENTS[1]

Identification Tests	Asphalt A[2]	Asphalt B[3]	Asphalt C[4]
Penetration at 77 F, 100 g, 5 sec	96	91	91
Penetration at 39.2 F, 200 g, 60 sec	24	25.5	20
Penetration ratio	25	28	22
Flash point, Pensky-Martens (°F)	445	465	440
Viscosity at 275 F (SSF)	138	126	119
Heptaine-xylene equivalent	20/25	25/30	20/25
Softening point, ring and ball (°F)	110	116	Not tested
Thin film oven test, 325 F, 5 hr:			
Weight loss (%)	0.51	0.53	0.42
Penetration retained (%)	53	53	55
Ductility of residue	100+	150+	150+
Miscellaneous tests:			
Oliensis spot test	Neg.	Neg.	Neg.
Sulfur, bomb method (%)	3.0	1.6	1.3
Construction data:			
Penetration at 77 F (before hot mix)	92	89	82
Penetration at 77 F (extracted)	48	47	43
Penetration retained (%)	52	53	53

[1] Construction data shown in Table 2 and Figs. 6, 7 and 8.

[2] Blended California coastal and valley asphalt.

[3] California valley asphalt.

[4] Blown California valley asphalt.

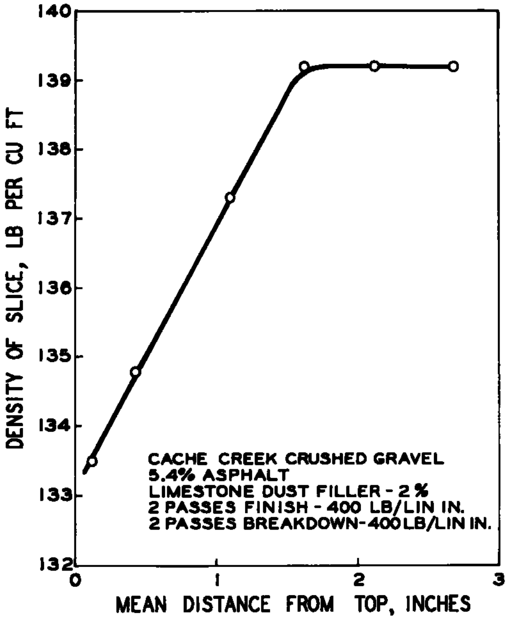

Figure 9. Density of sliced cores increases with distance from top of mix.

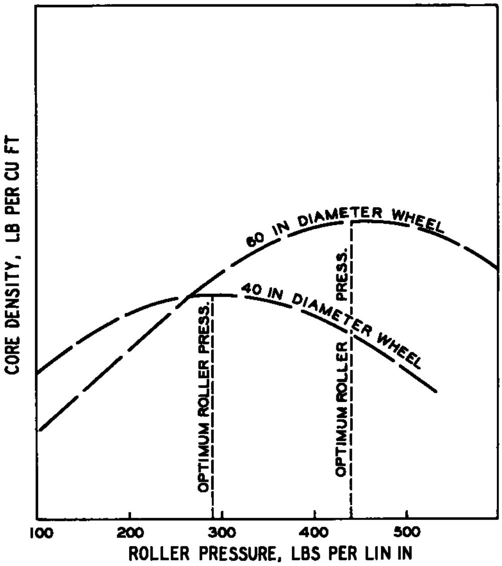

Figure 10. Density varies with roller pressure and wheel diameter.

give low maximum densities (Fig. 10).

Asphalt concrete is most often laid in courses about 2 in. thick; they are rarely greater than 3 in. or less than ¾ in. As shown in Figure 12, the thickness is quite important in determining the maximum roller weight that can be used effectively. Very thin layers are shown to tolerate much higher pressures than thick ones. This is because the close proximity of the plane of the stable base inhibits shear deformation and decompaction markedly. McLeod (3), in theoretical considerations, shows that thin layers of a given asphalt concrete have a much higher resistance to shearing displacement than thick ones.

At the optimum, where the maximum roller pressure is applied consistent with maximum compaction, the cohesion of the mix has become the factor limiting the resistance to shearing displacement (stability) of the mix. Accordingly, as the cohesion increases, so will the optimum roller pressure.

