SPECIAL REPORT

96

State of the Art:

Surface Treatments

Summary of Existing Literature

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State of the Art:

Surface Treatments

Summary of Existing Literature

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Subject Area

31 Bituminous Materials and Mixes
33 Construction
35 Mineral Aggregates
40 Maintenance, General

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Preface

In recent years, the use of surface treatments to improve the surface qualities of existing pavements has increased substantially. Such increase in usage of this method of construction can be attributed to the growing number of miles of low volume pavements and to the need for providing economical maintenance techniques to retain desired pavement performance levels. A need has arisen to compile the existing knowledge of surface treatment design and construction techniques in order that suitable design methods and good construction practices can be recognized and utilized for future constructions. The compilation and use of such information should enable surface treatments to be constructed that will perform quite satisfactorily for many years.

This report is the result of an extensive effort directed towards the compiling of all existing pertinent information on surface treatments. The first section of the report (Chapters Two through Eight) contains the results of a comprehensive library study. It is, in effect, a summary of the status of existing, published knowledge of seal coats and surface treatments. In this section, the basic constituents of a surface treatment, the aggregate and binder, and factors influencing their behavior in a finished treatment are discussed in detail. In Chapter Four, several known, current methods of design are discussed and the limitations of each noted. In addition, an Appendix presents each design method in detail and an example design is given when possible. Also included is a summary and a chapter on areas of needed research as suggested in the literature. The authors believe that the summarized information is a valuable contribution to this field of study and may help in arriving at a more universally accepted method of design and proper construction techniques that will lead to better performing seal coats and surface treatments.

The second section of this report consists of a bibliography on seal coats and surface treatments. It too is the result of a comprehensive library study. In this study, all pertinent articles, either available at the University of Illinois Library or listed in other articles, were referenced. In addition, several articles not readily available at the university library were obtained in order that they might be included in the study.

All information included in this report, including the bibliography, has been prepared from literature published before January 1967. The reader should be aware of this terminal date since information published after this time may add to the technical knowledge on seal coats and surface treatments presented herein.

—Moreland Herrin

Acknowledgments

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The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the State of Illinois, Division of Highways, or the U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads.

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Chapter One

INTRODUCTION

The term "surface treatment" is but one of many names given to a specific type of highway construction. Generally, it refers to a class of treatments that range from a very light application of liquid asphalt with fine cover aggregate to the more substantial two-shot screening seal. In this publication the term "surface treatment" will refer only to this type of construction. It will not include a thin premix of any kind.

Today many thousands of miles of highways across the world are surfaced by surface treatments. Surface treatments are selected as the type of surfacing to use whenever the anticipated traffic volume does not justify a high-type surfacing or when economical limitations do not permit a more expensive pavement surface construction. Moreover, surface treatments are often utilized for improving the surface qualities of existing pavements or to enliven an old, badly weathered surface.

Many miles of surface treatments have had excellent history of good performance. Conversely, many miles of newly constructed surface treatments have failed after only a short period of time. The loss of aggregate from the surface, bleeding, and cracking, which are the main signs of failure in these pavements, not only are considered as an economical loss, but also as a factor affecting the safety of motor vehicle operation. However, with suitable design methods and good construction techniques, surface treatments have been constructed that have performed quite satisfactorily for many years.

A number of factors influence the performance of surface treatments. Primarily they are related to the bituminous binder or to the cover aggregate. A wide variety of binders is available and the correct type must be selected for the prevailing conditions. Aggregate particles of the right size should be embedded in the exact amount of binder film, and must be held securely to the underlying surface. Unless all influencing factors are considered in the design, there will not be proper selection of the quantity and type of bituminous binder and aggregate needed, and a surface with good riding qualities and performance characteristics will not be provided.

This publication is an attempt to review the existing literature related to surface treatments and to summarize the available information. Knowing what has been done in the past allows one to profit by other people's mistakes. It also acts as a guide for works and investigations that need to be made in order that surface treatments will perform as they should and not verify the poor opinion that many persons have about them.

The authors of this publication have annotated articles that have pertinent information pertaining to surface treatment design and construction. Since mastering all of these articles would be an arduous task, to conserve the reader's effort the following sections and the Appendix contain a digest of these publications. Thus, this publication should be a benefit to the engineer who has a scant knowledge of surface treatments and also to the engineer who wants to expand his knowledge in this subject area.

This publication is not intended to be a treatise on surface treatments. However, references are given with each section that are related to the specific subject area. If the reader is interested in additional details, he can easily find the title and location of the original articles by referring to the bibliography.

Chapter Two

DEFINITIONS AND FUNCTIONS OF SURFACE TREATMENTS

The definitions and terminology used in the literature related to seal coats and surface treatments often reflect local experiences, and no unique definition has ever been accepted for seal coats and surface treatments. An accepted definition with properly defined functions is widely needed. This would greatly facilitate communications, in research, construction and the design of seal coats and surface treatments.

DEFINITIONS

A seal coat and/or surface treatment is defined in this report as follows: "A thin layer of aggregate and bituminous material which is directly subjected to the forces of vehicular traffic and in which the aggregate is bound to the underlying surface by being partially embedded in the film of bituminous material."

According to this definition, the terms "seal coat" and "surface treatment" may be used interchangeably and, unless otherwise noted, refer to a "single surface treatment." They refer only to the outermost layer of aggregate and bituminous material in a pavement and do not include prime coats, tack coats, road-mix surface treatments and macadams. The terms "double" and "triple surface treatment" are used to identify the type of construction when a second or a third surface treatment is placed upon the original.

A standard definition of the term "seal coat" or "surface treatment" has not been widely accepted. In many instances, they have been defined separately and in different ways. Some typical definitions of seal coats given in the literature are the following:

> ...a single application of asphalt binder, followed by a single application of cover aggregate, both placed on an existing bituminous surface (60-3).
>
> * * *
>
> ...a surface treatment applied to any type of existing pavement surface or on the surface of an asphalt base course (60-7). [Note: the term "surface treatment" is used to define the seal coat.]
>
> * * *
>
> ...a single application of bituminous binder covered with a single application of screenings (59-5).

Typical definitions related to surface treatments are:

> ...consist of the application of a thin layer of asphalt covered with crushed stone, washed gravel or coarse sand (53-2).
>
> * * *
>
> ...is the generic term to cover the entire range of applications of asphalt, with or without aggregate, to any type of road or pavement surface (60-7).
>
> * * *
>
> ...a single application of asphalt binder, followed by a single application of cover aggregate, both placed on a prepared gravel or crushed stone base (60-3).

These listed definitions of seal coat and surface treatment demonstrate not only that conflicts exist in defining these terms, but also that in some instances there exists a similarity between the terms, i.e., there is little differentiation between the terms. McLeod (60-3) has differentiated between seal coats and surface treatments only by the type of underlying surfaces. However, he employs the same method in designing and constructing these two types of surfaces. It is interesting to note that a seal coat, as defined by the Asphalt Institute (60-7), "... is a surface treatment...." The Asphalt Institute further defines surface treatments as "... applications of asphaltic materials ... with or without a cover of mineral aggregate, which produce an increase in thickness of less than one inch." Thus, a prime coat can be classified, according to this definition, as a surface treatment and thus also as a seal coat. Such definitions as these and others cannot be employed without the risk of resulting confusion.

A number of miscellaneous terms, such as "inverted penetration," "multiple and triple surface treatments," "retread," "armor coats," and "multiple lift surface treatments" have been used by different groups in different areas. Primarily these terms denote the use of seal coats and/or surface treatments in various numbers of layers and for various specific purposes.

FUNCTIONS OF BITUMINOUS SURFACE TREATMENTS

A surface treatment is mainly constructed to perform certain important designated functions, such as to provide a wear-resistant surface and to increase the skid resistance. However, aside from such primary purposes, other, less important benefits may also result from its construction. Thus, in the following listing, the more important functions of a surface treatment are given separately.

Primary Purposes of a Surface Treatment

1. To Provide an Abrasion-Resistant Surface. In the lower types of roads where the soil is stabilized either by compaction, or addition of cement, bituminous binder, or chemical compounds, the stabilized material does not have satisfactory resistance to the abrasive action of the tires. A wearing surface is required to protect the stabilized materials. If this protective measure is not taken, the excessive abrasion will reduce the constructed thickness of the stabilized material, and a shorter life and poorer performance of the pavement will result. In most cases a surface treatment is used to provide such a wearing surface.

2. To Increase Skid Resistance. Bleeding bituminous surfaces and polished, worn-out concrete pavements often induce hazards to the movement of a vehicle because of the lack of skid resistance. To increase the safety and convenience of road driving, it is a common practice to place an additional skid-resistant surface on such used pavements. This is done by the construction of a surface treatment with properly selected aggregates.

3. To Improve Light Reflection Characteristics. Dark-colored surfaces are often hazardous to the vehicle operator due to poor visibility and the lack of luminosity at night. In order to minimize the amount of light being absorbed, a surface treatment with light-colored aggregates is constructed over such surfaces. Aside from its light color, the comparatively rougher surface of the surface treatment is also helpful in reducing the glare of oncoming vehicles and in improving the visibility of dark-colored objects on the road, such as a child with dark clothes. Similarly, poor visibility on wet pavements can also be improved by the construction of a surface treatment.

4. To Provide Lane Demarcation. On high-type pavements where shoulders are often paved to increase their stability, a demarcation for traffic guidance is often needed between the shoulder sections and the traffic lanes. This can be done by constructing upon the shoulder either a rougher surface or a surface of a different color from the pavement. Thus, a surface treatment with light-colored aggregates (such as crushed limestone) applied to the shoulder will provide a demarcation in both color and roughness between the two parts of the pavement.

Secondary Purposes of Surface Treatments

1. To Seal the Underlying Surface. Entrance of air and water through the voids present in pavements, especially in the case of open-textured pavements such as bituminous macadams, is one of the main causes for road deterioration. Air and water, upon entering the pavement, can cause stripping, oxidation of the binder, a lowering of the stability of the base and/or the subgrade, and the breaking up of the whole structure during freeze and thaw. A surface treatment constructed on these pavements will seal the voids and reduce the amount of air and water entering the underlying pavement structure.

2. To Enliven Old Pavements. Old, dry, and weathered pavements may often not show signs of substantial failure, yet will still require the aid of maintenance to enliven them. Surface treatments are sometimes employed to improve the performance of these pavements. The construction of a surface treatment forms a protective layer with better riding qualities and covers the cracks and weathered structures.

3. To Improve Surface Irregularities and Appearance. Surface irregularities in a pavement resulting from poor construction, severe weather or traffic conditions can be improved substantially by the construction of a new surface treatment. With the irregularities reduced, better riding qualities and performance can be achieved from a more even surface. Sometimes, however, a surface treatment is applied to a pavement not for correction of any poor performance but simply to improve the appearance of the surface.

4. To Add Structural Strength. A major portion of the structural strength of a flexible pavement is provided by its thickness. This determines the amount of stress transferred to the subgrade. It is thought by some engineers that surface treatments either in one or multiple layers can be constructed to reduce the amount of stress in the subgrade. Lohn and Nevitt (47-1) suggest that the surface treatments provide structural strength by filling the voids and cracks and by sealing the surface. It is also suggested that the structural strength of a mat may also be increased by using an asphalt with high tensile strength and adhesiveness. However, many authors (50-1) (53-8) (58-1) have doubted whether surface treatments can sufficiently provide such strength and thus argue that they are not constructed for such a purpose.

Chapter Three

FACTORS INFLUENCING THE PERFORMANCE OF SEAL COATS AND SURFACE TREATMENTS

Many times, poor performance of a surface treatment can be traced to one of the constituent materials, either the aggregate or the binder. Other times, however, the behaviors of the materials are quite satisfactory and the failures that have developed are due to factors which are not related to these materials.

Regardless of whether the performance is primarily related to the materials or to other conditions, few basic studies have been made of the influencing factors. Most of the information that is available and that has been summarized here has come from the keen observations of the practicing engineer rather than from the results of comprehensive scientific investigations.

FACTORS RELATED TO THE AGGREGATE

The aggregate is a necessary part of a surface treatment primarily because the bituminous binder does not possess, by itself, all of the characteristics that are required for satisfactory performance of the surface treatment. The aggregate provides these needed qualities. For example, the bituminous binder will not support heavy wheel loads nor will it have very high skid resistance when wet. The aggregate, therefore, compensates for the binder deficiencies by transferring the wheel loads to the underlying surface and by providing a skid-resistant surface. The primary functions of the aggregate in a surface treatment are as follows:

1. To take the abrasion of the moving wheel load.
2. To provide a skid-resistant surface.
3. To transmit the wheel load to the underlying surface.

Occasionally the aggregate is used to provide other desirable characteristics that are not related to the performance of the surface treatment:

1. To provide proper light reflection characteristics by use of light-colored aggregate.
2. To provide a rough surface for satisfactory demarcation of shoulders or other related areas.

A number of factors related to the aggregate influence its performance in a completed surface treatment. These factors are discussed without regard to order of importance.

Amount of Aggregate

The statement that "the performance of surface treatments is affected by the amount of aggregate on the road surface" is so obvious that comments are hardly needed. Specifically, though, if not enough aggregate is placed on the road surface, bare spots of bituminous material will be present. This will result in low skid resistance when wet, stickiness when hot, poor abrasion resistance, and often, the specking of cars with the bituminous materials.

Several prominent engineers in the field of surface treatment design believe that the quantity of aggregate needed is that amount which is required to form a blanket one stone in depth, i. e., the surface should be completely covered with just one layer of stone. Actually, this statement should include the thought "when the aggregate is placed

so that its least dimension is in an upward direction." The aggregate particles under the forces exerted by rollers and moving vehicles will tend to rotate until they have reached their position of maximum stability. When in their final position, the correct quantity of aggregate needed depends only on the character of the aggregate: its size, its shape and its unit weight.

The amount of aggregate that must be spread on the road surface is greater than the amount needed to just cover the surface. This increase is due to such construction factors as the inaccuracy of spreading and whip-off. The magnitude of this increase ranges from 5 to 20 percent of the amount calculated to cover the surface one stone in depth. The actual percentage varies, however, and depends on the construction conditions in a particular locality.

Care must be taken in applying an excess of aggregate to the road surface. Not only is an excess uneconomical, but it also means that not all of the aggregate will be bound to the underlying surface by the bituminous material. This loose aggregate is easily whipped off by vehicle wheels and many times results in damage to other vehicles. One engineer (61-2) also says that aggregate excess is definitely not desirable, as the loose aggregate will cause loosening of some of the aggregate already firmly embedded in the binder film.

Thus, there should be just the right amount of aggregate needed for the surface treatment; an excess as well as a lack of aggregate are detrimental. The exact quantity needed depends on the aggregate to be used and the local construction conditions (51-3) (53-2) (54-2) (60-3) (61-2) (64-5).

Gradation

Although a well-graded aggregate is usually considered to be the best gradation for a compacted asphalt-aggregate mixture, it is quite undesirable for surface treatment construction. A one-size aggregate not only performs better in surface treatments, but also provides several advantages related to the design and construction of surface treatments. The one-size aggregate, however, needed for surface treatments has a very restricted gradation, much more than the "normal" one-size aggregates. For example, McLeod (60-3) defines a one-size aggregate for surface treatment purposes as those aggregates that have a gradation of 60 to 70 percent by weight of the aggregate passing the specified sieve and retained on a sieve having an opening that is seven-tenths of the specified size.

A one-size aggregate usually develops interlocking qualities that are better than those developed with nonuniform gradation. Since the interlocking provides lateral support to adjacent particles, it must be maximized to prevent displacement of aggregate under traffic. However, interlocking and mutual reinforcement must not be carried to the point where all of the interstices are filled. Some valleys are desired to supply drainage to prevent bleeding (48-3).

The desirability of having one-size aggregate is also apparent from the fact that the retention of the cover material decreases as the fine fraction of the gradation increases (54-2). Excess fines tend to fall to the bottom of the aggregate layer and become embedded in the surface of the asphalt. This action produces a film over the surface of the bitumen and prevents good adhesion and therefore poor retention of the cover aggregate. Material of size less than the No. 10 sieve also acts as a filler. As such, it tends to raise the level of the asphalt and cannot be counted on to function as cover material (53-2).

One of the most important advantages of using a one-size cover aggregate in a surfacing operation is that maximum contact is obtained between the tire and the surface. This increases the frictional area, and thus, there is better skid resistance so long as the correct quantity of binder is used.

Regardless of the desirability of using a one-size aggregate, it is often economically unfeasible. To reduce initial costs, allowable grading tolerances are often established which permit a small amount of both undersized and oversized particles in each of the different screening specifications. As the magnitude of the tolerance is increased, it is believed that performance qualities are sacrificed. Therefore, from the viewpoint

of overall economy, it may be better to expend more money initially to obtain a close, one-size aggregate that will perform well than to have lower initial costs and higher annual maintenance expenses (60-3).

Grading specifications utilizing close tolerances are not universally accepted. What one person such as McLeod calls a one-size aggregate does not necessarily meet the requirements for a material of that designation used by others. This discrepancy can also be found between state highway departments and national agencies such as ASTM. Such variations make the development and use of a universal design method next to impossible since most methods must be related to an aggregate of a specific gradation (48-3) (49-1) (53-2) (54-2) (54-4) (60-3) (64-5).

Size

The size of the one-size aggregate is another factor that must be given detailed consideration because of its influence on the finished surface. When a large-size aggregate is used, tires are prevented from making contact with the bitumen and thereby blackening the surface. One author (62-3) suggests the use of large aggregates for heavy traffic and smaller aggregates for light traffic. When using larger particles, the quantities of bitumen and cover aggregate are more easily and accurately determined. This facilitates the construction and produces good surface treatments.

As the aggregate size is decreased, the possibility of applying too much bitumen and filling the voids is increased. This possibility results from errors that could occur in construction procedures, through poor operation of the bituminous distributor, or through allowable tolerances. Regardless of the cause, the result is flushing and subsequent blackening of the surface which is undesirable.

When a small size aggregate is used, the design quantities can still be computed rather easily. However, more precise measurements of the variables to be used in the design methods must be made because there is a greater chance for the voids between the aggregate to be completely filled with binder. In other words, there is considerable chance that with small aggregates either bleeding will occur or else there will be loss of aggregate particles. Thus more stringent control must be exercised during construction because errors are more detrimental in this case.

When a nonuniform-size aggregate is used, as it has often been in the past, there is a tendency for several undesirable properties to result. Firm contact between the tires and the surface is made over a smaller area. This decreases the resistance to skidding, especially in wet weather. Contact is occasionally made between vehicle tires and the binder material resulting in a blackening of the surface and the creation of an undesirable appearance. Rough rides often result from large particles spaced far apart. There is also a great tendency for such large particles to be torn loose by traffic action resulting in early deterioration of the treatment. If the larger particles are not torn loose, wear will be concentrated on these few projections and they will soon become smooth and slippery. Also, construction of surface treatments utilizing a nonuniform size aggregate makes the determination of the quantities of binder and aggregate to be used more difficult.

From the preceding, there might be a tendency to conclude that one should always use the largest size aggregate readily available. This is not so, because of other factors desired of the finished surface such as a comfortable riding surface, little noise developed between tires and surface, and ease of maintenance. To obtain these qualities a maximum size of $^3/_4$ in. is normally used by most surface treatment designers.

McLeod reported (60-3) that the Country Roads Board of Victoria, Australia, has used the following sizes of aggregate with good results:

Percent of Jobs Done	Aggregate Size
25	$^3/_4$ in.
25	$^5/_8$ in.
23	$^1/_2$ in.
27	$^3/_8$ in.

This tabulation illustrates the fact that approximately 75 percent of the surface treatments laid down in Australia contain cover aggregate of size ½ to ¾ in. The use of such larger material in the majority of the cases with good results again illustrates that many desirable features are developed with aggregate that falls in this particular size range. When using the smaller aggregate (size ⅜ in. or less), one must be careful to exercise good judgment in quantity design because errors can be costly and are often detrimental to the finished surface.

No complete uniformity in practice can ever result nor is it justified. Judgment by the engineer for the particular conditions in the immediate area must always be made (54-4) (58-1) (60-3) (62-3) (62-4).

Shape

The shape of the aggregate particles used in a surface treatment greatly affects the interlocking qualities of the particles, and thereby, the stability of the treatment. The best interlocking qualities can be obtained by use of angular particles. These particles have many points of contact with one another and therefore do not have a tendency to shift their positions easily.

Rounded aggregate particles are sometimes used as a cover material; however, there is a sacrifice in stability since contact between adjacent particles occurs at only one spot. The rounded particles develop less strength due to interlock and have a tendency to push and roll under traffic stresses. When compacted they also have a higher void content than do angular particles and require more binder material.

When a rounded aggregate is the only material available, crushing is recommended to develop angular surfaces. This process may increase the cost of the treatment, but the additional benefits received usually justify the expense.

An extreme case of irregular shape was discussed by J. P. Kearby (52-3). He reported that the amount of flat and elongated particles should not exceed 10 percent of any gradation requirement when used for surface treatment purposes. He defines "flat" aggregate as one having a thickness less than one-half the average width of the particle and "elongated" as a length greater than twice the minimum dimension (52-3) (52-6) (53-2) (58-1) (60-3) (62-3).

Compaction

All surface treatments should be compacted during the initial construction stages so that desirable retention characteristics can be developed between the aggregate and the bitumen. The need for such compaction increases as the expected traffic volume increases.

During compaction the bituminous binder material is displaced from beneath the aggregate particles and moves upward and around them. At the same time, the aggregate particles tend to reorient themselves in such a way as to have a vertical thickness equal to the least dimension of the particle; the area of contact between the aggregate and the binder material is increased, thereby insuring better retention qualities.

Compaction of the aggregate in a surface treatment should be performed by both traffic action and mechanical rollers. Reliance for compaction by traffic only is neither good nor advisable because of the time lapse that could occur between compacting application. During this lapse, the consistency of the bituminous binder may become hard and oppose further aggregate embedment. Rapid deterioration of the treatment could result under such circumstances.

It is essential that the minimum void content be obtained early in the life of the surface treatment because material quantities (both aggregate and binder) are based upon this percentage. As such, the treatment cannot perform as designed until all of the design factors are realized.

Initial compaction of the treatment by roller should be performed immediately after the application of the cover aggregate and before stiffening of the bituminous material. It should be continued until the aggregate is well embedded in the bituminous binder and/or until the bituminous binder has hardened to the extent that it will hold the aggregate in place. Usually, ten complete coverages meet these requirements (55-3) (35-1) (55-3) (60-3).

