Setting Rate of Asphalt Concrete

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Mixes that shove excessively under steel wheel rollers, do not densify, or are tender to any type of distortion are defined as "slow setting." At times, these mixes remain tender for prolonged periods after laydown. Field and laboratory studies show that aggregate gradation and angularity, filler content, moisture, and compactive effort are important in determining the setting rate or toughness of a compacted mix.

Construction and mix variables are examined under controlled conditions to isolate those factors responsible for slow setting. Data presented show that high-quality, high-stability mixes compact better with increasing compaction temperature, but that in more unstable mixes increasing the temperature results in poorer compaction. The authors show the importance of mineral filler to both pavement density and toughness. An optimum filler-to-asphalt ratio exists for maximum compaction under steel wheel rollers. In addition, the amount of mineral filler in a mix was found to influence the setting rate of an asphalt pavement. Pavement toughness proved dependent on the type and degree of compaction. Pneumatic rolling substantially improves pavement toughness. Pavement setting is shown to be much faster in a mix with crushed, angular aggregate rather than rounded gravel.

The setting rate of asphalt concrete pavements is largely controlled by the construction practices and material properties investigated in this paper. Suggestions are given on how to achieve maximum densification and pavement toughness.

• THE PHYSICAL characteristics of freshly laid asphalt concrete often determine whether a pavement is approved by a highway agency or private customer. The criterion for an acceptable carpet may be either high density, low permeability, or toughness (i.e., fast setting). Compaction of the mix to a suitable high density, as required by the Corps of Engineers (1), results in the highly stable mixes necessary for airports. Appropriate compaction of a mix also results in low permeability (2), which is quite important in controlling the rate of asphalt hardening. Although unimportant from a long-term performance point of view, well-compacted mixes are tough and resistant to scuffing by power steering turns or penetration by sharp objects.

The paving contractor's criteria for an acceptable pavement are similar to those of the agency or individual directing and inspecting the job. The contractor wishes to provide tough mixes having high density and low permeability, but at minimum cost and installation time.

Situations frequently arise in the construction of asphalt concrete pavements for other than primary highways where, for economic reasons, considerable latitude is permitted in mix composition. As a result, some of these mixes shove excessively under steel wheel rollers and hence do not densify properly at normal rolling temperatures. Often these mixes are extremely tender to scuffing or penetration for prolonged periods after rolling. Such mixes are called "slow setting."

The authors' experience from a number of field reports and full-scale laboratory studies (3) has indicated that aggregate gradation and shape, filler content, aggregate
moisture, and rolling procedures are the major factors contributing to slow-setting pavements.

This paper is concerned with the factors affecting asphalt concrete compaction and toughness, including the amount of steel wheel or pneumatic rolling, rolling temperature, mix design, aggregate type, and filler content. The influence of asphalt type and grade is discussed in a paper by Schmidt and Santucci (4).

CONSTRUCTION AND MIX VARIABLES

The behavior of asphalt concrete under steel wheel rollers was first discussed by Nijboer (5). More recently, Schmidt, Kari, Bower, and Hein (3) reported full-scale laboratory and field experiments that substantiated Nijboer's work and proposed new concepts for the behavior of mixes overstressed during rolling. It was proposed that optimum roller weights, diameters, and number of passes for maximum compaction were dependent largely on the mix characteristics. These characteristics were the angle of internal friction (θ) and the cohesion (C) of the mix, the asphalt pore pressure, moisture content of the aggregate, and temperature of the mix at the time of rolling.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Aggregate</th>
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<tbody>
<tr>
<td></td>
<td>Cache Creek Crushed Gravel</td>
</tr>
<tr>
<td>Maximum size aggregate (in.)</td>
<td>⅝</td>
</tr>
<tr>
<td>Grading</td>
<td>(Fig. 2)</td>
</tr>
<tr>
<td>Asphalt content (percent by wt. of dry aggregate)</td>
<td>5.6</td>
</tr>
<tr>
<td>Hveem stabilometer S-value</td>
<td>-</td>
</tr>
<tr>
<td>Hveem cohesiometer C-value</td>
<td>-</td>
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<tr>
<td>Marshall stability (50 blows) (lb)</td>
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<tr>
<td>Marshall flow</td>
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*Asphalt content chosen on basis of Centrifuge Kerosene Equivalent (CKE) Test and optimum S-value.

Figure 1. Density vs breakdown temperature in understressed mixes. Figure 2. Gradings of aggregates in full-scale experiments.
Most of the data and many of the conclusions in the study presented here are the result of experiments performed under controlled conditions in the Full-Scale Paving Research Laboratory (6). Table 1 summarizes the characteristics of all of the mixes discussed.