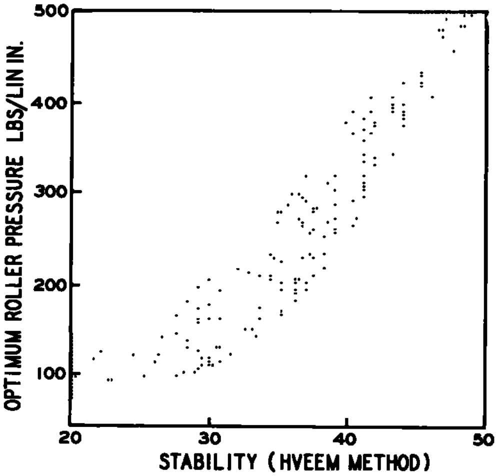

Figure 11. Optimum roller pressure depends on mix stability.

An example of the effect of reducing the cohesion of heavily stressed mixes by increasing temperature is shown in Figure 13 and Table 4. This figure, giving the results of several full-scale experiments, shows that no change in the density is obtained as a result of increasing the rolling temperatures. Also, both 300- and 400-lb per lin in. rollers are shown to give the same results. Possibly, these roller weights straddle the optimum for the mix being rolled.

As discussed previously, the cohesion of a given mix is controlled principally by amount and particle size of the filler and to a less extent by the mix temperature or penetration grade of asphalt. The source of asphalt is indicated to be a minor variable. However, unlike the previous case with understressed mixes, asphalt source would be expected to have some effect on determining the optimum roller weight. The effect should be obscured by minor changes in filler type or amount. Work is in progress to establish these points.

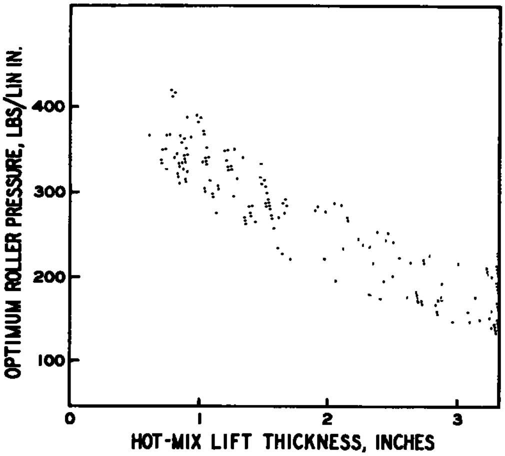

Figure 12. Optimum roller pressure depends on lift thickness.

ABNORMAL MIXES

Occasionally, a mix does not behave in the expected normal fashion; by conventional tests it appears quite stable,

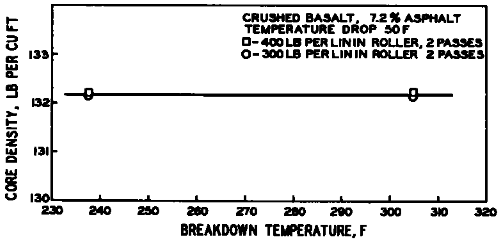

Figure 13. Overstressed condition density vs breakdown temperature.

TABLE 4

DENSITY VERSUS BREAKDOWN TEMPERATURE[1,2]

Core	Core Density (pcf)			
	300-lb/lin in. Wheel		400-lb/lin in. Wheel	
	238 F[3]	305 F[3]	238 F[3]	305 F[3]
A	133.03	132.84	133.62	131.32
B	132.28	133.76	132.38	133.00
C	130.81	130.95	132.45	131.86
D	131.40	130.89	130.66	131.37
E	132.98	132.94	132.24	131.71
F	132.56	131.40	131.71	133.95
Avg.	132.17	132.13	132.17	132.20

[1] Asphalt A, Table 2, used in these experiments.
[2] Data for Fig. 13.
[3] Breakdown temperature, in °F.

but under a heavy roller it shoves excessively. Such mixes are represented by points falling below the shaded area in Figure 11. According to normal stability tests, the mix shown should support a heavy roller and achieve high density. In practice, it will tolerate only a light roller and, accordingly, achieves a low density.

This discrepancy appears to be a result of significant differences between the conditions used in determining laboratory stability and the conditions occuring during field rolling. Some of these differences are:

1. Laboratory stability tests are run at 140 F; rolling temperatures are in the range of 225-300 F.
2. Laboratory tests are run on throughly dried aggregates; this is not always the case on aggregates used in plant mixes (7, 8).
3. Laboratory voids calculations are based on tests run at 77 F; in the field, mixes are normally compacted 200 F higher than this.

As a result, the volume of asphalt in the voids may be excessively high because the asphalt is not absorbed into porous aggregate until a sizeable drop in temperature occurs and until all steam has evolved from the aggregate. The effect is similar to the low stability observed in wet soils having high pore pressures.