Dusty and Wet Aggregates

One of the essential requirements for successful surface treatments constructed with bituminous materials is that "the bond between the asphaltic material and the stone must be great enough to prevent dislodging of the stone under traffic" (53-1). Several investigations have been conducted on factors that adversely affect bond strength. Many of these factors are related primarily to the aggregate and not to the bituminous binder. In tests performed by Benson and Gallaway (53-1) it was determined that either a coating of dust or a film of moisture on the cover material seriously delayed the adhesion of the aggregate to the binder. So adverse are dust and moisture to good surface treatment performance that several engineers believe that these factors are probably the most common causes of aggregate loss (35-1) (60-3) (63-2).

Dust behaves in much the same way as an excess of fines (material less than No. 10 sieve) in the cover material; that is, some of the smaller particles tend to fall to the bottom of the one particle thick layer and become embedded in the bituminous surface. This action produces a film over the surface of the bitumen and prevents good adhesion between the aggregate and the binder after compaction and subsequent reorientation of the aggregate particles. The foreign material retained on the aggregate is also detrimental to the development of adhesion since it too separates the binding material from the aggregate particles. Experimental work with several cover materials (53-1) indicates that the presence of even a small amount of dust will greatly increase the loss in aggregate retention. In Figure 1, the effect of dust on two different cover materials present in quantities ranging from 0 to 1.2 percent by weight of aggregate is given as reported by Benson (53-1). Interpretation of this figure indicates that for the presence of 1 percent dust there is a loss in aggregate retention of 12 percent by weight per unit area. As the percentage of dust present is decreased, the loss in aggregate retention is reduced at a non-linear rate. Figure 1 also shows the influence of wetting the dusty aggregate before its application, applying it wet to the road surface, and then allowing it to dry before compacting. Retention is improved since the dust is bound to the aggregate surfaces before spreading and, therefore, does not tend to separate from the aggregate particle and form a film over the top of the binder material (58-1). For the same material that was used previously, the presence of 1 percent of "saturated" dust instigates a loss in aggregate retention of 8 percent by weight.

Although wetting of the dust does tend to improve the retention properties of surface treatments during the initial stages of their lives, it is believed that such a procedure should not be adopted as standard practice and should only be used as a last resort. Since the dust particles will continue to separate the binder and the aggregate particles throughout the life of the treatment, it is thought that after drying, loss in retention will again be as great or greater than not wetting at all. As always, the best results can only be obtained by using a dust-free aggregate in the first place.

All cover aggregates will usually contain some moisture due to current methods of stockpiling out-of-doors. Small quantities of moisture usually present no serious problems in warm, dry weather, as is usually the case during the summer months, because of rapid evaporation. If moisture is allowed to remain after rolling, however, it can be quite detrimental to the new surface. Moist aggregate does not adhere well to the binder, and if traffic is allowed to use the facility before adequate bonding has occurred, the surface will be whipped to pieces rapidly. Under such conditions surface whip-off is quite excessive, often much greater than 10 percent (35-1).

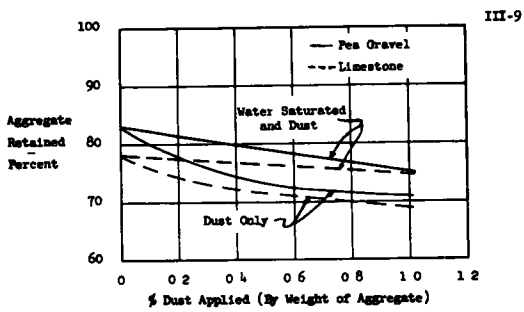

Figure 1. Effect of dust on the retention of aggregate (data taken from Benson, 53-1).

The results of some experimental work (53-1) on aggregate-moisture relationships are shown in Figure 2. The curves show a very marked reduction in the quantity of

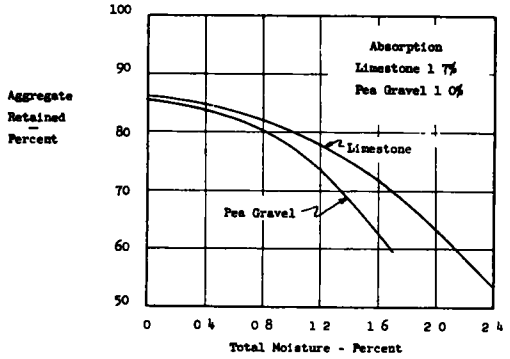

Figure 2. Effect of moisture on retention of aggregate (data taken from Benson, 53-1).

aggregate adhering to the bitumen with an increase in moisture content. Above a moisture content of 2 percent, the amount of aggregate retained is less than 60 percent. This condition is undesirable from two aspects: the deterioration of the surface treatment and the presence of loose material on the surface which is picked up and thrown by passing vehicles.

One method of dealing with the problem of dust and water is washing and drying the aggregate by mechanical means before application. This procedure solves the dust problem almost entirely.

Other methods of improving the adhesion between the aggregate and binder consist of coating the aggregate with either a bituminous material or a kerosene film before application. The bituminous material coats the aggregate while clean and dry. After such precoating the aggregate can be easily stored since absorption of water is no longer a problem. Precoating with a bituminous material thus guarantees good adhesion (57-1). The kerosene film coating should be applied immediately before the application of the aggregate to the road surface. This process also assists in the development of adhesion between the aggregate and the binder. The amount of kerosene used for such a coating should be restricted to ½ to 1 gallon per ton of aggregate (60-3).

All additional handling of the cover chips increases the cost of the surface treatment operation. But experience has shown that the longer service life and the better performance obtained by using treated aggregates more than offsets the initial additional expense (60-3). One cannot overemphasize the importance of the physical condition of the cover material. The success or failure of a particular surface treatment might well depend solely upon the condition of the cover material (35-1) (53-1) (57-1) (58-1) (60-3).

Crushing of Aggregate

Crushing of surface treatment aggregate may result from one or a combination of several of the following factors which are listed in order of importance: (a) aggregate is too soft, (b) weight of the roller is too heavy, and (c) the existing surface being sealed is very hard and does not allow the new material to penetrate into the surface when rolling is performed. These factors need little explanation and most of the corrective measures to be taken are obvious.

The crushing resistance of aggregates varies with type and source of the aggregate. Because of this it is very difficult to stipulate definite aggregate hardness criteria, since the meaning of such criteria also varies from place to place. Local experience must be used when judging this characteristic.

The degree of crushing has been proved to be a function of the original gradation of the material, the size and shape of the original particles, and the number of coverages with the mechanical roller. Tests conducted by Shelburne (40-4) indicate that approximately 1.3 times as much degradation occurs when rolling a crushed gravel as in rolling an uncrushed gravel. These same tests also indicated that breakage under roller action produced on a rigid base was approximately twice that encountered on a flexible base, and that most of the breakage was concentrated in the larger particles.

It is naturally undesirable to allow the crushing of aggregate to exceed certain specified limits since such action is detrimental to the service life of the surface treatment. Appropriate measures must be taken to keep the degree of crushing at a minimum whenever possible (40-1) (40-2) (40-4) (60-3).

Abrasion Resistance

The abrasion effects of traffic on a surface treatment aggregate can be considered in two phases—polish and wear. Polish of an aggregate is the first stage of abrasion

in which the points and edges of the aggregate particles as well as the surface roughness are lost. With sufficiently hard aggregates the time required to reach this condition is long enough to justify resealing when it occurs. However, when hard aggregate is not available and a soft aggregate is used, polishing may occur very soon after placement, and as a result, the design must be adjusted for this situation.

Wear of an aggregate refers to the condition of the aggregate during the time period required for the projecting particles to erode to a practically level surface. The rate of wear is dependent on the particle size, shape, and spread, as well as the aggregate hardness and vehicle tire characteristics. It takes a much longer time period to reach the wear phase than it does the polish phase. Polishing and wear are both detrimental to the pavement surface because when they exist, a surface with a markedly reduced coefficient of friction results. Such a condition is very hazardous to the motor vehicle operator under any conditions.

In general, surface treatment aggregate should be reasonably resistant to the abrasive effects of traffic. "A maximum Los Angeles rattler test abrasion loss of 35 is often specified for the aggregate; however, aggregate with losses up to 40 have been used successfully" (57-1).

It is always desirable to keep the abrasion loss as small as possible. However, it is not always economically feasible to do so. Use must be made of locally available materials and these, as such, may not always be of the most desirable quality (40-1) (40-2) (57-1).

Color

The use of light-colored aggregate in surface treatment operations is proving to be beneficial because of the luminosity characteristics that are obtained. Such aggregate provides better road delineation under adverse conditions of weather or at night. It also produces less glare and therefore less driver fatigue in sunlight. It is without question that such properties help to keep drivers alert and thereby reduce accident rates.

The desirability of using light-colored aggregate can be noted from past experience. Several states have used locally available dark-colored aggregate for surface treatment cover material. Drivers using these facilities often complained of losing sight of the pavement surface due to its blending into the surroundings. Such complaints destroy user approval and good will and occasionally cause the "black-balling" of this particular type of treatment. This situation can and should be avoided through proper selection of the aggregate in the first place.

Another important advantage to using light-colored aggregate stems from the fact that due to greater ease of driving, better traffic distribution on the facility is obtained. This is extremely important on facilities that have high traffic volumes and where traffic delays are to be avoided (48-3) (52-6).

Adhesion Characteristics

The aggregate must possess good retention characteristics to remain in a relatively stable position under the action of traffic. In surface treatments, the aggregate is only partially embedded in the asphalt and as such does not gain much support from other aggregate particles; that is, the interlocking and keying which is common in bituminous mixtures does not occur to the same degree in this type of treatment. Because of this situation, the development of a good bond between the aggregate and the asphalt in order to hold the aggregate securely is essential for satisfactory performance.

The development of adequate adhesion usually is not a problem if proper design and construction procedures are followed. Only in cases where excess moisture is present to facilitate stripping or where dusty aggregate has been used does the problem of inadequate adhesion arise (49-2) (51-1) (60-3).

Durability of the Aggregate

Surface treatment aggregate undergoes much exposure to the destructive elements of nature. Since the aggregate particles are not completely covered by protective

bitumen they must be more durable than aggregates used in bituminous mixes. They cannot possess a tendency to break up through the effects of air, water, and/or traffic exposure.

Since the durability of a given aggregate varies with location, local experience and good engineering judgment must be used when considering the aggregate for surface treatment use. No limits can feasibly be set for this durability factor since an aggregate that performs satisfactorily on one project may not perform so well on another project in a different area due to the new conditions encountered.

Several testing devices are available that have been or are being used to give an indication of the durability of aggregates in a particular area. Some of these are the Deval abrasion test, Page impact test, Los Angeles rattler test, sulfate soundness test, freezing and thaw tests and several others. Obtaining satisfactory results from one or more of these tests in the laboratory does not always mean that the tested aggregate will have satisfactory durability in the field. This is because "weathering is not a clear-cut process and to try to forecast the durability of an aggregate subjected to natural degradation in addition to man-made forces such as traffic" (48-2) is very difficult (48-2) (51-1) (60-3).

FACTORS RELATED TO THE BITUMINOUS BINDER

The primary purpose of the bituminous material is to hold the aggregate in place and bind it to the underlying surface. If this is not done, the surface treatment will have poor performance even though the bituminous material fulfills its secondary functions which are (a) to seal the underlying surface and prevent entrance of moisture and air, (b) to enliven old, dry, and weathered bituminous surfaces, and (c) to fill small cracks.

The bituminous binder must possess several important and distinct characteristics if it is to function as it should. Each of these factors must be fulfilled to a desirable degree in order that the surface treatment, in which the particular binder material is used, performs satisfactorily. Varying degrees of emphasis are placed on specific functions by different individuals. Since many of these functions are interrelated, however, no special emphasis or order of importance has been assigned to the factors in the list which follows.

1. The correct amount of binder must be used.
2. The bitumen must be of such character that good adhesion to the existing surface and to the aggregate chips is insured.
3. The bitumen must develop, within a relatively short period of time, sufficient cohesive strength to facilitate the opening of the road to traffic and to insure adequate aggregate retention under the action of the traffic.
4. The binder should be fluid enough at the time of spraying to provide for accurate and uniform application.
5. The bitumen should not become brittle or hard as a result of deterioration under conditions of natural exposure.
6. The bitumen must develop after a short period of time sufficient viscosity to prevent aggregate movement at any subsequent temperature of the pavement surface under the action of traffic stress.

Correct Amount of Bituminous Binder

As with other types of bituminous construction, there is an optimum amount of bituminous material that must be used in the construction of a surface treatment so that the surface will perform correctly. A minimum amount is needed so that the aggregate will be firmly held in place and bound to the underlying surface. On the other hand, there is a maximum amount since an excess of bituminous material will result in bleeding, blackening of the surface, and low skid resistance when wet.

The optimum bitumen content is influenced by many factors and all should be taken into account in the design of surface treatments. These factors are primarily related to the volume of the voids between the aggregate. This volume is in turn related to the size and shape of the aggregate and to the degree of compaction. It is also dependent on the amount of traffic using the facility.

The basic amount of bituminous material needed must be corrected to account for conditions at the construction site. An allowance should be made for the condition of the underlying surface, the type of liquid binder, and volume change produced in the material as it is heated. These factors are covered in detail in the next chapter, "Design Methods." There are many factors. They all influence the amount of binder that must be sprayed from the distributor and thus influence the performance of the surface treatment (35-1) (49-2) (53-2) (60-3).

Good Adhesion

The development of good adhesion between aggregate and binder is one of the paramount functions of the bituminous material. It will determine in many respects the service life and performance characteristics of a particular surface treatment since loss in retention, degree of whip-off, and durability are all related to the adhesive forces developed.

A lack of adhesion is caused by an excess of fines, an excess amount of moisture in the cover material, and/or by constructing the surface treatment when prevailing air temperatures are too low (60-3). Proper selection of aggregate and binder materials helps insure adequate adhesion development. Adhesion has not been covered in great detail here as there is too much about it in the literature already (41-1) (49-2) (58-1) (58-7) (60-3).

Cohesive Strength

Before the opening of a newly surface-treated highway to traffic, the bitumen must have developed sufficient cohesive strength to prevent the aggregate from being pulled out or whipped off of the surface by traffic once it is opened. Much initial damage can be done to the new surface if the needed cohesion has not developed to a sufficient degree.

To fulfill the two functions, development of adhesion and cohesive strength, the perfect binder should be quite fluid initially to allow time for placing and wetting of the aggregate, and then it must revert to a harder condition rather rapidly to facilitate the opening of the highway to traffic. This is very important and cannot be stressed enough. Neither bitumen nor tar are perfect binders. However, when proper precautions are exercised during construction, both materials can perform satisfactorily (47-1) (49-2) (57-7) (58-1) (65-3).

Uniformity of Application

Uniformity is of utmost importance to eliminate streaking and the detrimental effects to the pavement of having portions of the surface that have an excess of bitumen and other portions that are deficient in bitumen. It should be noted that good uniformity can never be obtained if defective equipment is used during construction regardless of the condition of the binder material.

Uniformity of application is a function of viscosity which in turn varies with the temperature of the binder prior to application of the cover aggregate. For best application the optimum viscosity required must be within the range of 25 to 50 sec Saybolt Furol or 60 to 110 centistokes (60-3). An approach for obtaining the optimum viscosity at application was recently used by McLeod (60-3). This method provides the rapid determination of the temperature to which the material must be heated in order to attain the optimum viscosity desired once the viscosity-temperature curve for the bituminous material being used is known. Figure 3 is reproduced from McLeod's article of a set of temperature-viscosity curves (straight lines within specified viscosity limits). Using Figure 3 or similar ones, the temperature required to attain a particular degree of fluidity for any grade of bitumen is determined by proceeding horizontally at the required viscosity until the intersection with the desired temperature viscosity curve. Proceed vertically downward from the intersection and read directly the desired temperature of application. Such curves for any specific grade of cutback asphalt are independent, for all practical purposes, of asphalt source or method of manufacture. Curves for asphalt cements, however, vary with binder source (49-2) (60-3).

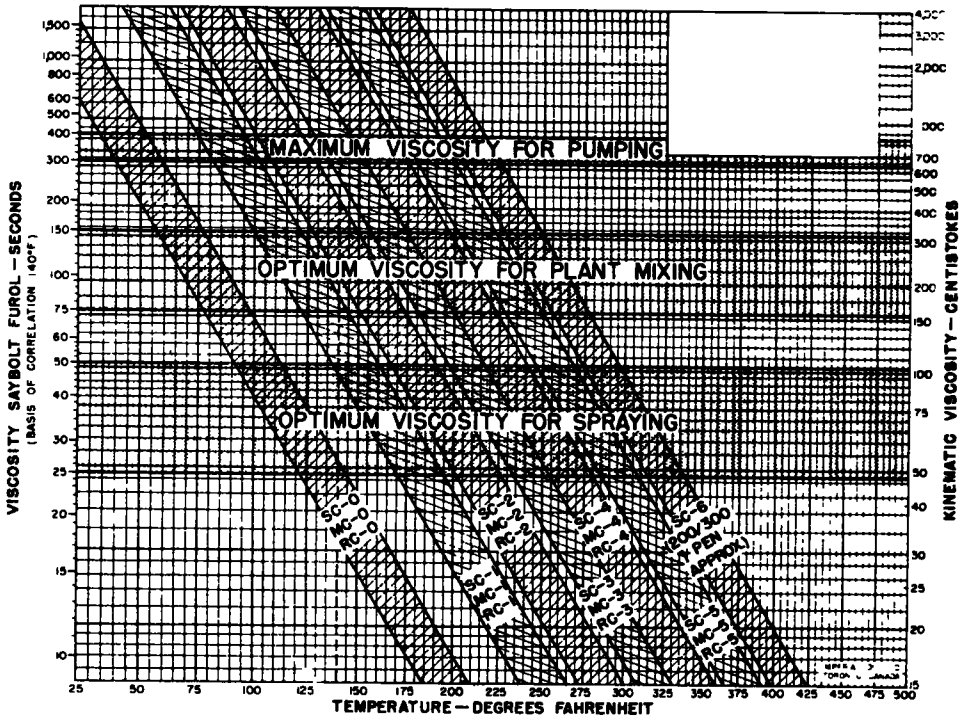

Figure 3. Temperature-viscosity relationship for liquid asphalt grades, with recommended viscosity ranges for spraying, mixing, and pumping (data taken from McLeod, 60-3).

Durability

The weathering of a bituminous binder and its subsequent deterioration with age is of great interest because it has resulted in the replacement of many surfaces which had otherwise been performing satisfactorily. Good durability or resistance to deterioration under service conditions is essential for prolonged service life and good performance of any pavement. Hardening and brittleness of a bituminous material on exposure may be caused by one or all of the following processes: (a) loss of oils by evaporation, (b) the chemical action of atmospheric oxygen, and (c) a change with age in the physical structure of the material.

Tests to determine the degree to which each of the previously mentioned factors affects the pavement have been performed. Conclusions drawn from this work show that most of the hardening of the bituminous material on exposure is due to oxygen attack or to volatilization after the initial curing period. As the age of the pavement increases, the amount of oxidation and volatilization occurring increases at a decreasing rate. Also, as the thickness of the treatment increases, the influence of oxygen attack and volatilization on durability decreases.

At low exposure temperatures, bituminous materials become hard and brittle—tars much more so than asphalts. The effect of temperature extremes on binder materials is also important to the performance characteristics and life of the pavement. Consideration should be given to this factor when selecting the bituminous material.

In one article, Benson (58-1) presented the following solution to the weathering problem. In order to delay the detrimental effects of brittleness in a bituminous pavement "there is a preference for using softer bitumens as the binder material." Benson reasons that since the bitumen is exposed to air, oxidation will occur rapidly and cause a hardening of the bitumen. It takes longer for a soft bitumen to reach a critical point where cracking and weathering will be excessive than it does for the harder bitumens.

As such, the life of the pavement increases. It should be remembered, however, that too soft a binder can be detrimental from the viewpoint of the other qualities desired, such as cohesion (47-1) (49-2) (58-7).

Binder Viscosity at Pavement Surface Temperatures

The viscosity and aggregate retention characteristics of a bituminous material vary inversely with the temperature of the pavement surface. When the bitumen is in a semi-fluid condition, it is unable to retain cover aggregate under traffic. Therefore, to prevent early or subsequent loss of cover material, the bitumen should possess inherent qualities which would prevent the "softening up" of the material within the normal temperature range encountered in service. In order to do this some groups are fluxing hard asphalt cements with kerosene on the job to produce desirable spraying and binder viscosities (49-2) (58-7) (60-3) (64-4) (65-4).

FACTORS NOT RELATED TO THE AGGREGATE OR BITUMINOUS BINDER

Several important factors pertaining to the constituent materials of a typical surface treatment have been discussed previously in this chapter. These are not the only factors which must be considered to obtain a surface treatment that will perform satisfactorily. The condition of the underlying surface, construction techniques, climatic conditions, and volume and type of traffic all influence the performance of the surface treatment. These factors, which are not related to the aggregate or bituminous binder are discussed in this section.

Underlying Surface

Prior to Placement of Surface Treatment—The subgrade and base constitute the foundation supporting the traffic loads. A surface treatment placed on this foundation primarily provides a wearing surface which resists the destructive action of traffic and transmits the vehicle loads down to the base and subgrade. Since the thickness of most surface treatments is relatively small, no appreciable strength is added to the structure by application of such a treatment. The underlying layers must possess initially all of the strength required to satisfactorily support the expected vehicular loads.

To obtain a surface treatment that will have good performance, the following base requirements are essential: (a) base constituents must be well-bonded through proper compaction, (b) base materials should have high supporting qualities, (c) the upper surface of the base should be as smooth as possible before sealing, and (d) the upper surface of the base should be clean and dry before sealing. The first two factors require little explanation. If an inadequate or poor base is used in an attempt to construct a surface treatment, no matter how good the surface treatment unsatisfactory results will be obtained. An adequate base will greatly reduce maintenance costs and will make possible the construction of relatively thin and economical surfaces that will have good performance qualities.

The condition of the upper surface of the base is a very important factor in attaining a lasting surface treatment. A detailed account of the factors influencing the underlying surface condition is given in Chapter Five. If the conditioning procedures mentioned in that chapter are met, a uniform and smooth surface should be available for the surface treatment. In addition, desirable characteristics such as adequate adhesion will be easily developed between the treatment layer and the existing surface.

Influence on Type and Quantity of Materials—The quantity and type of asphalt material and the size and quantity of the aggregate cover material to be used are affected by the condition of the underlying surface as well as the material of which it is made. Because of this, quantity allowances should be made for existing surfaces of crushed stone, concrete, or bituminous materials and their condition.

1. Asphalt Surface. The quantity of bituminous binder to use for a surface treatment is influenced by the bitumen content of the old surface. If the existing surface is spotty or has numerous rich and lean sections, a complicated construction practice must be followed to correct these areas. The adverse sections can be corrected

individually before application of the seal by heating and scraping off the excess bitumen when rich or by the addition of bitumen when "hungry," or else the amount of binder can be increased or reduced over these areas as needed by varying application rates during the surfacing operation when feasible. This latter procedure is very difficult even if a skilled distributor operator is available.