Understressed Mixes During Compaction

Mixes that behave normally during compaction may be separated into two classes, "understressed" and "overstressed." In Ref. (3), a mix is defined as understressed when an increase in compactive effort results in higher densities. Thus same mix is said to be overstressed when additional rolling causes a drop in the degree of compaction in the mix. Thus, there exists an optimum compactive effort which gives a mix its maximum density. In the understressed condition, raising the temperature of rolling results in higher densities. Figure 1 taken from Ref. (3), shows this effect. The aggregate grading for this mix is shown in Figure 2. This finding is consistent with work done by Parker (7) and Kiefer (8) on laboratory compacted cores. From Figure 1, asphalt type is shown to have little effect on the degree of compaction obtained in an understressed mix.

As might be expected, the viscosity of the asphalt binder at the time of rolling influences the final pavement density. Figure 3 shows that the final density of a mix increases as the viscosity of the binder at the time of breakdown rolling drops. The lower binder viscosity allows the aggregate particles in the mix to be forced by the roller into a more tightly packed condition. This behavior is limited to an understressed mix.

\[\text{Figure 3. Asphalt viscosity at breakdown temperature vs density in understressed mix.}\]

\[\text{Figure 4. Density vs breakdown temperature in overstressed mix.}\]

\[\text{Figure 5. Density vs viscosity of asphalts at breakdown temperature in overstressed mixes.}\]
Overstressed Mixes During Compaction

More stable mixes are able to tolerate heavy rollers and a large number of roller passes. This suggests that a high compactive effort is needed to overstress stable mixes. However, as mix stability drops, the point of maximum compaction, located between the understressed and overstressed conditions of a mix, is shifted to a lower level of compactive effort. Now, only a few roller passes, or low rolling pressures, are needed to overstress the mix. Raising the rolling temperature of a mix already in the overstressed range causes a drop in core density, as shown in Figure 4.

The viscosity of the binder during rolling influences final pavement density quite differently in an overstressed mix than it does for a mix in the understressed condition. Core density is plotted against asphalt viscosity at breakdown rolling temperature in Figure 5. The asphalt used was recovered from four separate test pavements whose compaction temperatures ranged from 215 to 300 °F. The recovered asphalt having the highest viscosity in Figure 5 binds the aggregate particles into a mix that is stiff enough to resist the decompactive action of the roller. This mix is able to stay under the roller wheel longer and thus compact more completely. As the rolling viscosity of the binder drops, the mix is more easily shoved away by the roller.

Critical Mixes

Uncrushed Rounded Gravel. —Mixes that become easily overstressed during rolling are usually slow setting mixes. These "critical mixes" are defined as those having
(a) low stability, (b) rather low fines content, (c) high sand fraction, and (d) small maximum-size aggregate. Aggregates that are not completely dried also create slow setting problems. The influence of aggregate moisture was not studied in the work presented here, but other investigators (3, 9) have discussed field problems involving mixes with high moisture contents. In addition to the items just listed, aggregate shape and surface texture contribute to the toughness of a mix. The most critical mixes are those produced from rounded, uncrushed material having a smooth surface texture. The aggregate used in most of the authors' research work was a smooth, rounded river gravel from Cache Creek in Northern California. Its grading is shown in Figure 2. Critical mixes of this type are commonly used for construction of driveways and parking lots.

A penetration test was selected for evaluating the setting rate or toughness of asphalt concrete mixes (3). The blunt-nose penetrometer shown in Figure 6 was used on experimental pavement sections prepared in the Full-Scale Paving Laboratory. This blunt-nose penetrometer is similar in design and function to the "pocket penetrometer" familiar to most highway contractors for use in soil compaction control. The time necessary for the 1/4-in. rod, loaded with a 16-lb weight, to penetrate 1/4 in. into the compacted mix is taken as a measure of pavement toughness. These readings are obtained as the pavement cools after rolling. Figure 7 shows the reproducibility obtained for a Cache Creek gravel mix having the same asphalt type and grade. The data shown in Figure 7 are taken from four separate, full-scale test sections placed about three weeks apart.

Mix temperature is measured with three-level thermocouple plus (6) placed in the pavement sections. Each thermocouple plug is positioned to record the temperature near the surface, midpoint, and base of the compacted mix. The pavement temperature at the time of penetration is obtained from the couple located 1/4 in. below the pavement surface.