EFFECT OF AGGREGATE POROSITY

Whenever the air voids in a mix become too low, the stability drops (9). This principle is well recognized both in aggregate-asphalt and soil-water systems (10). Figure 14 shows this effect in a dense mixture of aggregate and asphalt.

Unstable conditions caused by low voids

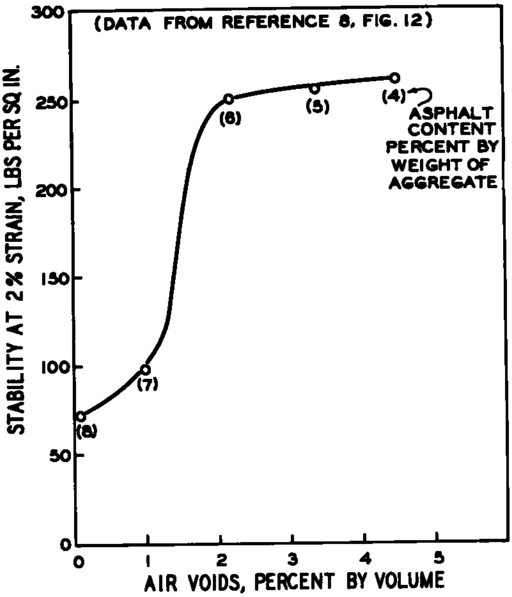

Figure 14. Mix stability is low when voids are filled with asphalt.

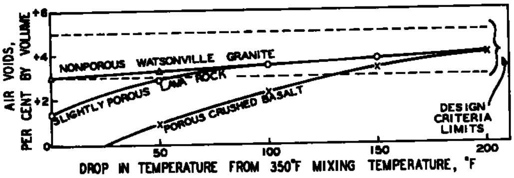

Figure 15. Air voids depend upon porosity and drop in temperature after mixing (dense mix).

can be present at the high rolling temperatures existing shortly after mixing and not be evident later at room or design temperatures. Examples of how this occurs are shown in Figure 15, where the effective voids contents at different temperatures are shown for aggregates having several porosities. The data used to construct these curves were obtained by immersing the aggregate mix at high temperatures in asphalt in calibrated flasks and observing changes in volume as the temperature was dropped in increments (11). Care was taken during preparation that the only air remaining in the mixture was in the pores in the aggregate.

With the nonporous Watsonville granite, there is little change in the effective voids content as temperature drops. This would be predicted from calculations based on the thermal expansion of the asphalt and granite. However, using a porous aggregate, striking changes in the effective voids content of the system are shown. This result also can be predicted if the thermal expansion of the entrapped gases is considered.

Dense mixes made with porous aggregates are shown to have zero voids contents at high temperatures. There is inadequate void space to accommodate the asphalt present. Under these conditions a mix would have a very low load bearing capacity.

Figure 16 was constructed from the same data, except that the gradation assumed was for an open mix. Under these conditions, only the most porous aggregates are shown to approach a critical voids content at high temperatures. This conclusion agrees with the observations that abnormal behavior does not occur in open-type mixes.

These experiments indicate that a greater absorption could be obtained if the asphalt and aggregate were mixed together at a higher temperature, thus allowing the mix to cool longer before rolling. The bigger drop in temperature, ΔT, causes absorption of more asphalt. Figure 17 and Table 5 give the results of full-scale experiments made to clarify this theory. The crushed basalt used (see Fig. 18 for grading) was the same as the aggregate used in the absorption experiments previously described. The curve shows that a maximum density is obtained for this particular mix and roller when the ΔT between mixing and rolling is about 65 F. Points on the curve include rolling temperatures varying from 222 F to 305 F. They fall close together if the ΔT is the same.

The series of experiments not only confirms the theory that a higher temperature drop would remove the excess asphalt from the voids, but also demonstrates that there is an optimum amount of asphalt to remove in a particular mix.

The abscissa in Figure 17 is plotted from left to right on the basis of a greater ΔT between the pugmill temperature and rolling temperature. Also plotted is the amount of asphalt estimated to be in the voids for the corresponding temperature drop. This was calculated from Figure 15, which was based on the same aggregate, gradation, and asphalt.

Also indicated is the increase in stability corresponding to the reduced amount of asphalt in the voids. As more than the optimum amount is removed, the mix becomes lean in asphalt and more difficult to compact.