If the existing surface is uniformly rich or uniformly hungry, the correcting procedure is greatly simplified. All that needs to be done is to increase or decrease the design application rate before starting the sealing operation. In addition to varying the amount of asphalt it is often desirable to increase or decrease the maximum size of the aggregate being used. On flushed rich areas, larger maximum size aggregates can be used to allow for embedment of the particles into the existing surface under the action of the roller and eventual traffic. In hungry areas, a smaller maximum size is often specified to allow for the absorption of the binder material by the existing surface. In either case, the percentage of voids in the final result should be approximately the same. No method of determining the correction for the amount of aggregate embedment in such areas has been established for easy use in current design methods.

2. Concrete Surface. A surface treatment by itself is very seldom applied to an existing concrete surface. Usually the older concrete surface is neither smooth nor level and therefore must be corrected before surface treatment application to prevent reflection "bumps" from occurring. Leveling courses of bituminous mix construction are commonly used in such cases to make the existing surface suitable for the treatment. Further discussion on this subject is beyond the scope of this review.

3. Crushed Stone Surface. A surface treatment can be applied directly to an existing crushed stone surface. Of course, such a surface must be capable of carrying the loads which will be imposed since the surface treatment will not appreciably change the strength qualities of the surface.

The surface should be relatively smooth and have very little dust or loose material present. Once this state has been attained, the surface treatment can be applied as follows: First a prime is needed to penetrate into the stone material and bind it together firmly. The bituminous binder is then placed and the chip cover provided. The construction procedures to follow are similar to those mentioned in Chapter Five. Such construction does not guarantee that the finished surface will be completely free of bumps. It does, however, provide a relatively stable facility since moisture is kept from the underlying material.

Construction Techniques

There are many construction techniques used today to simplify and improve the quality of modern surface treatments. These techniques are of utmost importance because: no matter how good the design or the materials used are, if the construction technique is no good, the surface treatment will not perform satisfactorily. Many of the construction techniques are mentioned in Chapter Five. However, two of the more important ones are stressed here in detail.

Control of Traffic—The control of traffic during and immediately after the construction of a surface treatment is very important. It is at this time that the treatment has its lowest stability and is readily damaged under adverse conditions.

The period of low stability is directly influenced by the prevailing weather conditions as well as the fact that all aggregate particles have not yet attained their "best" position (least dimension in the vertical direction). During this low stability stage, fast moving vehicles must be restricted from using the facility because of the irreparable damage that they could cause. Slow moving traffic (10 to 30 mph) on the other hand is not detrimental to the surface and is often even beneficial. Repeated applications of slow-speed traffic help to increase the stability of the surface treatment by causing reorientation of the aggregate particles and by facilitating in the development of adhesion by the kneading and compacting action afforded. Therefore, traffic speeds must be controlled.

The time required to obtain an interlocking mass of uniform appearance varies with the type and amount of traffic. If a road carries only very light traffic, the time required to reach the final state may be several hours. If this is the case, proper

selection of the binder material must be made to insure desired viscosities for longer periods of time (60-3).

During the actual construction of a surface treatment, one of several methods of traffic control can be exerted. Traffic can be kept off of the new treatment entirely by detouring it away from the project until the critical low stability period has passed. This method works well when detour routes are readily accessible. When such routes are not available, the method is not economically feasible over long stretches of pavement.

An alternative method of traffic control is to confine the traffic to only one-half of the facility being treated while treating the other half. This method is feasible under most situations. It is not, however, the most desirable because of the increased danger to workmen and the tendency to complete sections of the treatment rapidly so that they can be opened to traffic.

Either method can be, and often is, used with satisfactory results. Adaptability of the method is usually the influencing feature.

Inspection—From past experience it is evident that very lax methods of inspection have been used during the construction of many seal coats and surface treatments. The needless failures that have resulted from poor inspection practices have been costly and also have helped to make the general public feel that all such construction is inferior and undesirable. It is true that surface treatments are a low-cost form of treatment. However, with modern mechanical devices, large areas can be treated quite rapidly. Because of this mechanization, daily expenditures may be quite considerable, and it would seem that appropriate changes should be made in current inspection techniques to correct existing deficiencies.

Good construction practices are required at all times. If adverse practices are followed, then no matter how good the original design, the surface treatment will not perform as well as it could have.

Climate

The weather conditions of a particular region greatly affect the procedures used in the construction of a seal coat as well as the service life of that seal. Many of these conditions are difficult to take into account because there is no readily available method of evaluation.

Extremely hot weather is detrimental to the finished surface treatment because at high temperatures most bituminous binder materials approach a liquid state. When this occurs, the cohesion is reduced and damage occurs under traffic action. Cold weather is also detrimental because at low temperature the binder becomes brittle and often breaks up under the impact of traffic. Proper selection of the bituminous material to be used is of the utmost importance in eliminating the adverse effects of temperature. McLeod (60-3) presents several figures to facilitate the selection of the proper binder material.

The amount of precipitation in conjunction with varying temperatures also affects the procedures used. In areas of high precipitation and low temperatures, the seal will be subjected to repeated cycles of freezing and thawing, leading to early breakup and subsequent short service life. Excess moisture at normal temperature affects the stability of the base materials and may also cause failures.

Care should be exercised during planning stages to consider all of the adverse climatic factors that may affect the resulting surface. Proper designs should then be made taking into account all of these pertinent factors.

Volume and Type of Traffic

The volume and type of traffic influence the type of facility constructed, the service life of the facility, and the cost of the construction operation. On low-volume facilities, large expenditures are not feasible and often a gravel base material is satisfactorily surfaced with a bituminous material and cover chips. As the volumes increase, the strength of the pavement must increase so stronger bases and additional surface treatments are employed. Each is adequate only up to a certain volume limit. Beyond this

limit adequate strength cannot be had. It is commonly believed that surface treatments should be used only on light or medium type facilities; i. e., they should be used only on facilities carrying less than 2, 000 vehicles per day. McLeod (60-3) however, states that some single surface-treated highways in Australia are presently carrying more than 20, 000 vehicles per day (4-lane highway) and are performing well. This indicates the need for improvement in many current design methods.

The type of materials used in the base and surface treatment, the weather conditions, and the construction procedures all influence the effect that specific traffic volumes and/or types have on the structure. No single numerical value can be assigned to these factors which will adequately evaluate all of them at a given location.

Changing conditions bring about fluctuating traffic volumes as well as different traffic types, making it difficult to forecast the demands on a facility in the future. Because of this, many present roads are carrying volumes of traffic which greatly exceed their capacity. Such situations result in the early deterioration of the facility regardless of the design and construction procedures followed (39-1) (40-2) (41-2) (51-1) (60-3) (64-3) (65-5).

Chapter Four

DESIGN METHODS

Although surface treatments have been in use for approximately 60 years, during the first 30 years or so no formal design method existed. Quantities were determined by experience and/or precedent and this often resulted in surface treatments that had poor performance characteristics. Apparently, the first thorough investigation of factors influencing the design of surface treatments was conducted in the early 1930's by F. M. Hanson, a New Zealand engineer. These studies were quite fundamental in nature, and the findings were used as the basis of his design method and also of a number of later methods. By the mid-1940's, more interest had been generated in developing a desirable method of design, and a number of related investigations had been made.

Although the procedures in the various design methods are not the same in all details, there are a number of factors that are common to all. These factors are summarized herein. Also included are some important factors that are used solely in a particular design method. If additional detail is desired in regard to any particular factor, each of the design methods is summarized in the Appendix.

In designing surface treatments, the procedure is to determine (a) the type and amount of aggregate, and (b) the type and amount of bituminous binder required so that the surface treatments can be constructed properly and will perform satisfactorily. A considerable number of factors affect each phase of the design procedure. Although some of them might appear to be quite insignificant, often, if only one of the factors is not considered in the design, the treatment may fail.

DETERMINATION OF AMOUNT OF COVER AGGREGATE

The predominant feeling among engineers dealing with surface treatments is that the quantity of cover aggregate should be the "amount which is required to form a blanket one stone in depth" (53-2). Thus, the "correct" quantity of aggregate to be used in a particular surface treatment operation varies only with the character of the aggregate; that is, it is influenced by such factors as the size of the aggregate, the shape of the particles, the unit weight, and the percentage of voids between the aggregate. In no way is the required quantity of aggregate influenced by the amount of bituminous material which must be used.

It should be noted that two different aggregate quantities are determined in most design methods. One quantity is the exact amount that is needed to cover the road surface. This is sometimes referred to as the "correct" or "basic" quantity. The "field spread" quantity, or normally the "spread" quantity, is the amount of aggregate that must be spread on the road surface. This latter quantity is greater than the basic amount, since allowance must be made for aggregate whip-off and construction inaccuracies. In design, the basic aggregate quantity is usually determined first and then is modified to provide the spread quantity.

Basic Quantity

Direct or "Test-Board" Method—The most direct, and probably the most accurate, method for determining the basic quantity of cover aggregate in a surface treatment is the "test-board" method suggested by Kearby (52-3) (53-2), and its variations as developed by Mackintosh (61-2). A board of known area is covered with a sufficient quantity of aggregate which are placed with their least dimension upward so that complete coverage of the board with stone, one thickness in depth, is obtained. The weight of the aggregate on the board in pounds divided by the area of the board in square yards is

TABLE 1

COMPARISON OF "AVERAGE SIZE OF THE COVER AGGREGATE" AND QUANTITY OF COVER AGGREGATE NEEDED AS DETERMINED BY DIFFERENT METHODS

Design Method	Reference	Name of "Avg Size of Agg"	Avg. Size of Agg. (in.)	Agg Quantity (cu ft/sq yd 10% whip-off)
American Bitumuls	62-1	Average stone size	0.31	0 26
California	49-2	Effective maximum size	0.46	0.26
Kearby	53-2	Average mat thickness	0 311	0.28
Linckenheyl	53-5	Mean particle dimension	0 31	0.25
Lovering	54-4	Spread modulus	0.318	0.29

[a]All calculations are made with aggregates of the same gradation

the exact quantity of aggregate needed in pounds per square yard. This method is quite accurate and is especially good in that it indirectly accounts for all of the variables in the aggregate that influence the amount needed.

Calculated Method—Some engineers (35-1) (49-2) (53-2) (54-4) (60-3) prefer an indirect method for determining the quantity of cover aggregate needed and calculate this quantity from the "average size of the aggregate." Reasons are varied as to why the direct method is not used, but primarily they are related to other calculations that must be made in designing the surface treatment. The primary basis of determining the quantity of bituminous material needed is the average size of the aggregate. It was thought that since the average size of the aggregate must be computed for determining the bituminous quantity, it could also be used to determine the quantity of the aggregate. In other words, this method is a reverse procedure of that used in the test-board method where the average size of the aggregate may be computed from the basic aggregate quantity.

Average Size of Aggregate—The average size of the aggregate, as used in the calculated method, may be determined by a number of different procedures. Hanson (35-1) used a direct means of determining the "average least dimension" of the aggregate. With a pair of calipers, he measured the smallest dimension of at least 100 particles of the aggregate and averaged the results. Most of the other investigators, however, used the sieve analysis as the basis for determining the average size. One investigator (49-2) used the 90 percent size (i. e., the size of the aggregate that would have 90 percent of the material, by weight, smaller than that size). Another investigator (60-3) used the 50 percent size, but modified it to account for various influencing factors. Two investigators (53-2) (54-4) used a weighted average of the amount of aggregates on different screen sizes. Since the average size of the aggregate is determined in different manners, the computed numerical sizes will not be the same in all cases. In fact, there can be a fairly wide variation as given in Table 1.

Just as different methods have been employed for determining the average size of the aggregate, almost every investigator has used a different term to refer to the average size of the aggregate. Table 1 gives some of the names used.

Factors Influencing Average Size of Aggregate—All investigators have indicated that a linear relationship exists between the average size of the aggregate and the quantity (weight) of the aggregate needed per unit area, i. e., the weight quantity equals a constant times the average size of the aggregate. The proportionality constant used between these two factors, however, is not the same in all of the design methods. This is due primarily to the fact that the average size of the aggregate is determined in different ways in the various design methods. Therefore, when one particular investigator's method of design is being used to compute the aggregate quantity, it is very important to use the corresponding "suggested" method for determining the average size of the aggregate. Regardless of the proportionality constant or the method of determining the average size of the aggregate, there is not an appreciable difference in the quantity of needed cover aggregate as determined by the different methods. The values in Table 1 indicate approximately a 16 percent variation.

To convert the needed quantity of aggregate from cubic feet per square yard to pounds per square yard, the unit weight of the aggregate must be used. Several engineers (53-2) (58-1) use the loose unit weight of the aggregate. This unit weight is normally determined by the weight of the aggregate that can be placed without compaction into a 1-cu ft container. Thus, it is assumed that the unit weight of the aggregate in a "pile" is the same as it is in a single layer. This assumption, in all likelihood, is not correct. McLeod (60-3), possibly realizing this, uses the ASTM bulk specific gravity for the conversion. There appears to be no reported data to indicate which of these unit weights should be used or if some other one would be more correct.

Although the majority of the design methods do not consider the shape of the aggregate as a factor that would influence the amount of cover aggregate needed, several investigators do take this factor into consideration. Hveem, et al (49-2) noted that aggregates with the same gradation but from different sources gave somewhat different values in the areas covered. It was concluded that not all of the variables were considered in a sieve analysis and that other variables such as surface texture and aggregate shape should be considered. Nevitt (51-1) includes a shape factor in his theoretical equation which indicates that the quantity of the aggregates should increase as the aggregate becomes more cubical in shape. The shape factor of the aggregate is taken into account to a certain degree by the Country Roads Board of Victoria, Australia (60-3), in that the quantity of aggregate is related to the flakiness index. This index is determined by passing individual aggregate particles through a slotted-elongated opening. (See McLeod's Design Method in the Appendix.) According to this procedure, as the aggregate becomes less elongated (more cubical or rounded in shape) larger quantities of aggregates are needed to cover the surface of the road. In all likelihood, many of the design engineers do not take the shape of the aggregate into consideration because of the complexity of the problem. Regardless of this difficulty, it is interesting to note that if the needed quantity of aggregate is determined by the test-board method, the shape and also the unit weight of the aggregate are automatically taken into account.

Regardless of the position that the aggregates have when they fall onto the road surface, the particles will tend to turn and reorientate themselves under the influence of roller compaction and traffic loads (35-1). Eventually the least dimension will be in a vertical direction. Since the aggregates in this position have their largest area on the road surface, less aggregate is needed to cover the road surface after compaction than before. Similarly, as the aggregate is reorientated, the average thickness of the aggregate becomes less than when the aggregate was first applied to the road surface. The amount of voids between aggregate particles is also decreased as the particles reorient themselves. Hanson (35-1) determined that for the aggregate he used there was approximately 50 percent voids between the aggregates before compaction. The voids in the aggregates, however, were reduced to approximately 20 percent after compaction. These are only approximate values and the exact volume between the aggregate probably varies with the aggregate shape and other factors. This change in the aggregate's orientation is important not only for determining the quantity of the cover aggregate, but also for determining the amount of bituminous material needed. If the reorientation is not taken into account in design, the excessive use of both materials will result.

Field Spread Quantity

Several factors related to the construction phase influence the spread quantity of the cover aggregate. Aggregates may be lost through excessive handling, inaccurate spreading, and/or by being shipped off by traffic after construction. These factors apparently have been considered by all investigators. However, instead of being considered separately, they are usually lumped together, and the spread quantity is obtained by increasing the basic amount by a fixed percentage. In some instances, this allowance is included in a general equation and the exact amount of increase in the quantity of aggregate is not given; however, the percent increase is usually specified.

Whip-off is the main factor that is considered. The Country Roads Board of Victoria, Australia, observed that whip-off ranged from 2 percent for large cover aggregate to 10 percent for small cover aggregate. They also observed that 5 percent should be

allowed for wastage loss that occurs during handling and shipping. Thus they believe that if the basic quantity of aggregate is increased 15 percent, the amount of aggregate ordered for the job will be satisfactory. Other investigators use 10 percent to account for all of these factors (35-1) (53-2). Hveem, et al (49-2), noted that under some conditions depending primarily on the construction conditions, at least 20 percent allowance should be made. They believed that the whip-off allowance should not be constant, but should be based on the type of spreading equipment and other factors existing at a particular job site.

Mackintosh (61-2) warns against using a large surplus of cover aggregate. Not only is loose aggregate dangerous, since it may be whipped by vehicle wheels into the air and act as a missile, but it can also actually cause the loosening of some particles of aggregate already held firmly in place by the binder. Mackintosh suggests that "... excess chips should not be applied as an allowance for whip-off. The aim should be such accurate rates of spread and spray that there is practically no whip-off." He realistically concludes, though, that an allowance should be made of a maximum of 6 percent, though 4 percent is usually enough to account for losses and imperfect workmanship (35-1) (49-2) (53-2) (54-4) (60-3) (61-2) (65-4).

DETERMINATION OF TYPE OF AGGREGATE

In addition to computing the quantity of cover aggregate needed, a designer must also determine the type of aggregate to be used. For consideration here, the factors influencing the selection of the aggregate will be divided into three groups: quality, gradation, and size.

Quality of the Aggregate

General experience has indicated that the cover aggregate particles must inherently have certain characteristics to perform satisfactorily. They should (a) be clean and dry, (b) have the ability to adhere to the binder, (c) not strip in the presence of water, (d) be durable, (e) have abrasive resistance, and (f) be economical. These factors have been covered in detail, and the discussion will not be repeated here.

Although it is desirable that the cover aggregate have all of these qualities, it may not be possible to obtain a cover aggregate that is superb in all these characteristics. For instance, some aggregates may be quite satisfactory except that they have poor abrasion resistance. A designer must then consider all locally available aggregates, weigh one factor against another, and finally select the aggregate that has the best overall quality.

Gradation

If at all possible, the designer should select a one-size or a uniformly graded aggregate for use in surface treatment construction. McLeod (60-3), for instance, restricts aggregates for use in a surface treatment to a gradation of 60 to 70 percent by weight passing the specified sieve size and retained on a sieve having an opening that is $\frac{7}{10}$ of the specified size. For example, if the nominal size of the aggregate is $\frac{1}{2}$ in., then from 60 to 70 percent of the cover aggregate must pass the $\frac{1}{2}$-in. sieve and be retained on the $\frac{3}{8}$-in. sieve which has openings that are approximately 0.7 x 0.5-in.

Specifications for the one-size aggregate should be fairly restrictive and allow little oversize or undersize aggregate. Benson (58-1) suggests a fairly restrictive aggregate gradation: the ratio of maximum to minimum size should be 2:1 with approximately 5 percent tolerance for oversize or undersize. Another restrictive specification for one-size cover aggregates is used by the Country Roads Board of Victoria, Australia, as reported by McLeod (60-3), which requires that at least 55 to 70 percent of the aggregate, depending on the top size of the aggregate, must be between the nominal sizes. For example, at least 65 percent of the aggregate must be between the $\frac{3}{4}$ and the $\frac{1}{2}$-in. screens. This agency allows a reasonable amount of overage but specifies a very restrictive underage. For instance, cover aggregate of nominal size $\frac{1}{2}$ to $\frac{3}{4}$ in. should have no more than 0.5 percent passing the No. 8 sieve.

In some areas, it is thought that the use of such closely sized cover aggregate is too expensive for normal use. In these instances, greater overages and underages are allowed. ASTM, for instance, allows 10 percent of the aggregate to be greater than the maximum nominal size and 10 percent smaller than the minimum nominal size. They also permit wider nominal sizes, i. e., ¾ to No. 4 or No. 8, while the more restrictive one-size gradation specifications require the nominal size to be ¾ to ½ in., or at the most ¾ to ⅜ in.

Since surface treatments with the more restrictive one-size aggregates have had excellent service records, the designer has to decide whether to use a more expensive, closely controlled, one-size aggregate that will have good performance or to specify a cheaper, more open-graded aggregate that will probably have poorer performance. Many times this is a difficult decision to make. The decision should not depend on the type of aggregate that has been customarily used in the past; it should be based on the conditions existing in the locality at the time the surface treatment is to be built.

Size of Aggregate

Coinciding with the selection of the aggregate gradation, the designer must decide the top size or the nominal aggregate size to be used. Usually this is not too difficult, since various conditions dictate that neither too large nor too small an aggregate be used.

Surface treatments constructed with small-size aggregates have had a history of poor performance. Use of aggregates which are too small usually leads to bleeding and serious blackening of the surface or to the loss of aggregate. This is due primarily to the difficulty in applying the correct amount of bituminous material. For instance, when using a ¼-in. aggregate the difference between the amount of bituminous material needed and the amount that will cause flushing is approximately 1/12 gal/sq yd. In comparison, for a ½-in. aggregate the difference in amount is ⅙ gal/sq yd. Likewise, there is a difference of 1/23 gal/sq yd between the amount of bituminous material needed and the minimum amount that will hold the small-size aggregate in place (60-3). Thus, little variation in the bitumen quantity can be allowed when small size aggregates are used because even a small error can have serious results.

The maximum size of the aggregate must also be considered as it influences the surface texture of the finished road. Very large-sized aggregates create irritating noises and rumbles in the cars. If these conditions are desired (as in some shoulder construction and stopping lanes), aggregates greater than ¾ in. should be used.

Usually, the aggregate chosen is the largest size that will provide the desired surface texture. For normal conditions, where rumble is not desired, ½ to ¾-in. aggregates are used with heavy traffic, and ⅜-in. aggregates with lighter traffic. These sizes may be increased slightly if the old road surface is relatively soft and would allow some embedment of the aggregate (35-1) (49-2) (58-1) (60-3).

DETERMINATION OF QUANTITY OF BITUMINOUS BINDER

In most of the design procedures, calculations are made to determine a basic amount of residual bituminous material. This is the exact quantity or the optimum amount needed for the aggregate used. The basic quantity, though, must be modified to adjust for existing road conditions and construction practices. Thus, the amount of bituminous material to be sprayed from the distributor is usually different from the calculated optimum amount of bituminous material.

Basic Quantity

Basis of Quantity Determination—Although some engineers do not mention the basic idea they used in determining their design methods, the majority think that fundamentally the quantity of bituminous material needed is that amount required to fill the voids between the aggregate to an optimum depth (Fig. 4). This basic principle of surface treatment design was first stated by F. M. Hanson in 1935 (35-1). It is so simple and logical that most of the later design methods also utilize this idea.