The toughness of a finished pavement was found to be dependent on both mix density and the viscosity of the binder at the time of penetration. Mixes that densify properly become tough enough to resist distortion by the normal forces placed on a pavement. The ultimate condition for maximum resistance would be a solid rock mass. Such a condition is approached with a mix having a maximum density grading curve. In this case, the aggregate particles are so tightly interlocked that even severe external forces cannot cause damage. In critical mixes, the resistance offered by the binder viscosity becomes an important factor. The density of these mixes is usually very low. Unfortunately, there is no convenient way to measure the actual binder viscosity in the mix.

![Figure 7. Reproducibility of blunt nose penetrometer on Cache Creek mixes.](image1)

![Figure 8. Toughness of critical mixes increased by angular aggregate.](image2)
The best approximation to the binder viscosity is the viscosity of the recovered asphalt at the temperature used for the penetration test. Relationships between toughness and asphalt viscosity are given in Ref. (4).

Crushed Angular Aggregate. —Other aggregate mixes having the same grading and filler content as the rounded Cache Creek gravel may, in some cases, be critical mixes. Usually, they are not as easily overstressed as the gravel mixes. The toughness of one such mix, made with crushed, angular granite from Watsonville, Calif., is shown in Figure 8. This mix is much tougher than rounded gravel mixes.

**Importance of Mineral Filler**

Figures 9 and 10 show the importance of filler content for maximum compaction and toughness. There exists an optimum cohesion, as expressed by the filler-to-asphalt (F/A) ratio calculated on a volume basis, for maximum compaction under a roller. The binder volume (sum of filler and asphalt volumes) of the mixes shown in Figures 9, 10, and 11 was held constant. These mixes have gradings identical to the Cache

![Figure 9. Relation of filler-to-asphalt ratio to compactive effort.](image)

![Figure 10. Pavement toughness vs filler content.](image)

![Figure 11. Relation of filler content to toughness and aggregate type.](image)

![Figure 12. Relation of pavement toughness to pneumatic rolling.](image)
Creek rounded gravel given in Figure 2 except for the varying F/A ratio. The mineral filler referred to here are those aggregate particles passing a No. 200 mesh screen.

If toughness were dependent solely on density, then maximum toughness would be expected at the point of maximum density in Figure 9. Figure 10 shows this not to be the case. In Figure 10 toughness continues to increase as long as the F/A ratio is increased within the range normally found in asphalt concrete mixes. Thus, increasing the F/A ratio substantially increases the toughness of these mixes, even though the density obtained may be less.

The increase in toughness with increased F/A ratio is found in tough as well as in reasonably tender mixes. Figure 11 shows that both Cache Creek and Watsonville mixes become tougher as the F/A ratio increases.

Recent work by Winniford (10) suggested that the role of filler in an asphalt mixture is more than that of an inert, solid diluent. He shows that finely divided minerals behave as though they occupied a much greater fraction of the binder volume than can be accounted for by theory. The interaction of asphalt with mineral surfaces appears to cause an increase in apparent viscosity of the filler-asphalt mixture. Chemically, different minerals have different effects on asphalts. Thus, different mineral surfaces, particularly the fillers, are expected to affect the toughness of asphalt concrete in different degrees.

When properly used, pneumatic rollers densify a critical mix more effectively than steel wheel rollers. Figure 12 compares the toughness of the same mix compacted with steel only and with steel followed by a pneumatic compactor.

CONCLUSIONS

1. Slow setting is not a serious problem with high-stability mixes. The contribution of the high frictional resistance and cohesion of these mixes allows maximum compaction to be obtained under normal, optimum, rolling conditions. The high density of such mixes makes them especially resistant to penetration by sharp objects.

2. A mix having some combination of low stability, low filler content, high sand fraction, and smooth rounded aggregate of small maximum size is found to be a critical mix. It is not necessary for all of these conditions to be present in the mix at the same time. A mix with these characteristics is especially tender to scuffing and distortion.

3. Adequate compaction is not easily reached in critical mixes. These mixes are often overstressed, resulting in excessive shoving of the mix under the roller.

4. Increasing the concentration of filler improves the setting rate of asphalt concrete. There is an indication that this relation is due to the higher viscosity associated with filled asphalt systems.

5. Although not substantiated here, it has been inferred in other studies (10) that the interaction of asphalt with mineral surfaces appears to change with the type of surface in contact with the asphalt. Different mineral surfaces could have pronounced effects on the toughness of asphalt concrete mixes.

6. Pneumatic rolling often improves the density of critical mixes overstressed by steel wheel rolling. As a result, pavement tenderness is reduced. Substantial improvements have been shown in the setting rate of asphalt concrete mixes that were compacted with rubber tire rollers after the initial steel breakdown rolling.