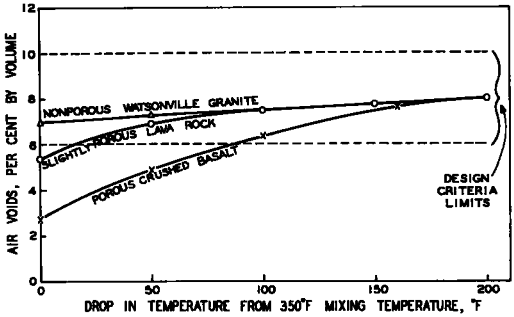

Figure 16. Air voids depend upon porosity and drop in temperature after mixing (open mix).

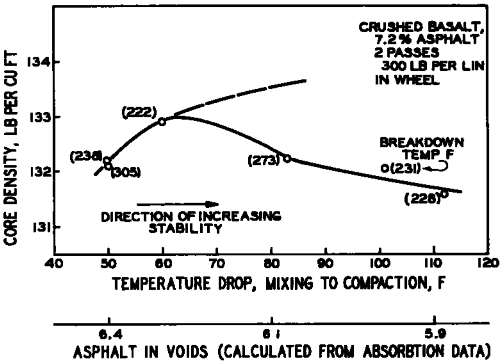

Figure 17. Asphalt absorbtion caused by drop in mix temperature influences core density.

TABLE 5

DENSITY VERSUS TEMPERATURE DROP[1, 2]

	Core Density (pcf)					
Core	Temp. Drop 50 F Bkdn. Temp. 238 F	Temp Drop 50 F Bkdn. Temp. 305 F	Temp Drop 60 F Bkdn. Temp. 222 F	Temp. Drop 83 F Bkdn. Temp. 273 F	Temp. Drop 101 F Bkdn Temp. 231 F	Temp. Drop 112 F Bkdn. Temp. 228 F
A	133.03	132.84	133.54	130.95	131.97	131.71
B	132.28	133.76	132.21	131.98	131.98	131.58
C	130.81	130.95	(136.04)[3]	133.07	132.36	130.93
D	131.40	130.89	133.40	132.73	131.00	131.56
E	132.98	132.94	132.44	131.06	132.69	131.41
F	132.56	131.40	132.86	133.59	132.47	132.46
Avg.	132.17	132.13	132.89	132.23	132.07	131.60

[1] Asphalt A, Table 3, used in these experiments.

[2] Data for Fig. 17.

[3] This value rejected from calculation of average on basis of Q test at 95% confidence level (12, 13).

This finding is similar to what would happen if more or less asphalt were added in the beginning to an ordinary, nonporous aggregate. With the porous aggregate, the effect is created by controlled adsorption.

The rise in the curve in the range of small ΔT's (up to 65 F) shows that the particular roller pressure used was more than optimum for the stability of the overrich mix. As the asphalt was removed by a greater ΔT, the stability finally increased until the roller used was just optimum. Removal of more asphalt by a still greater ΔT increased the stability to the extent that the roller pressure was below optimum. In this case, the density achieved was lower than was obtained with a less stable mix with the same roller pressure. The dotted line illustrates the increase in density that might have occurred if the roller pressure had been increased to the optimum amount corresponding with the increasing stability.

EFFECT OF MOISTURE ON ABNORMAL BEHAVIOR

Sometimes aggregate mixes are incompletely dried in the plant before they are mixed with asphalt. Some of the ways this can occur are:

1. The cold feed to the plant is saturated with water.
2. The aggregate is porous and difficult to dry.
3. The dryer is overloaded because of production requirements.
4. The hot coarse aggregate is held for an insufficient period in the hot bins for the water to be completely desorbed.
5. The temperature of the aggregate coming from the dryers is held down to avoid hot mix hardening.

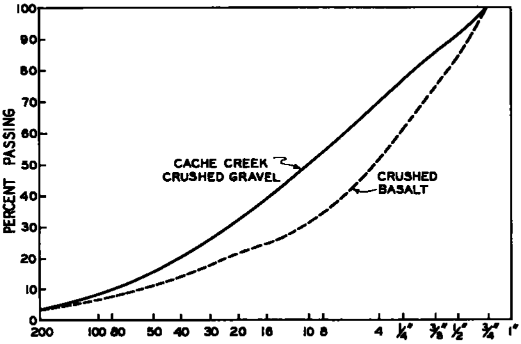

Figure 18. Gradings of aggregates in full scale experiments.

When the aggregate is incompletely dried at the time it is mixed with asphalt, water in the pores will continue to be vaporized or desorbed until equilibrium is reached. Evolution of steam may continue, although the temperature may have dropped substantially. During this time, absorption of asphalt will not occur in the pores evolving vapor.