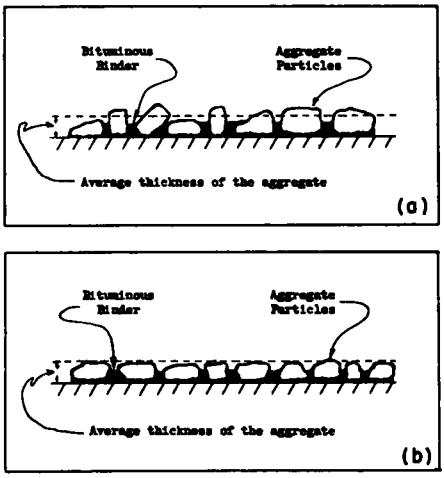

Figure 4. Cross section of a surface treatment: (a) immediately after application of the cover aggregates and (b) after compaction when the aggregates are in their final position (taken from McLeod, 60-3).

Since the amount of bituminous material required is dependent on the volume of the voids in the aggregate, this volume must be determined. Hanson observed that the aggregate particles, when first dropped on the asphalt surface, are oriented in various directions (Fig. 4a). In this state, the volume of voids is approximately 50 percent. After rolling and even under traffic loads, the aggregates tend to reorientate themselves so that they present their least dimension in the vertical direction (Fig. 4b). Under these conditions, Hanson reported that the voids between the aggregates will be approximately 20 percent. Hanson and other engineers (60-3) indicate that this relative void volume (20 percent) is independent of the size of the cover aggregate, regardless of whether it is ¼, ½, or ¾ in. in size. (It is probable, though, that this void space is dependent on the shape of the aggregate, but no data have been presented.)

Other investigators think that the percentage of voids between the aggregates is not a constant, but varies with the character of the aggregate. Several engineers (53-2) (58-1) (61-2) determine the volume of the voids by first compacting the aggregate in a large cylinder. Kearby (53-2) and Benson (58-1) weighed the aggregates and computed the percent voids from the loose unit weight of the aggregate. Mackintosh (61-2), on the other hand, measured the volume between the aggregate particles in the cylinder by measuring the quantity of water needed to fill the voids. In both cases the assumption is made that the aggregate in the one-stone thick layer on the road surface will have the same arrangement and voids as it will have in the cylinder. This assumption is very likely not true. Benson (58-1) even acknowledges that this assumption is incorrect, but he uses it nevertheless.

Once the volume of the voids between the aggregate has been determined, it can be multiplied by the depth (in percent) the aggregate must be embedded in the bituminous material to determine the volume of the binder needed. Some engineers actually compute the total volume of the voids and then use the percent of embedment to calculate the volume of the voids to be filled with binder (35-1) (53-2) (60-3) (61-2). Other engineers use a formula, in which the quantity of binder needed is related directly to the average size of the aggregate. In these cases they must assume an average percent voids and a constant percentage of voids to be filled (49-2) (53-5) (54-4) (55-5) (62-1). Regardless of the methods used, the engineers relate the volume of the bituminous material needed to the aggregate characteristics and to the type of traffic.

Influence of Size of Aggregate—Usually, the quantity of voids to be filled or the amount of aggregate to be embedded in the binder is directly related to the size of the aggregate. Almost all of the engineers assume that the quantity of bitumen required varies directly with the size of the aggregate. That is, a ½-in. aggregate will require twice as much binder as a ¼-in. aggregate.

Likewise, most engineers think that the amount of embedment of the aggregate in the bituminous material, percentagewise, should be a constant. For example, the ½-in. aggregate should be embedded the same percentage as the ¼-in. aggregate. Hanson (35-1) indicates that this percent should be 50 to 70 percent of the aggregate size, i.e., the 20 percent void space should be filled 50 to 70 percent. Other designers do not indicate the exact percentage of embedment as it is included as a constant with the volume of the voids. For instance, Lovering (54-4) indicates that the amount of bituminous material needed (in gal/sq yd), is equal to 0.4 times the size of the aggregate (in in.). The constant (0.4) accounts for the volume of the voids in the aggregate and for the percentage of embedment of the aggregate.

The majority of the designers assume that the quantity of binder needed is directly related to the size of the aggregate. There are two investigators, however, who indicate otherwise. Kearby (53-2) and Benson (58-1) relate the percentage of embedment to the size of the aggregate (Fig. 5). For aggregate sizes greater than ½ in., the percentage of embedment increases almost lineally with the aggregate size. However, for the smaller size, this relationship is no longer linear, but tends to become almost a constant. For instance, a 1-in. aggregate should be embedded 50 percent, whereas a 0.7-in. aggregate should be embedded 40 percent, and a ¼-in. aggregate 31 percent. It is interesting to note that these engineers suggest a percentage of embedment to be between 30 to 50 percent depending on the aggregate size. McLeod (60-3), however, suggests values which are considerably greater. These two engineers think, unlike the other engineers who believe that the quantity of binder varies directly with the size of the aggregate, that the binder quantity should increase in increasing amounts as the aggregate size becomes larger.

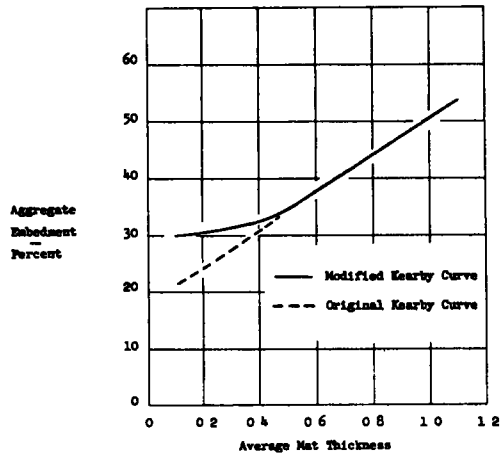

Figure 5. Relation of percent embedment to average mat thickness for determining quantity of asphalt (data taken from Benson, 58-1).

Influence of Shape of Aggregate—Although engineers have noted that the shape of the aggregate influences the amount of bituminous binder needed, it appears that few design methods take this aggregate characteristic into account. In all likelihood, as the shape of the aggregate is varied, the volume of voids between the aggregate is altered, and the amount of binder needed is changed. When the shape factor is considered in the design methods, it is not used to determine a revised void content, but to modify the average size of the aggregate.

Kuipers (55-5) uses a formula for computing the bitumen content in which the average size of the aggregate is multiplied by a factor related to the shape of the aggregate. Values quoted by him indicate that the shape factor should increase as the aggregate shape becomes more rounded. Thus, the "effective" average size of the aggregate is increased as the aggregate becomes more rounded.

The Country Roads Board of Victoria, Australia, as reported by McLeod (60-3), used the flakiness index to modify the medium size of the aggregate. (See Fig. 12 in the Appendix.) Normally, rounded aggregate has a smaller flakiness index than crushed stone. As the flakiness index of the aggregate becomes less, the medium size of the aggregate is modified so that a larger size of the aggregate is used in the design. That is, for aggregate of the same gradation, as the aggregate becomes less angular, the average least dimension of the aggregate increases.

In both of the previously cited design methods, the size of the aggregate to be used in the design calculations increases as the aggregate shape becomes more rounded. This means that the engineers believe that rounded aggregates require more bituminous material than crushed cover aggregate. The change is not an appreciable amount, but it can vary from 6 to 10 percent. The aggregate shape, though, should be considered in designing surface treatments, since a variation of 10 percent in the binder content, when small size aggregates are used, can result in failure of the surface treatment.

Influence of Porosity of Aggregate—Many of the designers note that the quantity of bituminous binder used should vary with the porosity of the aggregate. It appears that few engineers actually take this factor into account. If they consider the factor, they usually follow McLeod (60-3), who suggests that the amount of binder should be increased 0.03 gal/sq yd for a soft, absorptive limestone.

TABLE 2

COMPARISON OF QUANTITY OF BINDER NEEDED AS DETERMINED BY DIFFERENT DESIGN METHODS

Design Method	Quantity of Binder (gal/sq yd)
American Bitumuls	0.22
California	0.23
Kearby	0 28
Linckenheyl	0.19
Lovering	0.23

The California Design Method includes a variation in the porosity in the design method (see Appendix). A nomograph indicates that as a surface factor (K_c) is increased, the amount of bituminous material needed is also increased. Since the surface factor is determined by the centrifuge kerosene equivalent test, it is related directly to the porosity of the aggregate; thus, those aggregates with greater porosity require greater quantities of bituminous binder.

The amount of bituminous binder that will be absorbed by an aggregate also depends on the consistency of the binder and, thus, on temperature. Therefore, if a porous cover aggregate is placed on a layer of binder that is relatively cold, it will not absorb an appreciable amount of binder initially. However, when the temperature of the binder is increased, the aggregate will absorb more binder material. In some instances, what may appear to be an excess of binder may not actually be an excess when the aggregate has absorbed the warm binder. Because of this problem, some engineers suggest that porous aggregates should be avoided whenever possible.

Influence of Traffic—Traffic volume is used as a factor in computing the needed bitumen content in only a few design methods (35-1) (55-5) (60-3) (61-2). This does not mean, however, that it is a factor that is not considered by other engineers. For example, even though they do not include it in their design methods, at least two engineers (49-2) (53-2) note that it is a factor that should be considered, but indicate no method of taking this factor into account.

In all of the design methods that include the traffic volume in the design procedures, the amount of bituminous material needed is decreased as the traffic volume is increased. This allowance is made in recognition of the fact that under very low volumes of traffic not all of the cover aggregate particles will be completely reoriented so that they occupy the maximum area on the road surface. In other words, the void space between the particles of the cover aggregate when subjected to very light traffic is not reduced to the minimum amount and therefore greater amounts of bituminous material can be used. However, as the traffic volume increases, more and more particles are reoriented, and the voids between the aggregate are decreased; thus, less amounts of the bituminous binder must be used to prevent over filling of the voids and subsequent bleeding of the surface.

The manner of taking the traffic factor into account differs with various design procedures. Mackintosh (61-2) reduces the percentage of embedment of the aggregate as the traffic volume increases. McLeod (60-3), on the other hand, reduces the percent of the voids that can be filled. Kuipers (55-5) uses a formula for computing the amount of the bituminous material and includes a factor that increases the amount of the binder as the traffic volume is decreased.

The amount of the reduction of the bituminous material as the traffic increases also varies with the design method. In general, the voids between the aggregates on a road with medium traffic volume (greater than 2,000 vpd) must be filled with 28 to 40 percent less binder than on a road that will be subjected to very light traffic (less than 100 vpd). Although a surface treatment might not ordinarily be used for heavy traffic (greater than 15,000 vpd), if it is used, the reduction should be 50 to 60 percent of the quantity used for the very light traffic conditions.

Comparison of Basic Quantity of Binder as Determined by Different Design Methods—For those design methods that utilize the aggregate gradation for determining the average size of the aggregate, the basic quantity of binder has been computed. The gradation used was that given in the Appendix in the example of the procedure of the California Design Method. The quantities computed are given in Table 2.

There appears to be considerable variation in the design quantity of bituminous binder. The difference between the maximum and the minimum amount is almost 50 percent and there is over 20 percent variation between the average of all of the quantities and the extreme quantity. These large variations primarily indicate that all of the

factors influencing the binder quantity are not considered or, if they are included, the factors are not considered correctly.

Quantity of Bituminous Material To Be Sprayed

The amount of bituminous material that is to be sprayed from the distributor is not the same quantity as the basic amount normally computed by the different design methods. The basic quantity must be modified to adjust for conditions that exist at the construction site. These are in the order that the correction should be made: (a) condition of the underlying surface, (b) type of liquid bituminous material used, and (c) volume change in the bituminous material as it is heated for spraying.

Condition of Underlying Surface—In determining the basic quantity of the bituminous material, no allowance is made for that portion of the binder that will be absorbed into the existing road surface. In general, this allowance is made by adding or subtracting from the basic quantity a specified amount of the binder that is dependent on the road condition. For instance, Benson (58-1) suggests that no correction be made for freshly primed bases or seals on normal bituminous surfaces. However, if the surface is porous and cracked, an allowance of 0.05 to 0.10 gal/sq yd should be made for absorption. Similarly, on an existing rich surface or on a very heavily primed surface, a reduction of up to 0.05 gal/sq yd in bitumen should be made. Other design procedures specify corrections of similar amounts.

Hanson (35-1) reports that there should be little absorption of the bituminous material by the underlying surface. If the surface does absorb part of the binding material, then (a) the surface may not be fit to seal, or (b) the surface may need to be primed first, or (c) the binder may be too thin (in which case it will not hold an appreciable amount of cover aggregate). However, he does not mention what should be done in case the existing road surface has an excess of bituminous material.

Type of Liquid Bituminous Material—The basic amount of the bituminous binder is the amount of residual bitumen that must be used in the surface treatment construction. If the bituminous binder is an asphalt cement, then the quantity of asphalt cement needed is the basic amount corrected for the conditions of the underlying surface and volume change. However, if the bituminous material is a liquid, allowance must be made for the evaporation of solvents from cutbacks or water from emulsions. This is normally done by dividing the amount of residual bituminous material needed by the percent of the residual bituminous material needed by the percent of the residual bituminous material in the cutback or emulsion.

Volume Change in Bituminous Material—Regardless of the type of bituminous binder used (asphalt cement or cutback), it must be heated to a suitable temperature for spraying. Since the basic quantity of binder needed is determined in terms of its volume at 60 F, a final correction must be made to account for the volume change produced as the binder is heated to spraying temperature. This can be done by using the common temperature-volume correction tables for asphalt materials or by assuming the coefficient of expansion of the material to be approximately 0.00035 per deg F. The final corrected amount is the quantity of bituminous material that the distributor should spray on the underlying surface (35-1) (49-2) (53-2) (53-5) (54-4) (55-5) (58-1) (60-3) (61-2).

DETERMINATION OF TYPE OF BINDER

Factors which should be given considerable consideration when attempting to select the correct binder material for a specific surface treatment operation are discussed in the following. No one grade or type of bituminous binder will satisfy all of the requirements for every project due to the wide variations in the factors.

A brief discussion of the types of bituminous binders currently used is also given. Primarily, the advantages and disadvantages of each of the different types are discussed.

It is unfortunate that an analytical design method is not available that takes into account all of the factors and indicates the correct type of binder to use. The only analytical method available utilizes just two of these factors. This means that at present the choice of the type of binder to be used is an engineer's decision based primarily on personal experience.

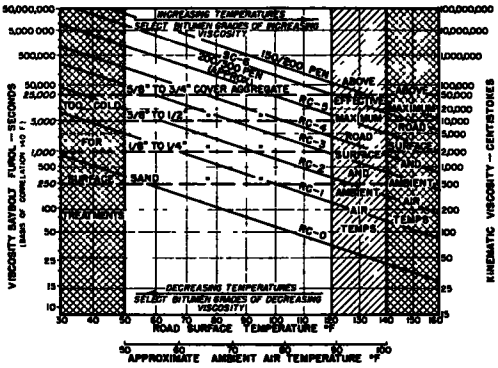

Figure 6. Influence of road surface temperature and size of cover aggregate on selection of bituminous binder for surface treatments or seal coats in Canada (data taken from McLeod, 60-3).

Factors Influencing Selection of Binder

Temperature—Once the binder is applied to the existing surface, its temperature is influenced greatly by that of the air and/or the road surface. Consideration of the air temperature is important because it directly influences the rate of curing of the binder. On warm days the binder will cure rapidly; on cold days the binder will cure slowly.

The temperature of the road surface is an indication of the viscosity of the binder at the time of application of the cover chips. Within one minute after application, the binder reaches the same temperature as the road surface (58-7). McLeod (60-3) indicates that desirable road surface temperature should be 60 to 130 F and that the temperature is related to an air temperature range of 50 to 90 F. Below 60 F, the binder will be too viscous to develop rapid initial adhesion with the aggregate. Above 130 F, the pavement surface will be so hot that the binder will not develop the adhesion and strength needed to hold the aggregate in place. The wettability as well as the strength and adhesiveness of the binder are directly dependent on the temperature of the road surface (52-3) (58-7) (60-3).

Viscosity—The viscosity of the binder at any time is a function of temperature. As such, it also influences the ability of the binder material to adhere to the chips and hold them in place. At low viscosities (i. e., high temperatures) the binder does not develop sufficient strength in a relatively short period of time to hold the chips in place. This is particularly evident on superelevated curves, grades, and under heavy or fast moving traffic. On the other hand, high viscosities do not permit proper adhesion of the chips to the binder because of the inability of the binder to wet the chips thoroughly.

McLeod (60-3) has developed some charts which "enable an engineer to select the correct grade (viscosity) of asphalt binder for a surface treatment or seal coat, for any specified size of cover aggregate, and for any existing road surface temperature or ambient air temperature in the shade." It is believed that McLeod's approach and the ideas he reported are good and therefore warrant explanation herein and future development as he suggests.

The design and construction requirements for successful performance impose two conflicting demands upon the binder material: (a) rapid initial adhesion between the aggregate and the binder (low viscosity), and (b) retention of the cover aggregate in place when the finished surface treatment is opened to traffic (high viscosity). A compromise between these requirements must be made since they are opposed to each other. McLeod reports that for Canadian climatic conditions and for one-size cover aggregates of 3/8 to 1/2-in. size, the compromise viscosity is about 10,000 centistokes or 5,000 sec Saybolt Furol. However, the value of the compromise viscosity varies with the size and type of aggregate as well as with the climatic conditions and, therefore, must be determined for particular areas or regions of the country.

Figure 6 is a typical McLeod chart for determining the proper grade and type of bituminous material at any road surface temperature so that the material will meet its two important viscosity functions. The chart consists essentially of temperature-viscosity curves for various grades of rapid-curing cutback asphalt. These curves can easily be determined in the laboratory. If the log-log of the kinematic viscosity is plotted against temperature on a linear scale, a linear relationship is found to exist between temperature and the viscosity. For any grade of cutback asphalt these relationships are practically independent of source or method of manufacture. This is not true, however, for asphalt cements. Asphalt cements from different sources probably have different viscosity-temperature curves. These curves, however, should be approximately parallel and lie grouped within specific bands of considerable spread. This

relationship has led McLeod to make the statement that "it is preferable to specify an asphalt binder requirement in terms of a viscosity-temperature curve rather than a penetration range at 77 F, when selecting asphalt cements for surface treatments and seal coats."

McLeod's charts are applicable for road surface temperatures in the shade in the range of 50 to 120 F. Below 50 F, the road surface is too cold for surface treatment construction and the binder will harden before it adheres to the aggregate as it should. A temperature of 120 F has been taken to be the practical maximum temperature that will occur for Canadian conditions. Occasionally a road surface will reach a temperature of 140 F; if it does, the viscosity of the binder will be so thin that it will not properly bind the aggregate to the underlying surface.

According to Figure 6, for a specific road temperature, McLeod suggests that as the aggregate size increases, the viscosity of the binder should also increase. In other words, it is thought that stronger binder (higher viscosity) must be used for the larger size aggregate.

To use McLeod's charts one merely has to determine the prevailing road surface temperature, proceed vertically upward at this temperature until the intersection with the compromise viscosity line for a particular size aggregate is reached, and then note which binder material's temperature-viscosity curve passes closest to this intersection. The binder whose temperature-viscosity curve is nearest to the intersection of the temperature and compromise viscosity lines is the desired material to be used for surface treatments because it best meets the conflicting demands placed upon it.

It is possible that the value of the compromise viscosity for a particular aggregate size is not constant with increasing road surface temperature. That is, the compromise viscosity curve need not be horizontal as shown in Figure 6. McLeod, however, assumes the horizontal relationship does indeed exist and developed this figure accordingly.

McLeod also reports that rapid-curing cutback asphalts, as used in the example figure, meet the viscosity demands quite well. They can be made quite fluid by addition of cutterstock (gasoline) and can provide the required rapid initial adhesion between cover aggregate and binder. The rapid-curing cutback asphalts also harden faster than other cutbacks after application to the road surface because of rapid gasoline evaporation. As a result, this material is better able to retain the cover aggregate under traffic stresses.

The use of McLeod's charts (60-3) is limited to certain areas or regions of the country. A universal set of charts has not been developed because of variations in conditions and materials at different locations. McLeod, however, suggests that it would not be difficult to make a set of charts for use in a particular area (53-1) (58-7) (60-3).

Climatic Conditions—Climatic conditions, other than the temperature at the time of construction, affect the choice of the binder used on a particular job. One of the most detrimental of these conditions is the presence of moisture. Cutback asphalts are seldom used in damp climates because they are difficult to cure in the presence of moisture. Emulsions can be used satisfactorily since the adhesive qualities are not affected by the presence of small quantities of water; however, no material can be expected to perform well when placed in rainy weather or in the presence of excessive moisture.

Humidity and wind currents at the time of application of the binder affect the rate of curing of the bituminous material. When the wind movements are extensive, more volatiles are removed from the surface of the pavement, and thus the curing rate increases. High humidity, though, causes a decrease in the rate of curing. This is due to the evaporated cutterstock molecules that tend to remain close to the pavement surface on humid days and provide a protective cover layer (48-3) (58-7).

Underlying Surface—Some consideration should be given to the condition of the surface to be covered. If the surface is badly cracked or spalled, the binder should have a fairly low viscosity to fill most of the voids and still retain a uniform surface. It must be remembered, though, that since a surface treatment is only one particle thick, it is impossible to use only a single surface treatment on a badly faulted or rough surface. Leveling courses are needed at such locations (60-3).

Cover Aggregate Size—As the size of the cover chips increases, the strength of the binder material required for retention of these chips increases

(58-7). This idea is related to the surface area of contact of the particles. Large particles of irregular surface area do not provide as intimate a contact with the existing surface as do small chips. This means that the viscosity needed to retain the chips after opening the job to traffic will have to be greater as the chip size increases. A constant value for viscosity cannot be established (48-3) (51-1) (58-7).

Traffic Type and Speed—The type and speed of traffic using the completed surface will greatly influence the type of binder material to be used. Fast-moving, heavily loaded, tandem-axle vehicles are currently the type of vehicle most detrimental to successful seal coating. As the speed increases, the adverse effects also increase. To accommodate the heavier traffic, it is essential that the binder develop sufficient cohesion to retain the aggregate chips before opening to traffic. The use of heavier grades of liquid asphalt and probably asphalt cements is required to meet this requirement (58-7).

Curvature of Alignment—The curvature of alignment influences the selection of the binder by being related to the influence of traffic on the pavement. That is, traffic will have a more detrimental effect on curved pavements than it will on straight pavements due to side-slip, acceleration and deceleration. Under these conditions, the binder will have to develop sufficient cohesion to resist the traffic forces. This necessitates the use of harder binders (58-7).

Methods of Construction—All binder materials do not adapt themselves to the same construction procedures. The methods of construction to be used for a particular seal coating operation, therefore, must be considered when selecting an appropriate binder material. In addition, equipment available for use also influences selection of the binder.

Economical Aspects—The original cost of the binder material is one of the prime factors influencing selection. Naturally, costs cannot be prohibitive at the start. The average maintenance cost of the pavement per year of service cannot be prohibitive either. Some compromise must be reached between the initial cost of the materials, the maintenance cost, and the performance desired. Although a surface treatment is a low-cost type of facility, the many miles of this type of treatment being placed today almost demand that the economical aspect be considered (51-1).