ACKNOWLEDGMENT

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REFERENCES


Discussion

W.H. CAMPEEN, Omaha Testing Laboratories—The writer wishes to discuss this paper from the standpoint of one who has designed, controlled, inspected, and observed the field performance of bituminous paving mixtures over a long period of time.

First of all, so-called "slow setting and tender mixtures" are nothing more than weak mixtures. Usually the aggregate in such mixtures consist of rounded particles and are therefore not conducive to the development of interlocking properties after consolidation.

In the laboratory, weak mixtures are detected by their low stabilities when compacted and tested by any one of several recognized methods. For instance, mixtures that show stabilities of less than 500 lb by the Marshall method would be considered weak and not suitable for most types of traffic.

In the field, weak mixtures are revealed by their behavior under normal rollers. Such mixtures when comparatively hot will flow under the rollers and either push ahead or displace laterally. Because of this behavior and because they must be allowed to cool before densification can be accomplished the authors choose to call them "slow setting and tender."

In the writer's opinion the use of the expression "slow setting" in connection with bituminous paving mixtures is incongruous. "Setting" is used to imply that strength is being increased by a chemical reaction or by the loss of some component part of the cementing agent, such as the setting of portland cement or the setting of cut-back asphalts. However, in bituminous paving, neither chemical reaction or loss of volatile matter is involved to any significant extent. Therefore, it is erroneous to say that they go through a process of setting. It is true, of course, that the paving mixtures gain strength on cooling by an increase in the viscosity of the bitumen, but the increase occurs to about the same extent in both "slow and fast setting mixtures." This point is brought out on the two curves in Figure 8 of the paper.

A final point concerns the control of the so-called "rate of setting." The temperature at which the mixture can be rolled, which also involves the element of time, reflects the stability of the mixture. Thus mixtures possessing high stability can be densified with heavy rollers at high temperatures and consequently would be rated as "fast setting and tough." On the other hand, mixtures possessing low stability must be densified with light rollers, or allowed to cool until they can support heavy ones without causing pushing, displacement, and tearing. These mixtures would be classified as "slow setting and tender."

It is evident therefore that "slow setting mixtures" can be corrected by increasing their stability. This is done primarily by including angular particles in both the fine and coarse fractions of the mixture, by providing a good gradation, and by selecting the asphalt content on the basis of 2 to 4 percent of residual voids. Because this is the procedure used in the designing of bituminous paving mixtures for both stability and durability, it automatically eliminates "slow setting and tender mixtures."
L.E. SANTUCCI and R.J. SCHMIDT, Closure—The writer's comments are greatly appreciated. They have added emphasis to several of the points discussed in the paper.

Specifically, the authors have pointed out that mixes that clearly exhibit slow setting qualities have a low stability. For this reason, the systems used to study this phenomenon were those made with an aggregate consisting of rounded, uncrushed particles having a smooth surface texture. This type of aggregate provides little interlocking resistance and, as a result, low stability.

The behavior of slow setting mixes under steel rollers reported by the authors agrees with the writer's opinions. For example, excessive shoving of the mix before the advancing roller has been photographed at the Full-Scale Paving Laboratory.

The authors have also been concerned about using "slow setting" as a description of this problem. The term "slow setting" connotes an hour-by-hour hardening of the asphalt. This is, indeed, correct. Evidence shows that pavements toughen in this way, quite independent of oxidation or compaction. It is therefore postulated that the more polar or active components gradually orient with the mineral particles and set up a matrix that is substantially tougher than the fresh asphalt. The authors agree that toughness or some other term might have been less controversial. However, the term most commonly used in the field to describe the phenomenon is "setting." Reference is made to a recent article (Engineering News Record, Feb. 8, 1962, p. 44) where the phrase "lack of set" is used. In the authors' opinion, "setting" is the most reasonable descriptive term at the present time.

As pointed out by the writer, and in the papers, one of the criteria of tender mixes is that because of their low stability, they must cool in order to support heavy rollers without causing shoving of the mixture. Although cooling will increase the stability, the authors are certain the writer has experienced the construction delays associated with these prolonged cooling periods and delayed rolling. In addition, the pavement may not be as fully compacted as a similar pavement compacted at higher temperatures. The poor compaction further increases the tenderness and results in higher permeability and an associated faster oxidation rate.

The writer agreed with the authors' predictions that slow setting mixes can be corrected with proper mix design. A mix containing angular particles, having a good gradation, meeting proper voids criteria, and having an adequate filler content will not be slow setting. However, the authors disagree with his statement that proper design is used for all bituminous paving mixtures; therefore, there is no slow setting or tender mixes. Actually, about one-half the asphalt concrete used is under conditions where specifications or controls are not enforced. These are usually the situations where slow setting is encountered.