It seems likely that the steam evolved from the rock pores may contribute to the volume of asphalt binder in still another manner besides preventing absorption. When steam evolves from the micropores, some of it is in the form of colloidal-size bubbles and remains for a while in the asphalt without breaking. This is suggested by the light-brown color asphalt acquires under these conditions. The volume of steam entrapped in the asphalt contributes to the total volume of liquid in the voids in proportion to the pressure on the system. Directly under the roller, where pressures are high, its volume would be reduced; in the low-pressure areas adjacent to the roller, its volume would be larger. Both of the suggested mechanisms give the effect of increasing the volume of asphalt in the voids at higher temperatures. A discussion of methods used to improve aggregate dryness before mixing is shown in Field Study C.

FIELD STUDIES

Typical case histories of field problems included in the appendix support several of the principles postulated in this discussion. The belief that a "tender" pavement is a poorly compacted pavement is supported by Field Study A, where penetration tests were made on areas with different amounts of traffic and subsequently by laboratory tests in which the same mixes were compacted different amounts. Another Field Study B, shows that the relative compaction is low on a mix reported to be tender. This example is typical of many others not included.

Field Studies C and D both substantiate the propositions that moisture remaining in the aggregate under the asphalt prevents absorption and causes low mix stability at high temperatures.

Field Study E confirms the importance of the filler content on the cohesion and bearing capacity of the hot mix. This overstressed mix was easily shifted towards a more optimum condition by any one of several fillers. Under these same conditions, changing the asphalt type had no noticeable effect.

SUMMARY

This discussion has covered many of the factors influencing the behavior of hot asphalt concrete under steel-wheel rollers. It includes situations where the mix is under- and overstressed and when it behaves in a predictable fashion or abnormally in a way that is neither predictable nor easily explained. General conclusions on how to obtain the best compaction cannot be given for all conditions. Instead, the following guidance is suggested for the several situations encountered in rolling hot mix:

A. For Normal Mixes Stressed Below Optimum

1. Increase roller weight.
2. Decrease roller diameter (usually not recommended).
3. Increase number of passes of roller.
4. Reduce cohesion of mix by using either a softer grade of asphalt or less filler, or by increasing the rolling temperature.
5. If roller weight cannot be increased, reduce stability of mix within specification limits by changing either aggregate grading or aggregate angularity, or by increasing asphalt content. This change is suggested only when there is no danger of subsequent instability under traffic.

B. For Normal Mixes Overstressed

1. Increase roller diameter.
2 Decrease number of roller passes.
3. Decrease roller weight.
4. Decrease thickness of each layer of asphalt concrete rolled.
5. Increase cohesion of mix by using a harder grade asphalt, adding or changing the type of filler, or lowering the rolling temperature.
6. Increase stability of mix by changing aggregate grading or aggregate angularity, or by decreasing asphalt content.

C. To Make Abnormal Mixes Behave More Nearly as Predicted from Design Tests

1. Adjust mix design to maximum permissible final voids content.
2. Dry aggregate thoroughly.
3. Allow an optimum temperature drop between mix and rolling temperatures.
4. Add a fine-grained filler if examination shows mix is low in fines.

D. To Reduce the Appearance of Surface Checking

1. Increase roller diameter.
2. Decrease roller weight.
3. Decrease number of roller passes.
4. Reduce sand fraction. (Use a mix gradation less prone to show checking; a coarser, more roughly textured mix.)

Pneumatic compactors are rapidly gaining popularity in compacting hot asphalt concrete. If correctly used, these rubber-tired rollers will give much greater compaction than is possible with steel-wheel rollers. They must be heavy enough and have high enough contact pressures. Furthermore, the mix should be rolled at the highest possible temperature; otherwise, many passes are required. Usually, poor compaction resulting from improper steel-wheel rolling can be readily corrected by proper pneumatic compaction if the pavement is still warm.

ACKNOWLEDGMENTS

The authors wish to acknowledge the valuable assistance of W.H. Ellis and R.S. Winniford, of the California Research Corporation, Richmond, Calif.; and of C.L. Monismith, Professor of Civil Engineering, University of California, Berkeley.

Appendix

FIELD STUDY A

Project Location

Access road, airport, San Joaquin Valley, California.

Complaint

Prolonged tenderness of the pavement. Pavement was soft and could easily be scuffed three days after construction.