Past Experience of the Design Engineer—Past experience is often useful and necessary when selecting the proper bituminous material to be used under unusual conditions. Better results can be obtained by an engineer who knows the behavior of a certain material under various conditions than can be obtained from an inexperienced engineer. As the engineer's experience increases, he is able to handle unexpected situations that arise with more ease and greater efficiency.

Individual Likes and Dislikes—The individual likes and dislikes of the engineer who is in charge of the surface-treating operation must be considered. If for instance, the individual has, at one time or another, experienced an unsuccessful job using one particular type of binder, he is likely to "blackball" that material. This attitude is human nature and difficult to correct. Under one set of conditions a certain binder may be undesirable, but under another set of conditions it may function more than satisfactorily. It is up to the engineer to decide which material can be used under the particular conditions. Past experience, when considered objectively, can greatly aid in obtaining the correct decision (58-7).

Types of Bituminous Binders

Generally speaking, there are two basic categories of bituminous binders: asphalts and tars. When taken as a group, tars have better adhesive properties than asphalts, but asphalts are more cohesive and less susceptible to temperature changes than tars. Each material has distinct advantages and disadvantages. Neither material is far superior to the other for all conditions encountered during the pavement life.

Several types of commercially produced asphalts as well as tars can be used for surface-treatment purposes. The advantages and disadvantages of each of the principal bituminous binders used today are discussed in the following material.

Asphalt Cement—Of all of the bituminous binders used for surface treatment construction, the asphalt cement is perhaps the best. Primarily, this material hardens quickly so that the aggregate is held in place better and thus there is less chance of the aggregate being dislodged by early traffic. In addition, it provides a very hard residue capable of developing high cohesive strengths. Also, asphalt cement has less tendency to bleed and its use provides a relatively impervious seal for the existing pavement surface. All of these desirable qualities help insure a surface treatment of long life.

The use of asphalt cement as a binder has several disadvantages. In some instances, it may be difficult to get the aggregate bonded to the asphalt cement binder. This is especially so if the underlying surface is too cold and causes chilling of the asphalt cement before the aggregate can be spread and compacted into the asphalt. This disadvantage can be eliminated by preheating the cover aggregate prior to its application. Adequate bonding is also difficult to obtain if dirty cover material is used or if the underlying surface is not thoroughly clean.

If the existing pavement has minute cracking, the asphalt cement binder will not penetrate into these void spaces. However, if cracking is extensive, the large cracks will be filled with this material, and thus an improved, new-wearing surface is provided (35-1) (47-1) (53-1).

Asphalt Cutbacks—Asphalt cutbacks are discussed in the following three categories.

1. Rapid-Curing Cutbacks. Rapid-curing cutbacks generally do not dry quickly enough to be the most desirable for surface treatment use. The curing time may be relatively short, but some time does elapse before the curing is completed. Under the action of heavy traffic, the rapid-curing cutbacks are often tracked and the cover aggregate easily displaced. However, once the curing has been completed, this cutback is an excellent binder. Primarily, this is because the material affords excellent cohesion because of its relatively hard base asphalt (80 to 120 penetration). Not only is an impervious seal provided when this material is used, but also good binding to a bituminous surface is afforded whether that surface is smooth, dusty, or clean so long as proper traffic control is exercised during the initial curing period.

In comparison with medium-curing cutbacks, the rapid-curing cutbacks are more suitable for surface treatment operations. They "set up" faster and do not have the tendency to continue migration into the existing surface as do the medium-curing cutbacks. (41-3) (47-2) (58-9).

2. Medium-Curing Cutbacks. Medium-curing cutbacks have been used in many instances for seal coating operations with successful results. If used properly and under good conditions, they perform quite satisfactorily. With enough time, relatively good cohesion is developed and an impervious seal is provided. They are also very useful for salvaging and resealing old, hair-cracked bituminous pavements. If the cutback is sprayed on the surface without delay, almost all of the original material reaches the road and the kerosene cutterstock immediately begins to soften the old surface. In this way, the cracks may be closed, and the surface is rejuvenated.

Many engineers, however, do not care to use medium-curing cutbacks for surface treatments. These cutbacks may allow aggregate to be displaced quite readily, especially immediately after construction before the cutback is completely cured. On the other hand, if construction is not influenced by traffic, the "slow" rate of curing is not particularly objectionable. Indeed, under such conditions the longer time period for curing is even advantageous since laydown and rolling times are less critical than those for rapid-curing cutbacks.

The medium-curing cutbacks many times have flushed excessively under heavy traffic and have produced slippery surface conditions. The lower viscosity cutbacks of this group (MC-0 and MC-1) also have a tendency to migrate into the existing surface. Such action commonly produces undesirable voids in the surface layer and often causes premature failure of the treatment (35-1) (47-1) (53-1).

3. Quick-Drying Cutback. Some "special" cutback asphalts have been made for the sole purpose of use in surface treatment operations (47-1). One such material is known as the quick-drying cutback asphalt. The exact composition of this material was not given. However, the author reported that a more volatile dilutent than that found in

regular rapid-curing cutbacks was used. Also, the quick drying was aided by the use of harder base asphalts. The main advantages to this "cutback," as reported by the author, is that it cures very rapidly and does not readily allow displacement of the aggregate under early traffic action (47-1).

Asphalt Emulsions—Asphalt emulsions are easy to handle and can be placed in and pumped out of storage without heating. In addition, no heating is required in the field for application purposes, and thus there is no fire hazard or resulting danger to workmen. A major advantage is that wet or damp aggregate is not objectionable. A clean cover material, however, must be used. Care must be taken that the cover material is spread immediately after the application of the emulsion to insure proper wetting or coating of the aggregate with the asphalt.

Asphalt emulsions are of such character as to require experienced personnel to apply them even under excellent conditions. They have questionable penetrating qualities and may not bond well with smooth surfaces (47-1). Under certain conditions, emulsions may react with certain soils and break prematurely. This creates a condition where the cover material will not adhere to the surface and the aggregate is readily thrown off by traffic. Under favorable drying conditions, emulsions develop strength quickly. However, applications should not be made toward evening, in very humid weather, or during cold temperatures, since the rate of drying will be reduced and traffic will have to be kept off for longer periods of time. Ordinary emulsions of Saybolt Furol viscosity 20 to 100 sec have a tendency to run off the road on steep grades and/or superelevated curves (49-2). This action does not provide uniformity of binder for application of cover material and results in serious raveling, flushing, and bleeding (47-1) (40-2) (49-2) (58-9) (63-1).

Tars—When prepared to the correct grade and consistency, tar is an excellent prime material (35-1). It is also a very good surface treatment material where a mineral aggregate cover coat is applied.

The main advantages of tars as binder material for surface treatments are good penetration qualities and ease of mixing with damp aggregate. Tar adheres as well as any other bituminous material to a macadam road and it will hold chips equally as well as the commonly used road oils (35-1). In addition, a slightly dusty road surface is not detrimental so long as sufficient tar is applied to cut the dust and hold the chips. Less stripping in the presence of excessive, continuous moisture usually occurs with this material than with asphalts (41-3).

Tars are quite susceptible to temperature changes—much more so than asphalts. They become soft when subjected to very warm conditions and brittle when cooled considerably below "normal" conditions. In hot weather, this material may bleed excessively and may require a great deal of sanding. Within a few years after placement, some tars tend to oxidize and become brittle under the action of air and sunlight. In addition, tars are generally more expensive than asphalts (35-1) (41-3) (47-1) (64-3).

DESIGN OF DOUBLE AND TRIPLE SURFACE TREATMENTS

Even though a large percentage of the surface treatments constructed are multiple-layered, there are few methods for determining the quantity of aggregate and binder needed for each layer of this type of surface treatment. In addition, there is little discussion of this type of bituminous construction in the literature. When it is covered, the discussion is usually general in nature, listing ranges of quantities of aggregate and binder to be used. For instance, McLeod (60-3) presents a table for double surface treatments (Table 6 in the Appendix). The data for this and similar tables were obtained from experience on a number of construction projects, and the exact quantities to be used will vary between jobs.

A slightly different approach is taken by Benson (58-1) who suggests that the design of multiple surface treatments be related to the quantities determined for a single surface treatment. He suggests the size of the aggregate for multiple surface treatments be selected to give approximately a 2:1 ratio between the first course and the second course of cover aggregates. For instance, if a ½ to ¾-in. aggregate is used for the first layer, the second layer should have a size of approximately ¼ to ⅜ in. The quantity

of cover aggregate for the second course should be determined in the same manner as the first course, i. e., the amount needed to cover an area one stone thick. This assumes that the aggregate will be placed as close together and in the same manner in the second course as in the first course. He also suggests that the proper bitumen quantity for double surface treatments should be 130 to 140 percent of that required for a single surface treatment as determined by an acceptable design method. For triple surface treatments, he suggests that the percentage be changed to 140 to 150 percent. According to Benson, the manner of distribution of the bituminous applications between the various courses does not seem to be particularly important.

A more analytical method of designing double surface treatments is suggested by Wood (59-4). This method is essentially an extension of a design for a single surface treatment (similar to Benson) with a number of modifications. The procedure is only applicable to a particular cover aggregate used in Texas as the author assumes that 1 cu yd of the aggregate for the second course will cover 210 sq yd. Additional assumptions are that this aggregate (for the second course) fills the upper voids of the first application of aggregate, that the thickness of the final construction is equal to the thickness of the first layer of cover aggregate and that the amount of air voids in the final construction will be 5 percent. The amount of binder needed is based on a volume percentage. This percentage is not a constant, but decreases as the amount of traffic increases. The author also recommends that 40 percent of the binder be applied in the first application and 60 percent in the second. Although the use of this method is severely restricted in its present form, the ideas behind the method should be used as a guide to the development of future, more desirable, design methods (55-4) (58-1) (59-4) (60-3).

Chapter Five

CONSTRUCTION METHODS

Many times a major portion of the failures or poor performance of surface treatments can be attributed to improper selection and condition of equipments and to poor construction techniques. Various investigators have studied this subject, and many construction procedures have been adopted to overcome a number of the constructional problems. However, there is a fairly standard sequence of operation in the construction of surface treatments that is appreciably the same in most areas. Some variation in these operations might be expected due to local experience, conditions and material (41-1) (49-3) (55-3) (57-6) (58-1) (58-10) (59-5) (60-3) (60-7).

CONSTRUCTION TECHNIQUES OF SINGLE-LAYER SURFACE TREATMENTS

The steps normally followed in the construction of seal coats and surface treatments are discussed in the following sections.

Preparation of Underlying Surface

The surface to which a surface treatment is applied should, except in extraordinary cases, always be cleaned and usually repaired before any bitumen is applied.

Repair—Patching is an essential operation in the treatment of surfaces that contain holes and depressions, and show base movement, serious cracking, or serious bleeding due to asphalt flushing to the surface. If such weak spots are not corrected, the surface treatment will almost immediately fail under traffic. Repair of such irregularities is carried out by removing all the loose and defective material to sufficient depth and replacing it with a suitable patching mixture or base material. The newly added material must be compacted to a high density so as to produce a tight surface conforming to the adjacent areas. Any waves or bumps which reduce the riding qualities of the pavement should be removed by such means as discs or heated planers, depending on the type of the underlying surface.

Cleaning—To develop a strong bond between the underlying surface and the surface treatment, the surface should be free from loose foreign materials such as sand, clay, dust, and dirt. Leaves, especially, should be removed from the surface. Revolving mechanical sweepers are usually used to remove these foreign materials. (In some instances, the cleaning operation has been carried out by flushing the surface with water.) If, however, mechanical sweepers are not available, the foreign materials can also be removed by hand brooms and picks, if necessary. The sweeping is done over the full width of the pavement.

Binder Application

Techniques of Application—Viscosity or fluidity of the bituminous binder at the time of application is a crucial factor in the proper distribution of the binder, and hence, in the overall performance of the surface treatment. The viscosity ranges suggested by different investigators are not in agreement. The lowest viscosity, ranging between 15 to 25-sec Saybolt Furol, has been used in Victoria, Australia, with satisfactory results (60-3). However, in North America, Saybolt Furol viscosities in the ranges of 25 to 100 and 25 to 50 sec have been recommended by the Asphalt Institute (60-7) and McLeod (60-3), respectively. Kearby (53-2) and many other authors have suggested that the binder should be applied with the viscosity of 40 to 60-sec Saybolt Furol.

Before the bituminous binder is sprayed onto the prepared surface, the length of spread should be determined. Knowledge of this length is important to the subsequent

proper placement of the aggregate and the development of desirable performance properties of the surface. If the length is too short, efficiency in placement is lost. If the length is too long the binder may chill before aggregate placement and cause poor bonding between the aggregate and the binder. Either case will result in added expense of construction.

The length of spread will vary depending on (a) the type of bituminous material used, (b) base conditions, (c) climatic conditions, and (d) the ability of the contractor to furnish the required materials and equipment to maintain uniform aggregate spreading and adequate rolling of the aggregate. Good engineering judgment and past experience are important in determining the spreading length.

Often bumps or bleeding surfaces will result when succeeding binder applications are not properly placed. To avoid bumpy transverse joints caused by the overlapping of the binder at the junction of two applications, the binder distribution should be started over a 3-ft width of building paper rolled across the pavement. By this technique, not only will the binder be prevented from overlapping, but also any nonuniform application of the binder on starting or stopping the spraying will mar only the building paper. This paper should later be removed and destroyed. At the end of the spraying, instead of building paper, drip pans are sometimes used to prevent dripping on the pavement. When the bituminous binder is applied in two or more longitudinal strips, each strip overlaps the preceding one by one-half the width of the spray from the end nozzle. If the bituminous binder cannot be applied over the full width of a two-lane highway, special guiding equipment should be attached to the distributor to guide it along a straight line marking the traffic lane division.

Bituminous Distributor—To insure the best performance, the distributors used in seal coat constructions, regardless of make and model, should be equipped with the following major parts and instruments and should be properly adjusted, inspected, and operated.

1. Distributor Pump. The ideal spray fan should be a solid sheet of bituminous material, which can only be formed when the material is pumped out under the proper pressure or pump speed. Positive-displacement-type pumps are most suitable for pumping binder since the flow to the spray bar is steady at all times regardless of the head or volume of the material left in the tank. Centrifugal pumps should never be used, because the material pumped to the spray bar varies with the head in the tank, and the rate of distribution decreases toward the end of the shot.

Distributors must be equipped either with a pressure gage or a pump tachometer to regulate the rate of distribution according to the correct pressure or pump speed. Some distributors are equipped with pressure-regulator valves, instead of a pressure gage, that are controlled by the operator. To obtain the proper setting for the pump, the speed or pressure should be increased in increments to as high as possible without distorting the spray fan or atomizing the spray. Care should be taken that the pump has enough clearance to operate freely so as to prevent freezing or breakdown in the pump.

2. Spray Bar. The binder is transferred under appropriate constant pressure through the spray bar to the nozzles. To insure a uniform pressure in the nozzles, a full circulating spray bar is most desirable. For clean and even startings and stoppings of shooting without dripping, suitable valves are used to control the flow of material.

The height of spray bar from the road surface must be adjusted to provide the desired overlapping of application sprays. If improperly adjusted, there is the danger of streaking, which will result in bleeding or a loss of the aggregate. The height of the spray bar should remain constant and parallel to the surface throughout shooting. However, in the actual operation, it sometimes varies due to the deflection of the springs as the load is discharged. To limit such variation to within one-fourth inch, either stiffer springs are used, or the frame is tied down to the axle during the discharge. This adjustment may also be achieved by reducing the load for each pass so as to cause a negligible deflection. In addition, if the full width of a two-lane pavement is being sprayed, every nozzle of the spray bar should be at equal distance from the pavement. Thus the spray bar should be adjusted to accommodate the crown of the pavement.

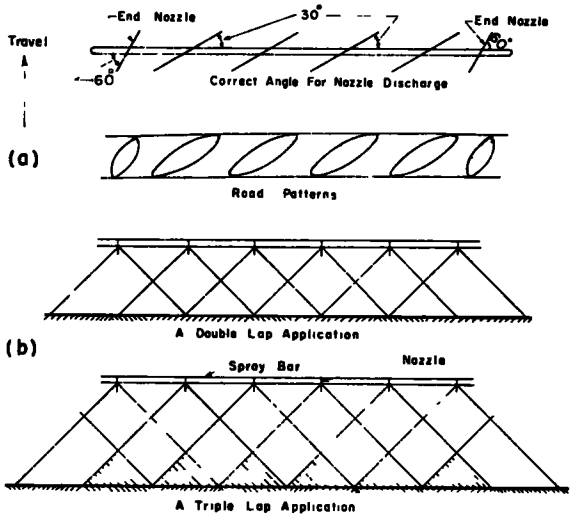

Figure 7. Influence of nozzle angle and spray bar height: (a) nozzle arrangements and road patterns, and (b) effect of spray bar height on distribution.

To cover the surface with the proper amount of binder, the height of spray bar should be adjusted to give an overlapping of double or triple laps (Fig. 7). In order to obtain such double or triple lap distributions, each alternate nozzle is closed, and the material is sprayed at the appropriate pump pressure. The height at which the spread forms a single lap is the height required to form a double lap when all nozzles are open. By raising the bar by an additional 50 percent, the triple lap is obtained.

3. Nozzles. Nozzles are selected with the appropriate-sized openings in order to provide the desired rate of binder application. There are several types and sizes of nozzles that can be used to obtain different rates of discharge. The all-purpose, ⅛-in. size nozzles are usually used in machines for distributions up to 0.35 gal/sq yd, whereas 3/32 in. and larger sizes are used for heavier applications. Nozzles must be placed in the spray bar with the proper angle in order to prevent interference of the fan spray. The long axis of the nozzle orifice should be adjusted to a sufficient angle to the longitudinal axis of the spray bar. This angle can vary from approximately 15 to 30 deg for different models of equipment (Fig. 7). Each time the sprayer is used, the nozzles must be thoroughly inspected. Any damaged or clogged nozzles should be replaced before application so as to prevent distorted spray of the binder.

4. Truck Speed Tachometer. To give an accurate check on the rate of discharge, every distributor should be equipped with a tachometer which is operating on a fifth wheel that rides on the pavement or on the rear tire. Since for each nozzle there is only one rate of discharge at which the most even distribution is obtained, the forward speed of the distributor can be adjusted to provide the desired discharge rate. To determine the setting of the truck's speed tachometer, the pump tachometer is set at some factor of the length of the spray bar in gallons per minute. From the desired rate of discharge, the forward speed of the truck can be easily calculated.

5. Distributor Tank. As a positive means of determining the amount of binder applied in each shot, the distributor's tank should be equipped with a dip stick marked in gallons per inch of length. By reading the distributor's dip stick before and after each shot, the rate of distribution can easily be checked.

Distributor's tanks are also equipped with a thermometer suitable for the range of temperatures used in surface treatment operations. The temperature of the binder in the tank should be adjusted to the temperature needed to produce the desired spraying viscosity. Measurement of the temperature should be made after the bituminous material has been thoroughly circulated in the tank.

6. Calibration Certificate. Some highway departments and agencies require calibrations of bituminous distributors and issue a calibration certificate as a permit for operation. The calibration certificate is withdrawn if any defects or malfunctions are observed in the parts or instruments of distributor. Several groups have developed and adopted suitable equipment for the calibration of the bituminous distributors (60-3). Usually the distributor stands on a perfectly level area and sprays the binder into a long steel trough which is divided into compartments, each 2 in. wide. By checking the amount of binder in each compartment after spraying, it can quickly be determined if the sprayer is calibrated correctly and if all the parts are functioning properly. If

they are badly worn and poorly adjusted, the sprayer might require a general overhaul before the certificate can be issued.

Aggregate Spreading

Method of Application—To obtain good adhesion between the aggregate and the binder, the aggregate should be spread and compacted before the binder chills or hardens. The "time limit" for aggregate placement depends on the same factors governing the length of spread. There is no exact method of determining this limit; good judgment must be used.

In very wide pavements where the binder is sprayed in several longitudinal strips, the aggregate spread is kept 4 to 8 in. back from the inner edge of the longitudinal strip to allow the succeeding applications of binder in the next strip to overlap slightly without covering the spread aggregate. Therefore, only one layer of cover aggregate is spread on the longitudinal joint, and a dividing-line hump is eliminated. To avoid the cross-joint bumps, the cover aggregate is spread on the building paper at the beginning and the end of each spreading. The rate of distribution should be checked by calculation using the weight of the aggregate spread from the trucks and the area covered by the aggregate.

Spreading Equipment—There are a number of spreaders used in surface treatment construction. These can be classified into three groups: mechanical, tailgate, and continuous spreaders.

1. The mechanical spreader consists of a hopper mounted on wheels with an auger across the bottom for uniformity of spread. In operation, the spreader is hooked to the back of the aggregate supply truck and is pushed backward over the sprayed surface. An adjustable opening in the bottom of the spreader is employed to control the rate of discharge.
2. The tailgate spreader, which is generally controlled by hand, is also attached to the tailgate of the supply truck. The human error in the hand operation of this type of spreader is its primary disadvantage.
3. The continuous spreader, such as the Flaherty Spreadmaster, appears to be the best type of spreader developed so far; it is widely used. The spreader is a self-propelled, motorized unit, which receives the aggregate from the supply truck into a hopper and feeds it to a spreader-box where it can be spread uniformly and continuously. This spreader-box is equipped with a unique apparatus: a screen is located in front of the spreader roll, forcing the coarser aggregate particles to drop on the binder first and allowing the finer particles that pass through the screen to drop on top of the coarse aggregates. Since divider plates are employed in the spreader box, any width between 2 and 13 ft can be spread satisfactorily by this machine.

Rolling Operation

Although some groups have suggested that the aggregate surface should be broomed before rolling, this is not recommended by the majority of organizations as a sound practice. Rolling should precede any sweeping, dray-brooming or cleaning operation.

Type of Rollers—The selection of the type of rollers (steel wheel or rubber tire) often depends on the condition of the surface and the toughness of the aggregates. Rubber-tired rollers are preferred on old, rough surfaces or when soft aggregates are used. In such cases, the first phase rolling is carried out by self-propelled, rubber-tired rollers, and the second phase with steel-wheeled tandem rollers. However, on smooth pavements, where the kneading action of rubber tires is not actually required, and when the aggregate will fairly well resist crushing, the first phase rolling is accomplished with steel-wheeled tandem rollers and then is backed with the rubber-tired rollers. Of course, in cases when only one type of roller is available, the selection of the roller is based on the condition of the pavement and the aggregate. The rubber-tired roller is usually thought to be the best all-purpose roller for surface treatment construction.

Rolling Methods—The cover aggregate is rolled immediately after spreading with either a steel-wheeled tandem or rubber-tired roller weighing not less than 5 tons.