Mix Composition

Aggregate Type—Crushed silicious gravel. Aggregate separated into three bins.
Aggregate Grading—The grading is shown in Figure 19.

Miscellaneous Mix Characteristics:

Asphalt content, %	4.9
Stability:	
Hveem stabilometer, S-value	52
Hveem cohesiometer, C-value	178
Penetration of extracted asphalt (77F)	73

Field and Laboratory Studies

Field studies were made to determine the relative resistance to displacement under load of the pavement, which had been rolled with a 51-in. diameter, 200-lb per lin in. roller. For this study, the Soiltest penetrometer was used. The time for penetration to a depth of ¼ in. under a load of 320 psi was measured. Tests were made across the pavement, from one edge to the other.

Laboratory specimens were compacted using various pressures on the Triaxial Institute kneading compactor. The penetration time of the Soiltest penetrometer at 320 psi was compared with stability and density values.

Laboratory Data

Foot pressure (psi) with 150 blows of Triaxial Institute kneading compactor	100	200	300	400	500
Density (lb/cu ft)	136.7	137.7	142.5	143.8	144.0
Hveem stabilometer value	22	28	33	35	35
Hveem cohesiometer value	63	87	106	152	165
Time per ¼-in. penetration (sec at 320 psi)	1.2	3.6	9.9	30+	30+

Field Data

Field Conditions	Penetration Time (sec) (load of 320 psi)
1. Tender areas; sections that could be scuffed	3 to 15
2. Areas that received traffic were tough, dense, and scuff resistant	60+

Discussion and Conclusions

Tenderness of asphalt concrete surface mixes is a result of inadequate compaction. Areas receiving rubber-tire compaction and well-compacted laboratory specimens were tough and scuff resistant. Inadequately compacted areas and specimens were tender and could be easily displaced.

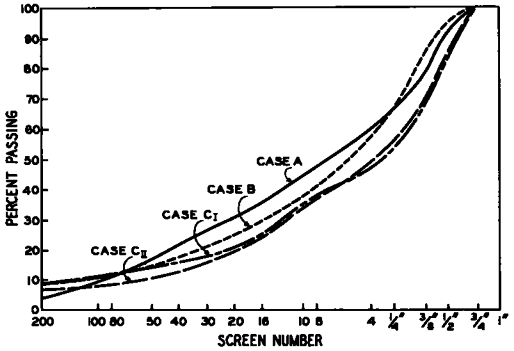

Figure 19. Gradings of aggregates in field problems A,B,C.

FIELD STUDY B

Project Location

Commercial airport, Hawaiian Islands.

Complaint

Prolonged softness of pavement. At high ambient temperatures the pavement was soft, lacked cohesion, and was easily scuffed.

Mix Composition

Aggregate—The aggregate was a very dense crushed lava rock. Extracted grading is shown in Figure 19.

Asphalt content, 5.3 percent.
Density measurements (pcf):

Core from pavement slab	147.9
Recompacted, 75-blow Marshall compaction	158.7
Recompacted in Triaxial Institute kneading compactor, California procedure	169.7

Test	Core	Laboratory Recompacted
Marshall stability	875	1,000+
Marshall flow	19	15
Hveem stability	12	43

Changes Made and Effect

Subsequent rubber-tired compaction eliminated tenderness.

Discussion and Conclusions

Prolonged tenderness and softness of the mix are a result of low density. Laboratory recompacted samples indicated that greatly increased field density could be attained. Rubber-tired rolling later improved density and eliminated tenderness.

FIELD STUDY C

Project Location

Primary state highway, Hawaiian Islands.

Complaint

The paving contractor had frequently built pavements which remained tender for prolonged periods after construction and pavements which were difficult to compact to the required densities.

Aggregate Composition

Crushed lava rock. Moisture absorption of coarse grading 2.6 percent; high specific gravity. The grading is shown in Figure 19.

Changes Made and Effect

Changes—The hot-mix plant operation was deliberately controlled to obtain conditions in which the mix would be dry in one case and have a significant water content in the other.

In the first case, the cold feed to the dryer was barely moist. It was dried at the normal rate and then allowed to "heat soak" in the hot bins for 15 min prior to mixing with the asphalt in the pugmill.

The same procedure was used in the second case, except that the cold feed was water saturated, and no "heat soaking" period was allowed. Both mixes were rolled with the same roller and number of passes within a period of one-half hour of each other.