The rolling operation is carried out by starting at the outer edges in a longitudinal direction and proceeding toward the interior, overlapping each preceding strip by one-half width of front roll. The first-phase rolling operation should be completed within ½ hr and cover the entire surface. For the second-phase rolling operation, however, the self-propelled pneumatic rollers are often employed, and rolling is continued until the binder has hardened. The speed of the rollers must not exceed the speed at which the tires pick up and suck up the aggregate. Towed pneumatic-tired rollers are not recommended, as the turning wheels will tend to dislodge the aggregate.

Broom Dragging—Many engineers use broom dragging between the first and second-phase rolling operations. This is to aid in the proper distribution of the aggregate and also to help individual aggregate particles attain proper orientation. Some engineers, however, will not use the broom drag because they believe that the operation loosens the aggregate already in place. The point at which the disadvantage outweighs the advantages varies with conditions and should be considered for each situation separately. The brooming operation should not be confused with initial and/or final sweeping which is performed for entirely different reasons.

Final Operation

After rolling is finished, loose aggregate may be present on the surface. This aggregate is that portion which was spread but did not adhere to the bituminous binder. It may amount to as much as 10 percent of the entire spread. Loose aggregate produces hazardous situations; it may cause breakage of windshields and degradation of other particles. Thus, it should be removed before the road is opened to traffic. Rotary and other types of brooms are employed to sweep the loose aggregate off gently without disturbing the adherent aggregate. The sweeping operation is usually carried out the day after the rolling has been completed when the bituminous binder will be sufficiently hard to prevent any of the adherent aggregate from coming loose again.

Traffic Control

Traffic must be controlled on newly constructed surface treatments to prevent the loosening of the aggregate. Aggregate particles whipped off the surface by the traffic, in addition to economic loss and low performance, will create driving hazards to the motorists. It is most desirable, therefore, to detour the traffic completely until the binder is sufficiently hard to keep the aggregate in place. However, if a complete detour of traffic is not possible, the speed of through traffic must be limited to 20 mph and possibly controlled by a pilot truck. Pilot trucks are usually equipped with big, easy-to-read signs and lead the traffic at low speed through the newly constructed sections. The length of the period during which traffic control is enforced depends entirely on the external factors governing the binder setting. Even under ideal weather conditions, this period is at least two hours for asphalt cements. This time should be extended when poor weather and low temperature prevail or when other types of binders are used.

Inspection

It must be emphasized that to achieve satisfactory results, careful inspection should be made at all steps during the construction of the surface treatment. A group of well-trained inspectors, under the supervision of an experienced, informed engineer should be present. They should carefully inspect every aspect of the construction to insure that the specified requirements have been met and that the best construction procedures have been followed.

Weather

In the construction of any type of surface treatment, the weather is a most important factor irrespective of the materials used. A suitable time of the year should be selected for construction so that there will be no adverse weather effects. The ideal condition is hot, dry weather with no possibility of rain. Most engineers insist that under no

circumstances should the surface treatment construction be carried out at air temperatures below 60 F. However, the temperature of the pavement surface is even more important than the air temperature and this pavement surface temperature should not be less than 50 F at the time of rolling. Since adhesion of aggregate to the binder is affected by the presence of water, work should not proceed during a rainy period, or just after rain when the aggregate in the stockpile is still quite moist.

CONSTRUCTION OF DOUBLE AND TRIPLE SURFACE TREATMENTS

Double and triple surface treatments are constructed to provide smoother surface texture and longer life, or to protect an underlying layer of inferior quality cover aggregate. Double surface treatments are nothing more than two single surface treatments constructed one on top of the other, with the exception that different-sized cover aggregates may be used. When three surface treatments are built one on top of another, it is called a "triple surface treatment."

Before placing an additional layer, the underlying surface treatment should be opened to traffic for a period of time. This will allow the particles of the cover aggregate to be thoroughly compacted and rotated so that they will adopt the final position in the pavement, i. e., with the least dimension upward. Then the surface is swept and cleaned to prepare it for the construction of the additional layers. Binder application, aggregate spreading, rolling and final operations are carried out the same way as outlined for the construction of a single-layer surface treatment.

Chapter Six

FIELD PERFORMANCE

Miles of surface treated roads have been built that have performed quite satisfactorily for many years. However, surface treatments also have been constructed which have shown signs of failure after being subjected to traffic for only a short period of time. Although good surface treatments can be constructed, the latter situations indicate a definite shortcoming in the design and/or construction procedure and techniques that were used on those jobs.

To remedy some of these deficiencies so that all surface treatments will perform satisfactorily, a study ought to be made of the conditions of a number of actual surface treatments and the performance evaluated while taking into account the design method and construction procedures used. As both poor and well-performing surface treatments are studied, the deficiencies in the design and/or construction techniques may become apparent and the necessary corrections can be made.

EVALUATION OF PERFORMANCE

Success in any field performance study rests on the ability to distinguish between poor or good serviceability and to evaluate correctly the conditions of the pavement during its service life. The major observable conditions that indicate poor performance in surface treatments are discussed in the following.

Loose Aggregate

The loss of cover aggregate and the resultant piling of this material in the center or along the sides of the highway are a sign of poor serviceability. Usually the higher the percentage of loose aggregate, the poorer is the performance of the surface treatment. The presence of loose aggregate could result from the use of an insufficient amount of binder, the use of the wrong type of binder, dusty or wet aggregate, poor compaction, or improper control of traffic during the construction. Rainfall immediately after the construction of a surface treatment will also influence the loss of aggregate from the surface. In addition, the volume and type of traffic using the facility during its service life are major factors influencing the loss of cover material (60-3) (60-8).

Polished Aggregate

Use of polished and worn aggregate reduces the skid-resistant qualities of surface treatments and thus induces hazardous driving situations. (Lack of skid resistance may also be due to other factors such as bleeding and presence of loose or foreign material, which are in themselves signs of poor service.) The extent of polishing depends on the type of cover aggregate used as well as the traffic conditions to which it is subjected. In many instances, only the aggregate in the wheelpaths is polished under traffic. However, this is enough to give rise to poor serviceability. As a result, resurfacing may be required to provide a new nonskid surface for safe motor vehicle operation (51-1).

Nonuniformity of Surface Texture

The riding quality of a particular pavement is greatly affected by the uniformity of its surface. There are many construction practices which, when incorrectly followed, can result in a nonuniform surface texture. One of the principal malpractices is the nonuniform application of binder material to the existing pavement surface caused

primarily by defective distributors. In the spots where insufficient binder has been applied, the aggregate is likely to be lost. This results in an accumulation of loose material which can be very detrimental to passing vehicles. On the other hand, at locations of excess asphalt, flushing of the binder to the surface is common. In addition, transverse and/or longitudinal ridges of aggregate form, and in so doing, greatly decrease the riding quality of the pavement (60-3) (60-8).

Bleeding

Blackening of the surface in the wheelpaths is one of the first signs of bleeding caused by the presence of excess binder material. Sometimes bleeding occurs in the wheelpaths because additional densification of the cover aggregate under traffic tends to decrease the void content of the surface layer. In newly constructed surface treatments, passing lanes rarely show signs of bleeding since they have not received sufficient traffic to cause densification of the cover aggregate. However, after a period of extensive traffic use, the darkened areas sometimes extend over the entire pavement surface. During wet weather these areas present a great hazard to traffic as the smooth binder material impairs the skid-resistant qualities of the pavement. In warm weather, bleeding creates a sticky surface. Vehicles passing over such a pavement soon become covered with the asphaltic material much to the consternation of the motorist (60-3) (60-8).

Cracking

Cracks impair the waterproofing function of a surface treatment and the riding quality of the surface. The performance of the surface treatment is related to the type, the severity, the location and the degree of cracking. Cracks in the surface that reflect the underlying depressions and weak spots are usually indicative of a poor patching operation to the old surface before application of the surface treatment. Other cracks may be formed by the hardening and weathering of the binder in the new surface treatment. Deep cracks are an indication of base failure. This situation renders the pavement unsuitable for traffic. However, since the failure is independent of the surface treatment, it should not be considered in the evaluation of the surface treatment (60-8).

RATING METHODS

To evaluate the performance of a surface treatment, a detailed survey of its condition should be made utilizing suitable methods at periodic intervals during its service life. Personal opinions of the riding quality from visual examinations and actual test driving and the use of mechanical measuring devices are the bases of different rating methods used today. When these methods are used to rate test sections of materials of known engineering properties and which were constructed and used under carefully controlled supervision, much useful information can be obtained. The common methods employed in rating the serviceability of surface treatments are discussed in the following.

Visual Rating

To rate a surface treatment visually, trained observers drive over the section and after visual examination report their personal impressions of the riding quality and condition of the surface. The human error and variation in subjective judgment are the disadvantages of this approach.

Failure Count—To obtain a failure count for a particular stretch of highway, trained observers are sent to survey the facility under study and to record in detail the location and type of distress encountered. Such information can then be used for future performance studies and also for determining the exact causes of failure (46-1).

Comparative Rating—A group of observers after making a detailed inspection of a particular section of pavement are individually asked to report their "rating" of the overall serviceability of that section. The observers rate the existing condition by assigning numerical values of previously established meaning which denote their opinion of the performance of the facility. This type of rating is very general and does not give an indication of the type or extent of the failure (46-1).

South Dakota Condition Rating—A more thorough method of pavement rating, developed by the South Dakota Highway Department, employs independent rating of the major factors affecting the performance of surface treatments (60-8). The evaluator drives over the entire project but stops only at predetermined intervals for detailed inspection. The driving characteristics and the uniformity of the surface are evaluated as are the factors influencing its performance. These factors are chip retention, skid resistance, uniformity of binder application, cracking and bleeding. Values ranging from 0 to 20 are assigned to the pavement surface to indicate an evaluation of the previously mentioned factors. These numbers are further grouped (0-5) (6-10) (11-15) (16-20) and classified as poor, fair, good, and excellent respectively. The sum of the numerical values assigned to the surface for each factor considered indicates the overall serviceability of the surface.

1. Excellent (16-20) is assigned to a surface which has an even distribution of chips which provide good skid resistance for motor vehicles. Such a surface has a uniform texture both longitudinally and transversely with few or no open cracks. Bleeding is not noticeable and slight blackening is seen only in a few spots.
2. A good (11-15) condition is one in which there are some loose chips in the center of the road, but with enough aggregate adhering to the surface to provide satisfactory skid resistance. Surface texture varies slightly according to changes in application rate, to bleeding and to some loss of aggregate. Although some cracks are evident, the original crack pattern has not been re-established. Bleeding is observed only in a few localized areas.
3. Fair performance (6-10) is assigned to a surface with considerable loss of aggregate in the wheelpaths or other localized sections. Bleeding, loss of aggregate, and aggregate polishing have caused some sections of the surface to become slippery. Surface texture is not quite uniform, and longitudinal ridges may occur which could impair driving characteristics. An extensive crack pattern has developed in both the longitudinal and transverse directions. Bleeding has progressed sufficiently far in the wheel lanes to reduce skid resistance.
4. Poor performance (0-5) indicates a surface devoid of chips over the entire area, thus providing no skid resistance whatsoever. Surface texture is rough and uneven with possible longitudinal ridges. Cracking in such a surface is extensive and the mat itself is subject to the forces of weathering. Bleeding is so severe that the purpose of the cover aggregate is practically nullified.

A similar rating method can be employed to rate the underlying surfaces before application of the bituminous surface treatment. The information obtained by rating the underlying surface can be very helpful in comparing the performance of different surface treatments. This rating method can also be used to indicate locations where an old surface treatment needs to be replaced (60-8).

Instrumental Rating

Instrumental rating methods overcome many of the disadvantages of the visual rating methods by replacing personal judgment with machine-recorded data. These data can be evaluated to determine the conditions of certain surface characteristics which are related to the overall serviceability of surface treatments. Three types of instruments are often used in the condition survey of surface treatments.

Profilometer—The profilometer measures and records the gradual change in pavement slope and profile. This information can then be correlated with the surface roughness (46-1).

Roughometer—The roughometer measures and records all changes in pavement slope over a certain predetermined stretch of highway. A "run" is made over the pavement after construction and before opening to traffic. Additional runs are made subsequently, and a relative roughness rating made. This information can then be correlated with pavement performance.

Skid Resistance Measuring Devices—Suitable skid resistance measuring devices can be employed to measure the relative change of slipperiness of a pavement with time.

Since the slipperiness results mainly from bleeding, nonuniformity of binder application, and/or loss of aggregate, the data obtained by such devices usually will give a good indication of the overall serviceability of the pavement. Occasionally, however, some pavements have high skid-resistant qualities even though their overall performance is poor. Therefore, care must be exercised when using this method rating.

SERVICE LIFE

To be economical, a surface treatment should retain its surface characteristics and function as designed during its service life. Accordingly, the surface treatment should satisfy the requirements for safe and convenient motor vehicle operation without requiring excessive repair or maintenance work.

Surface treatments can last for a considerable time provided they are designed and constructed properly. A number of references give the following "lives" to such surface-treated pavements. McLeod (60-3) suggests that good surface treatments should perform satisfactorily for a period of 15 years. In Texas, properly designed and constructed surface treatments have performed well for 14 years under the anticipated traffic (58-1). The Bureau of Public Roads has studied the lives of different types of surfaces throughout the country. It reported that at the time of the study (1953), the average age of surface treatments was 10.9 years, with a remaining life expectancy of 5.9 years (56-2). Thus, they expect the service life of a surface treatment to be approximately 16.8 years.

In practice, a large number of surface treatments have failed after a short period of time and have brought the average life of surface treatments to 10 years (60-3). Many of the factors that affect the expected service life of a surface treatment have been discussed. If these factors are considered and the surface treatment is designed and constructed correctly, it should last considerably longer than most people believe.

These reported estimations of service life of a surface treatment are valid only when the highway carries light to medium traffic varying from 25 to 300 vehicles per day (58-1) (60-7). If future traffic is expected to exceed this limit, the surface probably should be built to higher standards through stage construction and more advanced surface-treatment techniques.

The structural features of double and triple surface treatments have significant effect on service life. Although few data are available, the multiple-layer surface treatments are expected to have longer service life than single-layer treatments. The Asphalt Institute (60-7) has listed the single-layer surface treatments in short-life pavement categories and multiple-layer surface treatments in medium-life categories. No indication was given, however, of how many years of service could be expected from either type of construction.

The scarcity of performance data definitely indicates the need for more work in this field. At present very few studies have been made to correlate the current design methods and the performance of surface treatments constructed using these methods, and much research is needed in this area (56-2) (58-1) (60-3) (60-7) (64-1).

Chapter Seven

SUMMARY AND CONCLUSIONS

The selected annotated bibliography relating to seal coats and surface treatments was derived from a survey of over 500 articles. Many of these, however, contribute little to the general knowledge of surface treatments. Only approximately 20 percent of the literature was considered valuable by the authors and was used as the basis of summarizing the status of current knowledge.

The following conclusions were drawn primarily from a relatively small amount of pertinent literature available. Some of the conclusions were stated forthright in articles by various engineers. Other conclusions, however, were inferred from existing data or from the obvious lack of such information.

1. By reviewing existing literature, one readily notes the inconsistencies in terminology relating to seal coats and surface treatments. It is evident that no universal definitions exist. There is an apparent need for widely acceptable terms which would facilitate communication among engineers dealing with surface treatments.

2. Although some surface treatments have performed poorly, there are records of a number of surface treatments that have had excellent performance. Such good performance has not been limited to warm weather regions. Canada, Sweden and many other cold weather countries have produced excellent performing surface treatments. In addition, good performance has not been limited to surface treatments carrying only light traffic volumes. Many treatments have performed quite satisfactorily under medium to heavy traffic.

3. Surface treatments are not recommended for heavy, high-speed traffic, as such traffic tends to readily displace the cover aggregates.

4. The major restrictions for good surface treatment construction are as follows: (a) weather conditions during construction must be favorable as the temperature of the air and road surface and the presence of moisture greatly influence construction of a good surface treatment; (b) the underlying surface must be stable, clean, and dry before application of the bituminous binder material; and (c) the application of bituminous binder must be rigidly controlled in order that the "optimum" amount may be placed correctly.

5. Surface treatments fail predominantly by (a) flushing or bleeding of the binder due to the presence of excessive amounts; (b) loss of aggregate caused by insufficient amounts of binder; and (c) streaking produced chiefly by the nonuniform application of bituminous material. All of these major types of failure are related to the bituminous binder and can be eliminated by careful design and construction practices.

6. Surface treatments serve several important functions such as providing an abrasion and skid-resistant surface. However, this type of construction does not appreciably strengthen the pavement and will not allow an increase in the existing traffic loads.

7. The gradation of the aggregate is very important. A closely controlled, one-size aggregate is considered the best type of cover material to use. In most areas, this type of aggregate is generally more expensive than aggregate with greater amounts of overage and underage, but the resulting increase in performance may warrant its use.

8. Asphalt cements retain the cover aggregate better than any other type of bituminous material. However, adhesion between this bitumen and the aggregate is more difficult to obtain and the stone should be applied as soon as possible after the asphalt cement has been sprayed on the road surface.

9. It appears that the basic principles set forth by F. M. Hanson in 1935 form the basis for the majority of current design methods.

10. The quantity of aggregate has not been considered to be a critical factor so long as the surface is completely covered. Because of this, considerable variation in the

"spread" amount has been allowed. This should not be the case as too much excess can be very detrimental.

11. It appears that the different design methods indicate a wide variation in the amount of bituminous material to be used. This is even more critical than it seems since there is an optimum amount of binder required, and since little variation from this amount can be tolerated.

12. There is no desirable analytical method of obtaining the type and grade of bituminous material to be used. McLeod has suggested one approach, but it still leaves many important design factors to be evaluated empirically by the engineer.

13. There is no analytical method for designing multiple-layer surface treatments. At present they are "designed" primarily from experience.

14. There has been little research, either in the laboratory or on actual field test sections, related to the various factors that influence the performance of surface treatments. It is possible, however, that much unreported research data do exist. This apparent lack of research information has caused many of the current design and construction practices related to surface treatments to be developed over the years by trial and error.

15. Many engineers believe that since surface treatments are inexpensive and relatively simple to construct care is not required during their construction. This usually results in a lack of control and/or necessary supervision of construction and subsequently produces poorly performing surface treatments.

Chapter Eight

SUGGESTED RESEARCH

In the literature related to surface treatments and seal coats, there is usually no direct mention of the areas in which research is needed. The areas are usually implied by the lack of information available regarding a particular subject or by the indication that a decision must be made by experience. (Definitely, many decisions must be made by experience, but not all as is done in some surface treatment construction projects.) These areas of needed research tend to fall into three categories:

1. Research related to the basic behavior of the materials.
2. Research related to the design of surface treatments.
3. Research related to construction phases.

Although not strictly a research project, there is one area in which there is a dire need: standardization of terminology related to surface treatments. Because of the wide variation in usage over the United States and the rest of the world, it would be desirable for a national or international group to define the terms for common use. Then, and even though it would be a greater problem, the definitions should be widely adopted by all engineers.

The research suggested here, in all likelihood, does not include all of the research needed in relation to surface treatments. However, the most important ones are probably included. As the important phases are investigated and as the knowledge is advanced, the list should be revised.

The research projects are not listed in any order, especially not in the order of importance. Decisions as to the priority to be given vary with time and should be made with due regard to existing conditions.

RESEARCH RELATED TO BASIC BEHAVIOR OF MATERIALS

1. Type and magnitude of the forces which are applied to the aggregate in a surface treatment by moving wheel loads.
2. Method of correlation of rheological and failure characteristics of bituminous binder to actual field conditions.
3. Means for developing the best adhesion between the aggregate and the binder, since little strength is developed by aggregate interlock and aggregate friction.
4. The feasibility of using gravel or crushed gravel as cover aggregate.
5. The size of aggregate needed in relation to the traffic conditions.
6. Gradation and top size of both the first and second layers of aggregate that are used in double surface treatment construction.
7. Interlocking effect of the second layer of aggregate in a double surface treatment.
8. Importance of reducing the size of the aggregate in the second application of a double surface treatment.
9. Most suitable type and grade of bituminous binder needed, considering the aggregate, temperature, and other influencing factors.

RESEARCH RELATED TO DESIGN OF SURFACE TREATMENTS

1. The development of an analytical method to determine the influence of an aggregate shape factor on the amount of aggregate needed.
2. The correct specific gravity to convert the quantity of aggregate from cubic feet per square yard to pounds per square yard.

3. The feasibility of converting the quantity of aggregate determined by the test-board method to the average size of the aggregate.

4. Means of computing the volumes of the voids between the aggregates as influenced by (a) size of the aggregate, and (b) shape of the aggregate.

5. The relationship between the volume of the voids between the aggregate in a layer one stone thick and the voids in the aggregate in bulk quantity.

6. The maximum and minimum amounts that the aggregates can be embedded in the bituminous binder.

7. Determination of the extent of aggregate penetration into the underlying surface so that a reduction in the amount of bituminous quantity can be made.

8. Additional study on the influence of the physical condition of the aggregate (wet or dusty) and determination of acceptable limits.

9. An analytical means, such as McLeod suggests, to determine the type and grade of bituminous binder to be used.

10. A design method for double surface treatments which includes (a) the quantity of aggregate needed in the second application, and (b) the quantity of binder needed, as it is not the same as two single surface treatments.

11. A design method for "graded" aggregate, i. e., aggregates with an appreciable amount of overage and underage, especially the manner for including the fine aggregate in the design.

RESEARCH RELATED TO CONSTRUCTION PHASE

1. The most desirable way of measuring the serviceability and determining the performance of surface treatments. This probably means the use of more mechanical instruments to eliminate the human error in judgment.

2. The means of producing, economically, one-size aggregates with little overage or underage.

3. Means of determining the amount of bituminous binder that will be absorbed into the underlying surface.

4. Determination of how much compaction (passes of the roller) is needed to produce the minimum vertical aggregate dimension under varied conditions.

5. Determination of desirable traffic speeds during the early life of the surface treatment.

6. Although not strictly a research project, a means is needed to educate the construction personnel as to the best practices for surface treatment construction.

7. Test sections, built under controlled construction conditions, are needed to evaluate design features and construction techniques.

SELECTED ANNOTATED BIBLIOGRAPHY

Many references have been published that contain very valuable data related to furthering the knowledge of the design and construction of surface treatments. These references are annotated so that one can obtain an idea of the information and useful data available in the article. All pertinent articles were reviewed. Selection of those references that were annotated was based on an appraisal of the article by one of the authors of this publication. Since the selection was based on a personal evaluation, some articles may not have been annotated that contain information pertaining to a particular subject.

The annotated articles pertaining to surface treatments have been given a reference number based on the year of publication and the arrangement within that year. The articles are arranged chronologically and within a particular year, alphabetically according to their authors. For example, an article numbered 58-2 means it was published in 1958 and is the second article according to the alphabetical arrangement. Articles without a listed author are placed last in that year.

The references are specifically limited to thin bituminous surfaces using cover aggregate. They include single and multiple-layer surface treatments and seal coats, but do not include prime and tack coats and earth oiling. In addition, neither articles that deal with related phenomena such as adhesion nor text books or specifications were reviewed.

28-1 Emmons, W. J. THE BITUMINOUS SURFACE TREATMENTS OF ROADS AND PAVEMENTS. Proc., Highway Research Board, Vol. 8, p. 284, 1928.

The functions of surface treatments on several types of roads are covered and the required properties of the bituminous materials and the aggregates are given. Surface treatments are placed to waterproof the underlying material, to eliminate dust and to prevent disintegration of the base. The type and amount of the bituminous material needed are discussed in general terms.

30-1 Bruce, A. G. MATERIALS AND METHODS FOR LOW-COST ROADS. Public Works, Vol. 61, No. 1, p. 1, January 1930.

The current method for designing surface treatments is given and construction techniques are discussed. Very general.

30-2 Myers, J. E. DETERMINATION AND CLASSIFICATION OF THE IMPORTANT CHARACTERISTICS OF BITUMEN FOR USE IN SURFACE APPLICATIONS, MIXED IN PLACE AND SIMILAR ROAD SURFACES. Proc., Highway Research Board, Vol. 10, p. 63, 1930.

A portion of this report discusses the important properties of the bituminous binder used in surface treatment construction. The two main qualities of the binder to be considered are drying time and cementing value. The type of asphalt should be related to the density and the size of the void of the underlying surface. When the surface is dense and has small voids (clays, sand-clay, loam-gravel), the bituminous material should have low viscosity and low cementing value (sic). High viscosity bituminous binders with high cementing values and quick drying qualities should be used on the more open road surfaces.

30-3 Pauls, J. T. BITUMINOUS TREATMENTS USED ON ROADS OF INTERMEDIATE TYPE IN THE WESTERN STATES. Public Roads, Vol. 11, No. 10, p. 189, December 1930.

This paper is a report of an inspection trip to western parts of the United States to obtain information on the design, construction, maintenance and behavior of different types of bituminous treatments. Various types of asphalts were found to be in use. Description is given of "armor coat" and "multiple lift" types of construction.

31-1 Jones, H. C., and Tarwater, E. L. BITUMINOUS TREATMENTS ON SAND-CLAY AND MARL BASES IN SOUTH CAROLINA. Public Roads, Vol. 12, No. 9, p. 217, November 1931.

This is a report of an experimental project. Primarily it was directed toward mix-in-place construction, but some surface treatments were used. Difficulties were experienced in placing the treatments on bases whose surfaces tended to loosen or ravel easily. Methods were devised to correct this problem.

33-1 Williamson, J. S., and Critz, P. F. SURFACE TREATMENT OF TOP SOIL ROADS. Public Roads, Vol. 13, No. 11, p. 169, January 1933.

Experimental surface treatment sections were constructed with the type of binding material as a major variable. After five years, with average traffic of 800 vehicles per day, most of the sections were in good condition. However, two materials failed to prove satisfactory. One was a cutback asphaltic oil with highly volatile distillate which was used as a primer (it penetrated only a little). The other was a slow-curing cutback oil that developed a slippery surface in wet weather.

34-1 Gray, B. E. BEST PRACTICE IN THE ACHIEVEMENT OF NON-SKID ASPHALT SURFACES. Proc., Highway Research Board, Vol. 14, Part I, p. 199, 1934.

Non-skid surfaces are obtained primarily by the way in which the bituminous materials are used. There should be a correct relationship between the asphalt binder and the aggregate. In fact, in re-treatments the greatest error is in using too much bituminous material. A table with suggested asphalt quantities based upon cover aggregate size is given.

34-2 Martin, G. E. SKID RESISTANCE OF TAR ROAD SURFACES. Proc., Highway Research Board, Vol. 14, Part 1, p. 217, 1934.

Factors causing low surface friction in bituminous pavements are discussed. In addition, the characteristics of the stone for surface treatments needed to make the surface non-skid are covered in detail.

35-1 Hanson, F. M. BITUMINOUS SURFACE TREATMENT OF RURAL HIGHWAYS. Proc., New Zealand Society of Civil Engineers, Vol. 21, p. 89, 1934-35.

This is a very comprehensive study of surface treatments (slightly less than 100 pages). The author was the first to establish some fundamental principles of the relationship between the aggregate and the bituminous binders. He determined that the quantity of the binder is related to the volume of the voids between the compacted aggregate. The asphalt must not fill all of the voids because a slick surface will result. The asphalt then should fill the voids in the aggregate to one-half to two-thirds of the compacted height of the aggregate. He recommends one size aggregate and notes that since the final layer is only one stone thick, the volume of

aggregate needed should be the amount to cover the surface with one layer of the stone plus 10 percent for construction allowances.

36-1 SURFACE TREATMENT TYPES. The Asphalt Institute Manual, Number Two, Asphalt Road Construction, 1936.

This publication (127 pages) deals entirely with surface treatments. It covers a number of items related to surface treatments, such as history, asphaltic products used, influence of various factors, maintenance, etc. It does not, however, give any method for design of surface treatments.

37-1 Kelley, E. F. REPORT OF COMMITTEE ON CHARACTERISTICS OF ASPHALTS. Proc., Highway Research Board, Vol. 17, p. 328, 1937.

The answers to a questionnaire concerning the service of asphaltic road materials were summarized. Failures were attributed to poor quality asphaltic materials in all sections of the U. S. and cracked asphalts appeared to cause more trouble than uncracked products. After a discussion of the control of asphaltic products, some research was suggested that seemed to be promising in this field.

37-2 Wood, W. H. SELECTING ASPHALTIC PRODUCTS FOR VARIOUS TYPES OF SURFACE TREATMENT. Proc., National Asphalt Paving Conference, p. 157, 1937.

A general discussion is given of reasons why certain types of asphalts should be used for surface treatments. The selection of type is related to the viscosity of the asphalt, the type of aggregate to be used, the traffic, etc.

39-1 Critz, P. F., and Beckham, W. K. EXPERIMENTAL BITUMINOUS-TREATED SURFACE ON SAND-CLAY AND MARL BASE. Public Roads, Vol. 20, No. 2, p. 21, April 1939.

Results are given of experimental test sections constructed with various bituminous materials on sand-clay and marl bases. Types of constructions are presented and some performance data are given.

39-2 Hardenbergh, W. A. HOW TO MAINTAIN HIGHWAYS AND STREETS. Public Works, Vol. 70, No. 5, p. 34, May 1939.

A fairly detailed description of maintenance of surface treatment is given. Quantities of aggregate and binder, however, are reported only in approximate amounts.

40-1 Fahnestock, T. V. FACTORS GOVERNING THE SELECTION OF AGGREGATES, PRACTICE IN NORTH CAROLINA. Proc., National Asphalt Conference, p. 169, 1940.

Since aggregate for surface treatments should not degrade, requirements for abrasion resistance were determined. In addition, since there is less loss in gravels, smaller size gravel can be used than crushed stone. Other requirements are given.

40-2 Rader, L. F. FACTORS GOVERNING THE SELECTION OF ASPHALT SURFACE TYPES. Proc., National Asphalt Conference, p. 192, 1940.

A number of factors are presented that should be considered in selecting an asphalt surface type. Surface treatments are included. One section deals entirely with the selection of surface treatments or mat construction.

40-3 Shelburne, T. E. SURFACE TREATMENT STUDIES. Proc., Association of Asphalt Paving Technologists, Vol. 11, p. 44, 1940.

Contrary to the name, this article is not related to surface treatments and seal coats according to the modern usage of the term. In the paper, "surface treatment" refers to mineral aggregates that have been mixed with fluid bituminous material on the road to obtain a wearing course less than 1 in. thick. Considerable information is given about this type of construction, especially degradation of the aggregate under rolling. See Reference 40-4 also.

40-4 Shelburne, T. E. CRUSHING RESISTANCE OF SURFACE-TREATMENT AGGREGATES. Engineering Bull., Purdue University, Research Series No. 73, Vol. XXIV, No. 5, September 1940.

The crushing of aggregate by road rollers in compacting surface-treatment aggregate was studied. The resistance of the aggregate to crushing varied with the type and source of the aggregate. The rate of degradation was more rapid with open than with dense gradations. As the weight of the roller was increased, the degradation increased although not proportionally. Also, more breakage occurred (approximately twice the amount) when the rolling was done on a rigid base instead of on a flexible base.

41-1 Rader, L. F. SELECTING ASPHALTIC SURFACE TYPES. Better Roads, Vol. 11, No. 3, p. 27, March 1941.

Various types of bituminous surfaces are discussed. For surface treatments, the following factors are necessary: a smooth and well-bonded base; a base of high supporting qualities; hard, tough, stripping-resistant, one-size aggregate; and bituminous materials of good binding qualities. No design method is given.

41-2 Shelburne, T. E. FUNDAMENTALS OF SURFACE-TREATMENT CONSTRUCTION. Proc., Twenty-Seventh Annual Road School, Purdue University, Engineering Bull., Vol. 25, No. 3, p. 82, January 1941.

This is a fairly short summary of the data generally covered by the author in other articles. (40-3) (40-4) (41-3)

41-3 Shelburne, T. E. BITUMINOUS SURFACE TREATMENT. Engineering Bull., Purdue University, Research Series No. 82, Vol. XXV, No. 4, July 1941.

This is a comprehensive treatise (183 pages) on surface treatments, primarily road-mix surface treatments. Part of it is written as if it were a text book and thus is fairly basic. Aggregates as well as bituminous materials are covered rather thoroughly. However, the factors to be considered in selecting the type and grade of bituminous materials are covered in generalities. Equipment and construction techniques are also given and the results of a number of condition surveys are reported.

43-1 Goldbeck, A. TESTS ON A SPECIAL TYPE OF DOUBLE SURFACE TREATMENT. The Crushed Stone Jour., Vol. 18, No. 1, p. 15, March 1943.

This special type of surface treatment consisted of laying the aggregate first and then spraying on the bituminous material. The action of the aggregates and bitumen were discussed. Sections of this type of construction were tested in a circular test track. Tentative conclusions indicated this procedure is satisfactory provided the proper quantities of material are used.

44-1 Withycombe, E. IMPROVEMENT IN ARMOR COAT CONSTRUCTION AS DEVELOPED IN HIGHWAY DISTRICT I. California Highways and Public Works, p. 13, November-December 1944.

California specifies that the air temperature shall be above 65 F when bituminous binder is placed on double surface treatments. This is to insure that the second layer of hot asphalt completely penetrates the voids in the previously applied cover aggregate. (When this is not done, raveling and pitting soon occur.) The air temperature in one place in California rarely gets above 65 F because it is located near the ocean. A method of splitting the various applications to help overcome this problem is presented.

45-1 Melton, C. R. Bituminous Surfacing a Road in Wet Weather. Public Works, Vol. 76, No. 7, p. 26, July 1945.

This is an account of placing a surface treatment during rainy weather. It is general in nature. When weather conditions were suitable, all operations were completed very quickly. The surface appeared to be quite satisfactory after four years.

46-1 Goetz, W. H. SEVEN YEARS' PERFORMANCE OF A BITUMINOUS SURFACE TREATMENT TEST ROAD. Proc., Highway Research Board, Vol. 26, p. 272, 1946.

This is primarily a report of the performance of bituminous surface treatment (sic) test sections constructed seven years previously. The work on these sections was first reported by Shelburne (40-1) (40-2). This was a road-mix type of construction with a thickness less than 1 in. The test sections showed rather remarkable performance and longevity, which is attributed chiefly to good soil conditions, good drainage, adequate base, low traffic density, and especially, careful workmanship during construction. Successful performance seemed to depend more on the uniformity of mixture and grading of aggregate than on the type of bituminous material or source of aggregate.

47-1 Lohn, R. N., and Nevitt, H. G. STUDY OF SEAL COATING. Proc., Association of Asphalt Paving Technologists, Vol. 16, p. 31, 1947.

The following sections are covered rather thoroughly: (1) functions of seal coats (one of the functions is to "increase the structural strength of the bituminous course"), (2) construction requirements for seal coat bitumens, (3) types of seal coats (in which is covered the approximate quantity of bitumen needed), (4) types of asphalt sealing materials, and (5) relative costs of sealing materials. It is concluded that the best bituminous material for seal coat work is a quick-drying cutback asphalt with a relatively hard asphalt base (40-50 penetration).

48-1 McKesson, C. L. FUNDAMENTALS IN SURFACE TREATMENT WITH EMULSIFIED ASPHALT. Proc., Association of Asphalt Paving Technologists, Vol. 17, p. 288, 1948.

This is an article devoted to explaining how asphalt emulsions are used in surface treatment construction. Quantities of materials are given in general ranges. The author states that the quick setting emulsion asphalt is an ideal binder because: (a) "Water wets aggregate readily and carries colloidal asphalt with it; (b) emulsified asphalt does not congeal on cooling as does hot asphalt with high loss of cover; and (c) it produces a coating of pure sticky asphalt free from solvents or lubricants which must evaporate before the binder becomes fully effective."

48-2 Melville, P. L. WEATHERING STUDY OF SOME AGGREGATES. Proc., Highway Research Board, Vol. 28, p. 238, 1948.

A number of surface treatments had failed because of disintegration of poor aggregate use as the cover stone. An investigation was made to determine means to test aggregate that would identify these poor aggregate. It was learned that by wet grinding the aggregate to fine size, the poor aggregate had higher loss in weight, and also the soils, produced by the grinding, had highest liquid limits.

48-3 Nevitt, H. G. CONSTRUCTION OF OPTIMUM SEAL COATS. Proc., Association of Asphalt Paving Technologists, Vol. 17, p. 264, 1948.

No data are given, but important considerations are given to the factors that should be considered in seal coat construction. One of these is skid resistance and another is desirable finished surface characteristics. The idea of an optimum aggregate size is introduced and requirements are discussed that will provide proper adhesion of the aggregate and the binder. This article does a good job of discussing a number of factors basic to seal coat design and construction.

49-1 Hank, R. J., and Brown, M. AGGREGATE RETENTION STUDIES OF SEAL COATS. Proc., Association of Asphalt Paving Technologists, Vol. 18, p. 261, 1949. (also discussion)

The brush-method of determining the amount of aggregate retained in laboratory-prepared seal coats was developed by the authors. This method of test was used to evaluate the influence of the following factors on aggregate retention:

1. Source of asphalt—has little effect upon the retention.
2. Penetration of asphalt—as the penetration decreases the loss becomes greater. This is due to the difficulty in embedding the aggregate in the harder asphalts.
3. Rolling—there is a marked improvement in the aggregate retention, especially when asphalt cements are used. On the other hand, rolling is not as critical with liquid asphalts.
4. Type of liquid asphalt—rapid-curing cutbacks produced better retention than asphalt cements.
5. Aggregate grading—fine material hinders the embedment of the aggregate.
6. Temperature—it appears that about 70 F should be the minimum temperature allowed for seal coat work.

49-2 Hveem, F. N., Lovering, W. R., and Sherman, G. B. THE DESIGN OF SEAL COATS AND SURFACE TREATMENTS. California Highways and Public Works, Vol. 28, No. 7-8, p. 3, July-August 1949.

Six distinct purposes are listed as to why seal coats and surface treatments are used. Two analysis charts are given that indicate the relationship or influence of all factors that may affect the choice and performance of (a) screenings, and (b) bituminous binder.

A method is given for determining an "effective maximum size" of the aggregate. Once this criterion is determined the quantity of screenings needed and the quantity of asphalt to be used can be determined. Two charts are given for these determinations. (The quantity of asphalt is based on the effective maximum size, the porousness of the surface, and the porosity of the screening.)

The authors state that this method should clarify the design of seal coats some, but that this method would probably need modification when more data are available.

49-3 Kiefer, C. V. THE USE AND ABUSE OF SEAL COATS. Crushed Stone Jour., Vol. 24, No. 2, p. 11, June 1949.

In addition to stating some functions of seal coats, the author gives some suggestions as when and when not to seal. Sealing should be done only in warm weather and at the first sign of distress. One should not seal to correct cracking due to base failure, to try to correct pushing or shoving or unless one is sure it is needed.

Hanson's method is given for determining the quantity of aggregate and asphalt. (35-1) The desirable properties needed by the asphalt for seal coat work also are analyzed. Among these are flow characteristics, viscosity, good weathering properties, adhesion, and correct residual asphalt content.

Suggestions are also given as to how to construct the seal coats correctly. The most pertinent ones are (a) the aggregates should be applied as soon as possible on the asphalt; (b) all seal coats should be rolled with a roller and the traffic should be kept off until the binder "sets up."

49-4 McKesson, C. L. SLIPPERY PAVEMENTS—CAUSES AND TREATMENTS. Proc., Association of Asphalt Paving Technologists, Vol. 18, p. 1, 1949.

After covering skid resistance and a vapor seal in bituminous pavements, this article discusses the causes of slippery bituminous pavements. They are (a) excessive binder, (b) bitumen flushed to the surface, (c) slipperiness due to previous seal coats from loss of aggregate, etc., and (d) low bitumen "glassy" pavements. Retention of cover aggregate is very essential in providing good skid resistance as well as having the correct amount of binder.

49-5 Ryker, R. P. SEAL COATS. Proc., Northwest Conference on Road Building, University of Washington, p. 99, 1949.

In addition to explaining Hanson's method for designing surface treatments, the author gives a number of reasons for sealing and selecting the type of asphaltic binder for surface treatments.

50-1 Goetz, W. H. FLEXIBLE PAVEMENT RESEARCH. Proc., 36th Annual Purdue Road School, Extension Series No. 71, Vol. 34, No. 3, p. 121, May 1950.

Included in a discussion of bituminous surfaces are some statements on considerations that must be given to surface treatments. They should be designed not for structural strengthening of the pavement, but for resistance to weathering action, resistance to skidding, providing a dustless wearing surface, resistance to the abrasive action of traffic, and to provide a "roof" for the pavement.

50-2 Waller, A. C. WINTER DAMAGE TO LIGHT OIL SURFACES. Proc., Northwest Conference on Road Building, University of Washington, p. 83, 1950.

Measures that should be taken to prevent or minimize winter damage to surface treatments are discussed. They include (a) raise the grade where needed, (b) improve drainage, (c) widen to keep side drains as far as possible from the road, and (d) using at least 6 in. of thoroughly compacted stone base.

51-1 Nevitt, H. G. AGGREGATE FOR SEAL COATING. Proc., Association of Asphalt Paving Technologists, Vol. 20, p. 343, 1951.

This is a comprehensive article (over 100 pages long) on seal coating. Many factors relating to seal coat performance are discussed (surface texture, toughness, film thickness, a bitumen tolerance, etc.). Formulas are given for determining the quantity of aggregate and bitumen. While

the equations are in a rational form, some of the variables in the equations are difficult to determine exactly and must be estimated.

51-2 Scott, F. S. BITUMINOUS PAVING FOR LIGHT-DUTY ROADS AND STREETS. Proc., Northwest Conference on Road Building, University of Washington, p. 16, 1951.

The author discusses primarily the selection of a number of bituminous paving methods for road construction. He does discuss, though, the factors that must be considered in waterproofing the base and in providing an abrasion-resistant surface. In a brief discussion of double surface treatments he suggests that an SC-6 be used as the second layer of bituminous material.

52-1 Bangert, N. R. ANTI-SKID TREATMENT OF SEAL COATED PAVEMENT. Roads and Streets, Vol. 95, No. 52, p. 80, 1952.

The California Division of Highways has adopted a method of roughening slick seal coated pavements in which the seal coat binder is heated until it is soft and then it is grooved by a rake-type drag.

52-2 Brundan, W. TREATMENT OF OPEN TEXTURED ASPHALT CARPETS. Surveyor, Vol. 111, No. 3173, p. 829, 1952.

This article deals with the treatment of open-textured asphalt surfaces which have shown signs of trouble in the early years of life. By application of a surface treatment, the surface was thoroughly sealed and raveling was arrested. Aggregate used in this work ranged from ¼ to ⅜ in. size. This article also contains recommended quantities of tar and aggregate for these treatments.

52-3 Kearby, J. P. THOUGHTS AND THEORIES ON PENETRATION SURFACES. Roads and Streets, Vol. 95, p. 82, August 1952.

Asphalt surface treatments are defined as the application of a thin layer of asphalt bitumen covered with crushed stone or washed gravel. A method is recommended for determining the amounts of asphalt and aggregate for construction of the one course asphalt surface treatment. It is mentioned that the amount of asphalt should be limited so that only a portion of the aggregate is embedded. Uniform graded aggregates, using the coarser sizes, are more desirable. The amount of asphalt required is controlled by the size, shape and percentage of voids in the compacted aggregate. Proper embedment of aggregate in the binder is emphasized. Also a minimum temperature of aggregate, air, base or surface is suggested. (53-2)

52-4 Schultz, J. R. HEATED SEAL CHIPPING. Roads and Streets, Vol. 95, No. 1, p. 74, 1952.

In Wisconsin, a raveled bituminous concrete surface on a heavy-duty road was seal coated with heated chips of crushed limestone. The aggregate, ⅜ in. - No. 10, was heated to 340 - 400 F and was rolled while still hot. Traffic was excluded until the aggregate cooled.

52-5 Williams, F. H. P. RECOVERY OF UNCONTAMINATED SAMPLES OF BINDER FROM SURFACE DRESSING. Chemistry and Industry, No. 18, p. 402, May 3, 1952.

A method is discussed for obtaining uncontaminated samples of binder from surface treatments. These samples are needed in order that the changes that have taken place in the viscosity of binder after it was laid can be investigated. Preliminary experiments have shown that polythene sheetings,

0.01 in. thick, stuck to the road surface with the binder being used for the surface treatment and that surface treatments can be successfully laid over such a membrane. Results of experiments with different thickness of sheets of polythene are given. Another advantage is that polythene is virtually unaffected by tar binder.

52-6 SKID RESISTANCE ON DIFFERENT SURFACES. Public Works, Vol. 83, No. 9, p. 86, September 1952.

Surface treatments were among the many different types of surfaces tested for skid resistance. When wet, bleeding asphalt surfaces had a friction resistance that was much lower than when the surface was dry. Also it was suggested that rounded gravel not be used for cover aggregates without being crushed, since the rounded gravel had considerably lower friction than the angular aggregate.

52-7 REPORT OF THE ROAD RESEARCH BOARD FOR 1952. Road Research, Department of Scientific and Industrial Research, England, p. 55, 1952.

It is reported that a cationic adhesive agent, that was used in a full-scale trial, has proved to be satisfactory for prevention of wet weather damage. It is applied either by precoating the aggregates or by sprinkling it onto the binder. A simple laboratory test developed to estimate the efficiency of the treatment is presented. Aggregates are lightly pressed into binder on which a creosote solution of the agent has been sprayed. After five minutes the aggregates are removed from the binder and the adhesion is examined visually.