Effect of the Changes—

	Case I	Case II
Visual appearance of hot mix	Black	Brown, tiny bubbles visible on close inspection
Temperature of hot mix from pugmill (°F)	300	280
Field compaction temperature (°F):		
Top ½ in. of mix	245	245
Center of mix	280	270
Bottom ½ in. of mix	250	250
Analysis of pavement specimens:		
Moisture content, ASTM D 95 (%)	Trace	0.0065
Asphalt, Abson recovery (%)	6.1	6.1
Aggregate grading, after Abson recovery	See Figure 19	
Recompacted by Hveem kneading compactor:		
Hveem stabilometer value	59	60
Hveem cohesiometer value	461	343
Condition of finished pavement	Very tough and dense, resists movement	Soft, tender, easily displaced

Conclusions and Discussion

The only significant difference between these two mixes appears to be moisture content. Yet, there was a striking difference in the "tenderness" of the finished pavement. Moisture apparently causes the softness because it prevents asphalt absorption. Also, it causes the mix to be unstable at high temperatures and poorly compacted under the roller.

Incomplete aggregate drying is due to either insufficient dryer capacity of inefficient operation. More complete water removal can be obtained by recycling the aggregate, by using two dryers in series, or by using a longer dryer. The operating efficiency can sometimes be increased by decreasing the dryer tilt, which increases the residence time of the aggregate in the dryer. Also, intermittent operation causes poor drying because in the operating conditions are not uniform.

Advantage is seldom taken of the water removed from the aggregate during storage in the hot bins. "Heat soaking" of the coarse aggregate in the hot bins for at least 15 min allows the larger rock to reach equilibrium with respect to temperature and moisture content. The coarse bins should be run as full as practical in order for the rock to "soak" for a maximum period.

FIELD STUDY D

Location

Ohio.

Complaint

The mix pushed and shoved during rolling and had a "light-colored, dull appearance."

Mix Composition

Aggregate Type—The mix was made by combining two bins. The coarser one consisted of a "not particularly silicious" crushed gravel; the fine one, of natural sand.

Grading—The grading (Fig. 20) shows the mix to be dense, probably with low voids in mineral aggregate.

Stability—Not established.

Moisture content of mix—0.4 percent water by ASTM D 95.

Change Made and Effect

When the plant throughput was cut from 130 to 110 tons an hour to more thoroughly dry the aggregate, both the off-colored mix and rolling difficulties disappeared.

Discussion and Recommendations

The mix behaved in an abnormal manner because asphalt was prevented from being absorbed into the aggregate by the evolving steam. The mix was unstable at high temperatures. Thorough drying of the aggregate is the best solution to the problem. However, the mix would not be as sensitive to a small amount of water in the system if a more open grading were used, as in Field Study E.

FIELD STUDY E

Location

Ohio.

Complaint

1. The asphalt collected in small areas of the coarse aggregate particles. Black glossy coatings delivered at the mix plant turned light in color en route to the job.
2. The mix did not have good "handling" properties in areas where hand raking was necessary.
3. The mix pushed excessively in front of the roller.
4. The pavement remained tender and was damaged easily for several weeks.

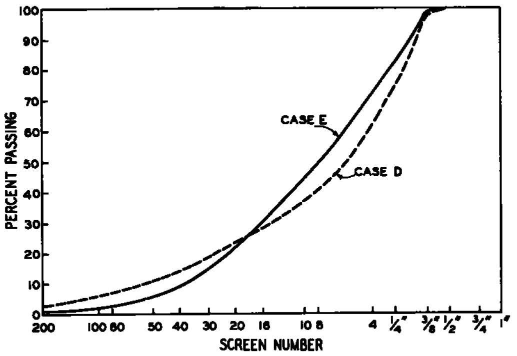

Figure 20. Gradings of aggregates for field problems D, E.

Mix Composition

Aggregate Type—The mix was made by combining two bins. The coarse bin consisted of slick uncrushed silicious gravel; the fine one, of a natural sand. In one instance there was 0.4 percent water in the aggregate in the coarse bin.

Design Grading—The grading is shown (Fig. 20) to be low in the sand fraction (-16 mesh). It is especially low in the fines (-200 mesh) content.

Design Stability of Mix

1. Hveem stability, about 30.
2. Cohesion (Hveem), less than 200.

3. Marshall stability, about 700.
4. Marshall flow, about 18.

Design Asphalt Content

5.8 percent of 70-85 penetration grade.

Design Voids in Total Mix

Approximately 7 percent air voids were calculated for specimens compacted by both the Marshall and kneading compactors.

Effect of Making Changes

1. The asphalt source was changed from a Venezuelan to a Mid-Continent type. No differences were apparent either in laboratory studies or in the behavior in the field.
2. All symptoms causing complaint disappeared when 1.5 to 2 percent of limestone dust, hydrated lime, or natural fines were added to the mix. The mix compacted to a tough surface resisting damage; the raking became normal, and the mix appeared black on delivery.

Discussion and Conclusions

An economical solution to the problem was made by obtaining a sand fraction containing more natural fines. Although the coarse aggregate in the hot mix contained substantial water, the high voids content in the mix prevented this from causing a critically low stability. By the definition used, this was not an abnormal mix. The difficulties were caused primarily by a low mix stability and low cohesion at high temperature, which was corrected by increasing the filler content.

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Discussion

W.H. CAMPEN, Omaha Testing Laboratories, Omaha, Neb.—The authors are to be complimented for having done a fine job of showing the interrelationships of roller, stability and density of bituminous pavement mixtures. They have put in writing in a systematic manner what experienced designers and field inspectors have had to know in order to construct stable and durable asphalt pavements.

For instance, they give a number of corrective measures which might be taken if a mixture is understressed or, in other words, if the mixture can not be densified properly. This condition came into being in recent years when mixtures had to be made stronger (had to have more stability) to prevent shoving and rutting. The remedial measures suggested are sound. However, if the stability and other properties are to be preserved, the only remedial measure known at this time is the use of pneumatic-tired equipment having tires inflated to 90-psi pressure, and loaded to 6,000 to 8,000 lb per tire, in addition to heavy-steel rollers.

In regard to overstressed mixtures, rather than to adjust the mixture or change rollers, the practical thing to do is to allow the mixture to cool until it can be densified without tearing it up. This procedure is widely used.

In connection with any discussion on understressed and overstressed mixtures it must be understood that mixtures are usually designed not only for stability but also for voids. Changing gradation, filler, or the asphalt content will also change the voids. For this reason, the changing of the mixture should not be recommended. It is assumed also that the original designer was thoroughly qualified.

As far as correcting abnormally acting mixtures is concerned, it would seem that the authors prove by their own field studies that the abnormality is due to improper rolling, insufficient drying of the aggregate, or improper mixture design. Field studies A and B show that the tenderness or lack of stability is due to lack of density. Studies C and D show that moisture in the mixture as laid is the cause of lack of cohesion, density, and stability. Study C also shows that improper grading and excessive asphalt are the cause of shoving and other signs of weakness. It appears, therefore, that the abnormality lies in the method of preparing and laying of the mixtures rather than in the lack of correlation between the predicted and actual behavior

The authors also speak of mixtures which are inclined to tear even if proper rollers are used. There are such mixtures, and experience has shown that these mixtures are either deficient in asphalt or contain an excess amount of materials passing the No. 40, No.80 and/or No.200 sieves. For instance, a ¾-in. maximum size asphaltic concrete containing 60 percent on the No. 10 sieve, 70 percent on the No. 40 sieve, 80 percent on the No. 80 sieve and 90 percent on the No. 200 sieve, would tear. By increasing the amount retained on the No. 40 sieve to 80 percent and making corresponding increases on the other fine sieves, but keeping the amount on the No. 10 sieve at 60 percent the tearing condition would be corrected.

CLOSURE, R.J. Schmidt, W.J. Kari, H.C. Bower, and T.C. Hein—Mr. Campen's comments are appreciated, since they represent many years of experience in constructing and testing asphalt pavements. His statements lend added weight and emphasis to several of the corrective suggestions made in the paper.

Specifically, concurrence with his comments on pneumatic rolling is indicated by the final paragraph of the paper. Also, it is agreed that the short-range solution to rolling an overstressed mixture is to allow it to cool before rolling. However, this solution is not always practical on large projects because of the excessive roller operator overtime involved. On one project, this required as much as 4 hr overtime per day and was easily corrected by a slight change in filler content of the mix.

Mr. Campen's extensive experience with paving may lead him to conclude that there was no discrepancy between predicted and actual behavior of the mixes mentioned in the field studies. However, the authors know of no laboratory tests that would predict the field problems described in the report. It was only after the problem occurred and further investigations were made that it was possible to arrive at the proper corrective action in each case. Inasmuch as the mixes were the results of normal good design practice, it is felt appropriate to describe their behavior as abnormal until proper corrective action is taken. We are also indebted to Mr. Campen for his detailed explanation on how to redesign mixes which are inclined to tear. Our corrective Step 4 was intended to summarize this procedure.

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