53-1 Benson, F. J., and Gallaway, B. M. RETENTION OF COVERSTONE BY ASPHALT SURFACE TREATMENTS. Texas Engineering Experiment Station, Texas A & M College, Bull. 133, 1953.

Investigations were conducted by Texas A & M College in the laboratory to determine the influence of certain factors on the retention of coverstone in surface treatments. In the experiments, the Kearby method was used to determine the amount of binder. Using three kinds of asphalt binder and two types of aggregates, pea gravel and crushed limestone, it was concluded that the time interval between the application of the binder and the aggregates as well as the gradation of the aggregates greatly influence the retention of the cover aggregate. The Kearby method of determining the optimum asphalt content appears to be satisfactory for aggregate sizes above ½ in. However, the method ought to be modified for smaller size aggregates. (54-2)

53-2 Kearby, J. P. TEST AND THEORIES ON PENETRATION SURFACES. Proc., Highway Research Board, Vol. 32, p. 232, 1953.

A practice is recommended for determining the amounts and types of asphalt and aggregate for a single surface treatment. The square-yard-test-board method was used to determine the effective mat thickness and the spread ratio of the aggregate. An asphalt-quantity chart is presented that relates the amount of asphalt needed to the depth that the aggregate is to be embedded in the asphalt, the percentage of voids in the aggregate, and the thickness of the aggregate. The influence of gap-graded aggregates and flat and elongated particles on the performance of surface treatments are also discussed.

53-3 Lewis, W. A. SURFACE DRESSINGS FOR PROTECTING SOIL FORMATIONS. Engineering, Vol. 176, p. 793, December 1953.

This article deals with four investigations which have been made on the use of various types of surface treatment for the protection of soil formations.

Sites selected for these experiments were silty clay, heavy clay, marl, and sandy clay. It was concluded that a satisfactory waterproof layer could be produced by surface treatment techniques and that a double application of surface treatment was much better than a single application for carrying traffic and maintaining a waterproof layer.

53-4 Motl, C. L. SEAL COATING IN FALL, WINTER, EARLY SPRING. Roads and Streets, Vol. 96, No. 1, p. 118, January 1953.

The Minnesota Highway Department has investigated the practice of placing a thin seal coat to prevent spring breakup and alligator cracking. This thin coat can be applied any time during the fall, winter or early spring when the bituminous surface is dry and the air temperature is above freezing. By placing a thin coat of bituminous material (MC, RC, RT) and hand spreading over it a light application of sand, a watertight, flexible, sealing film is provided.

53-5 Prohsch, H. RESEARCH WORK IN FOREIGN COUNTRIES CONCERNING THE PROPORTION OF BINDER TO AGGREGATE IN SURFACE TREATMENTS WITH BITUMEN AND CUTBACK BITUMEN AND THE PROPORTION USED IN GERMANY IN ROAD CONSTRUCTION. Strasse und Autobahn, p. 161, March 1953. (In German)

Construction of surface treatments in West Germany are discussed. Various methods of design of surface treatments from several countries are given and comparisons are made. In addition, the purpose of the binder and factors influencing its selection are covered.

53-6 Robinson, D. A. TOWARD PRECISION SURFACE DRESSING. Surveyor, Vol. 112, No. 3207, p. 571, 1953.

This article briefly discusses the functions of surface treatments and indicates that success in surface treatment construction depends primarily on (a) the right amount of binder, and (b) uniform distribution of the aggregate. Binder distributors are discussed in detail and reference is made to work done by the Association of Road Surface Dressing Contractors to measure the transverse distribution of bitumen from the machines used.

53-7 REPORT OF THE ROAD RESEARCH BOARD FOR 1953. Road Research, Department of Scientific and Industrial Research, England, p. 55, 1953.

It is reported that 36 adhesive agents have been tested by the method of laboratory test presented in "The Report of 1952." The Road Research Laboratory also has developed a distributor pump which is driven from the main engine of the vehicle. By correct choice of the gear ratio, the machine is mechanically set to deliver the required quantity of binder per yard moved, irrespective of road speed.

53-8 PROTECTION OF SUBGRADES AND GRANULAR BASES BY SURFACE DRESSING. Department of Scientific and Industrial Research, Road Research Laboratory, Road Note No. 17, 1953.

Surface treatments, which are not a structural part of the road, are discussed as a means for protecting soil formations and bases from weathering. The type and amount of binder and the number of layers are functions of the protection required. It is stated that the mechanical properties of the aggregate used for this type of work are not as important as are needed in aggregates for normal surface treatments.

54-1 Bacon, J. O. ASPHALT STABILIZED BASE COURSE AND SURFACE TREATMENT. Proc., 3rd Annual Georgia Highway Conference, February 1954.

This article discusses construction practices for single surface treatments over stabilized bases in Georgia. It was found that the rate of binder application is a function of the type of binder and the type of base. One of their requirements is that the speed of the traffic on the new surface treatment must be limited to 15 mph for some time after the construction is completed.

54-2 Benson, F. J., and Gallaway, B. M. STUDY OF SOME VARIABLES AFFECTING RETENTION OF AGGREGATES BY ASPHALT SURFACE TREATMENT. Roads and Streets, Vol. 97, p. 113, April 1954.

Laboratory-scale surface treatments were prepared and the amount of aggregate adhering to the asphalt binder was determined by a brush-off procedure. A number of variables were studied and conclusions reached. Among these were:

1. For field use, the quantity of aggregate should be the optimum amount plus 10 percent.
2. More aggregate will be retained as the grade of the asphalt cement becomes softer.
3. Greater aggregate retention is obtained in surface treatments constructed with rapid-curing cutback binder as the curing time is increased before traffic is allowed on the construction. (The authors suggest at least a 48-hr curing time for RC cutbacks.)
4. Cover aggregate should be as uniform in size as is practical and should be applied as soon as possible after the asphalt binder is applied.
5. Retention of the aggregate is reduced when the aggregate becomes wet or dirty.
6. The Kearby method was suggested as a good procedure for determining asphalt quantity for a single surface treatment.

54-3 Gordon, R. S. A BIBLIOGRAPHY AND ANALYSIS OF BITUMINOUS SURFACE TREATMENT—THEORY AND PRACTICE. Thesis, Master of Science in Civil Engineering, Purdue University, 1954. (unpublished)

This thesis presents an analysis of surface treatment theory and design methods. It contains information about aggregate sizes, bituminous material, and methods for determining quantities of each. The annotated bibliography lists articles pertaining to surface treatments published prior to 1954 and is quite comprehensive.

54-4 Lovering, W. R. SEAL COATS, ECONOMIC USAGE. Western Construction, Vol. 29, No. 4, p. 60, 1954.

The advantages and limitations to seal coating are discussed as well as the conditions under which seal coating should not be done. A method is given for calculating a spread modulus based on the gradation of the cover aggregate. This modulus is directly proportional to the spread of the aggregate obtained in the laboratory. The author also relates that California has been successful in using a seal coat produced by mixing an open-graded aggregate with 5 percent asphalt in a plant.

54-5 Winters, W. F. HOW TO IMPROVE ASPHALT QUALITY. Public Works, Vol. 85, No. 4, p. 84, April 1954.

Primarily this article deals with the characteristics of asphalts to which rubber has been added. The author's report indicates that rubber improves the adhesion of the asphalt and that actual seal coat projects with rubberized-asphalt were an improvement over other types fo construction.

54-6 REPORT OF THE ROAD RESEARCH BOARD FOR 1954. Road Research, Department of Scientific and Industrial Research, England, p. 52, 1954.

In connection with tests conducted by the Road Research Laboratory to determine the best rates of spread of binder, a series of four experiments has been laid on roads in four areas to cover rather different climates and traffic conditions. No results are given.

55-1 Alcoke, W. H. SEAL COATS WITH LATEX TESTED. Roads and Streets, Vol. 98, p. 143, July 1955.

A combination of asphalt and Firestone synthetic latex is discussed as a suitable binder which maintains desirable properties over a wide range of temperature. Using a full-scale laboratory test track, latex, applied separately on the binder by means of spreaders, was found to be more advantageous than an asphalt binder combined with 5 percent latex. The latex in the spreader should be kept under pressure to prevent clogging and breakdown of the emulsion. Performance from the point of loose aggregate and adhesive characteristics indicates that the asphalt rubber mixture is better than unrubberized asphalts.

55-2 Compton, R. K. SEAL COATINGS PRESERVE AIRPORT PAVEMENTS. Public Works, Vol. 86, p. 134, March 1955.

This work resulted from studies by the U. S. Army Corps of Engineers of the behavior of asphaltic concrete under high-tire pressure from aircraft. They determined that seal coating with cutbacks is a good countermeasure against deterioration of the pavement that is caused by excess voids in the pavement, low asphalt content, or lack of traffic in some areas of pavements.

55-3 Harris, J. R. SURFACE TREATMENT OF EXISTING BITUMINOUS SURFACES. Proc., Association of Asphalt Paving Technologists, Vol. 24, p. 253, 1955.

The method of construction of surface treatments over existing bituminous surfaces in the state of Texas is discussed. It is assumed that surface treatments are properly designed to fulfill their functions. The bituminous binder used in Texas is an asphalt cement ranging in penetration from 135 to 230. The significance of the control of the binder distribution, the spread of the coverstone, and rolling are emphasized. The comment is made that pre-coated aggregates shorten the curing time and eliminate dust.

55-4 Hebert, E. C. A REVIEW OF FUNDAMENTALS IN SURFACE TREATMENTS. Proc., Association of Asphalt Paving Technologists, Vol. 24, p. 234, 1955.

This article contains some fundamentals to be considered in surface treatment construction of single and multiple course. Control of traffic for a period of 24 hours increases the effectiveness of any maintenance operation. It is reported that 100-200 penetration asphalt cement seems to provide the best performance. The application temperature of the binder should be controlled to avoid streaking. It was also suggested that the best viscosity was 40 to 60-sec Saybolt Furol. Also covered are some primary requirements for coverstone and driveability.

55-5 Kuipers, J. P. MODERNE OPPERVLAKTEBEHANDELING. (Modern Surface Dressings.) Wegen, Vol. 29, No. 5, p. 129, 1955.

The purpose and elements of surface treatments are discussed in this Dutch article as well as the application in practice. Two simple equations are given for determining the quantities of cover aggregates and binder. Some factors, not normally considered in design, are used in determining these quantities. The roughness of the underlying surface is considered in computing the volume of the aggregate needed, while a "traffic factor" is taken into account in determining the amount of asphalt to be used.

55-6 Martin, J. T. PRECOATED DOUBLE SEAL TRIED ON TEXAS ROADS. Roads and Streets, Vol. 98, p. 136, April 1955.

This is a general description of experiments in Texas that used precoated double seal. Rates of application of asphalt and stone on two projects are listed.

55-7 Munsey, S. V. BITUMINOUS MATERIAL FOR TREATMENT AND PATCHING IN VIRGINIA. Roads and Streets, Vol. 98, p. 141, July 1955.

Virginia's method of classifying bituminous materials is described. The bituminous materials are grouped according to the use of the material rather than to the type of material. A newly developed portable patcher has been quite beneficial in maintenance work. It produces dry, hot aggregate that is needed for a good patch.

55-8 Pauls, J. T. SURFACE TREATMENT OF EXISTING ASPHALT PAVEMENTS. Proc., Association of Asphalt Paving Technologists, Vol. 24, p. 261, 1955.

This paper discusses the objectives of surface treatments and suggests that the laboratory work should be more closely correlated with the field work. Some discussion is given to the effect of fine aggregate (less than No. 10) in influencing the amount of binder needed. Asphalt cements in the 120-300 penetration range are satisfactory when used in dry weather and with dry aggregate, but rapid setting asphalt emulsions have proved to be satisfactory with wet aggregate. Avoidance of over rolling and control of the speed of the traffic are also emphasized.

55-9 Schuelie, W. H. RECENT DEVELOPMENTS IN EQUIPMENTS USED FOR SEAL COATS OR SURFACE TREATMENTS OF EXISTING BITUMINOUS SURFACES. Proc., Association of Asphalt Paving Technologists, Vol. 24, p. 242, 1955.

This paper discusses equipment used for surface treatment purposes. It is concerned with distributors, aggregate spreaders and rollers, as well as with other equipment such as brooms. The comments of various equipment manufacturers to suggested future equipment developments are included.

55-10 Schuelie, W. H. TRENDS IN DESIGN OF EQUIPMENT FOR SEALCOATING OR SURFACE TREATMENT OF EXISTING BITUMINOUS SURFACES. Roads and Engineering Construction, Vol. 93, No. 55, p. 48, 1955.

New developments and trends in the design of equipment for seal coating or surface treatment of existing bituminous surfaces are discussed. Problems of design and manufacturers' answers to questions concerning current trends and ideas are also given. (55-9)

55-11 Zube, Ernest. USE OF ASPHALT-LATEX EMULSION IN THIN WEARING SURFACES FOR STEEL BRIDGES AND STRUCTURES. Proc., Highway Research Board, p. 248, January 1955.

To provide a wearing surface for steel bridges with checkered or open grid type floors, and at the same time to reduce the dead weight, asphalt-latex emulsion was used as a binder for crushed aggregate to provide a thin wearing surface. This report describes in detail the construction procedure and the tentative specifications for placing this type of wearing surface.

55-12 PREVENTION OF WET WEATHER DAMAGE TO SURFACE DRESSINGS. Road Research Laboratory, Department of Scientific and Industrial Research, Road Note No. 14, London, 1955.

Even if proper construction techniques have been used, new surface treatments may fail if rain displaces the binder from the aggregates. Three methods are recommended to prevent this. In two of these processes a solution of the adhesion agent (quaternary ammonium compounds or long chain amines and amides) in creosote is applied to the interface between the binder and the aggregate. In the other method the adhesion agent is incorporated in the binder before spraying.

56-1 Cornthwaite, A. B. HOW VIRGINIA CONTROLS SEALING QUALITY. Roads and Streets, Vol. 99, No. 1, p. 160, April 1956.

Virginia Department of Highways has adopted specifications to control seal quality. Conditioning and preparation of the base, as well as rolling and adhesion tests for binders, are included in these specifications. Cutback asphalts and high penetration (200 plus) asphalt cements should meet adhesion requirements with the dolomite aggregates, but only liquid bituminous materials should meet adhesion test requirements with the hydrophyllic aggregates. Minimum acceptable air temperature and other climate control specifications are given. Also included are test procedures for measuring the adhesion of the bituminous materials.

56-2 Gronberg, G. D., and Blosser, N. B. LIVES OF HIGHWAY SURFACES—HALF CENTURY TRENDS. Proc., Highway Research Board, Vol. 35, p. 89, 1956. Also: Public Roads, Vol. 29, No. 2, p. 17, June 1956.

The average age and life expectancy of eight major surface types including surface treatment, which is classified as an intermediate type of construction, were studied. Data compiled from information obtained from 25 states indicate that the average age of intermediate surfaces was 10.9 years and that the remaining life expectancy was 5.9 years.

56-3 Peters, J. EXTENSION OF THE LIFE OF SURFACE DRESSINGS AND FRAYED SURFACES. Surveyor, Vol. 115, No. 3337, p. 132, 1956.

This brief article describes a bituminous mortar which improves the performance of surface treatments. The mix is composed of a pit sand and a stable, high penetration asphalt emulsion (Lomix, manufactured by British Bitumen Emulsions, Ltd.). It is mixed at the plant in concrete mixers in the ratio of approximately 20 gallons of bitumen per ton of sand. The mixture is applied to newly sprayed surfaces after about a week and is spread by squeegees. Rates of application are given in the article. This mixture was found to extend the life of surfaces on which it was tried by at least eight years. No bleeding was found to occur in tar-sprayed surfaces.

56-4 THE REPORT OF THE ROAD RESEARCH BOARD FOR 1956. Road Research, Department of Scientific and Industrial Research, England, p. 48, 1956.

The first section of this report discusses the control of the rate of spread of the binder with the geared-metering pump system previously developed. It is reported that variations in the rate of spread with this equipment were on the average less than one-fifth of the variation of the conventional constant pressure pumps.

In the second part, the prevention of wet-weather damage to fresh surface treatments by dissolving the surface active agents in the binder is discussed. This way of using surface active agents has been considered more convenient than other methods. The quantity of agent necessary for good adhesion is decided both by the test temperature and by the viscosity of the binder at a standard temperature. The minimum quantity of a particular agent was obtained by using the immersion tray test at different temperatures and at different grades of bitumen.

57-1 Benson, F. J. SURFACE TREATMENT FOR HIGHWAYS. Public Works, Vol. 88, No. 5, p. 108, 1957.

This article describes the essential functions of a surface treatment (waterproofing layer, non-skid surface, color or lane demarcation), the characteristics of the aggregate to be used as well as the quantity required, the type and amount of bitumen used, and the use of the Kearby Curve in determining the depth of embedment. Cubical or pyramidal particles with maximum to minimum size ratio of 2:1 should be used, ideally. Other important considerations are stripping and loss of adhesion which can probably be evaluated by the ASTM Immersion Compression Test. Precoated aggregates probably will reduce the problems of moisture and dusty aggregates.

57-2 Gallaway, B. M. DURABILITY OF ASPHALT CEMENTS USED IN SURFACE TREATMENTS. Proc., Association of Asphalt Paving Technologists, Vol. 26, p. 151, 1957.

Ten different surface treatment projects on primary and secondary highways constructed in the summer of 1954 in various parts of Texas were studied. The construction procedure used was similar in each case. The asphalts used were penetration grades and varied from 132 to 250.

Tests were performed on the asphalt recovered from samples taken after one year and were compared with the results obtained from samples taken immediately after construction. This study may continue for a six-year period to evaluate the asphalt characteristics and pavement performance, as well as to study other influencing factors, such as traffic, rainfall, and temperature.

Other studies such as service evaluation by close-up photographs and the effect of artificial sunlight on microfilms of the asphalts were also conducted.

57-3 Gould, B. W. FLAKY AGGREGATES FOR USE IN BITUMINOUS SEAL COATS. Commonwealth Engineer, Vol. 44, No. 9, p. 74, April 1957.

Flaky aggregates are described as those having a width to thickness ratio of more than three. Bleeding will occur when small particles of the flaky aggregates break under traffic and become embedded in the binder. Experiments in Sweden have shown that the flakiness changes under rolling due to breakdown of the particles. The resulting aggregate is better shaped and is of a more uniform size. The author suggests that the thickness of the aggregate be controlled by using a set of sieves with elongated openings.

57-4 Peyton, R. L. ENGINEERING HIGH QUALITY SEAL COATS. Proc., Second Annual Highway Short Course, Engineering Experiment Station, University of Arkansas, Bull. No. 24, March 1957.

Production of high quality seal coats requires that engineering properties of the materials such as aggregate, binder, and road surface be known. Besides the above-mentioned properties, other factors which also must be considered in the design and construction of seal coats are (a) rate of applications, (b) uniformity of applications, (c) control of traffic, and (d) weather condition. These factors were discussed in detail.

57-5 Shattuck, C. L. PROTECTIVE SEAL COATS FOR BITUMINOUS PAVEMENTS. Military Engineer, Vol. 49, No. 327, p. 44, 1957.

These coal tar pitch emulsion seal coats were particularly developed for asphaltic concrete pavements which do not receive the advantage of continuous rolling under a full traffic pattern. This type of seal coating is used for aircraft refueling, parking and maintenance areas. It is applied in a minimum of two coats without any topping aggregate. If an abrasive surface is desired, coarse sand may be incorporated in the first coat and then the second coat seals in all loose particles. One advantage of this seal coat is that the cured film of coal tar pitch emulsion is resistant to petroleum derivatives which dissolve asphalt.

57-6 PRECOATED AGGREGATE FOR SURFACE TREATMENT. Roads and Streets, Vol. 100, No. 1, p. 219, January 1957.

This article discusses the advantages and disadvantages of pretreated aggregates. Precoated aggregates used in one experimental section showed a decrease in the needed rate of binder application. Elimination of dust and bleeding, and decrease in the loss of aggregates were listed as advantages. Surfaces constructed by precoated aggregates also require less rolling and only pneumatic rollers need to be used. The possibility of streaking is indicated as one possible disadvantage.

57-7 THE REPORT OF THE ROAD RESEARCH BOARD FOR 1957. Road Research, Department of Scientific and Industrial Research, England, p. 57, 1957.

Viscosity ranges for bitumen for surface treatments are limited by the fact that the binder must be sufficiently fluid to wet the chipping aggregates when they are spread on and rolled. However, they also must be sufficiently viscous to hold the aggregate in place against the action of traffic when the binder has cooled to road temperature. In experiments described, some 40 sections covering 1½ miles of road were laid in the spring, summer, and autumn. The viscosity range and rates of spreading of the bitumens used are given. It was found that for work in the spring and autumn, a cutback bitumen should be more fluid than 200 sec at 40 C, while for work in summer on heavily traveled roads, it should be more viscous than 50 sec at 40 C. Measurements are being made every three months of the changes in viscosity of the bituminous films.

The use of hot or precoated aggregates, improved the wetting of the chips. However, precoated aggregates should be used in mid-winter only as an emergency measure.

58-1 Benson, F. J. SEAL COATS AND SURFACE TREATMENTS. Proc., 44th Annual Road School at Purdue University, Engineering Extension Department, Series No. 95, p. 73, April 1958.

Although a single surface treatment does not add much structural strength, it is suitable for light traffic. When used as such, it has an average life of

14 years and provides a waterproof, non-skid surface. Aggregates should be cubical or pyramidal in shape and must be uniformly graded with a maximum to minimum size ratio of 2:1. The aggregate quantity, as determined by a spread test, should be increased 10 percent to get field quantity.

The mat thickness determines the amount of bitumen needed. This bitumen should be fluid initially and then should revert to a harder condition rapidly. RC cutbacks and soft asphalt cements are most desirable. The amount of bitumen must not only provide sufficient aggregate embedment, but also must satisfy surface absorption requirements.

Multiple surface treatments are used with large stones at the lower layers and with the top layer having aggregate one-half the size of the lower layer. The bitumen for the top layer is 130-140 percent of lower layer and should have a viscosity at the time of spreading of 40-60 seconds. Pneumatic-tire rollers and mechanical spreading devices are recommended for use in surface treatment construction.

58-2 Bixby, H. M. BITUMINOUS PRETREATED AGGREGATE FOR BITUMINOUS SURFACE TREATMENT. Crushed Stone Jour., Vol. 33, No. 2, p. 12, 1958.

A crushed stone producer developed some equipment to eliminate dust in aggregates used in surface treatments by precoating them. MC-0 is used for precoating in amount equal to 0.5 percent of stone weight. Aggregates are spread and rolled and the results indicate less dust, more retention of fines and a better appearance.

58-3 Clark, H. C., and Hignell, E. T. EFFECT OF HUMIDITY ON CURING OF LIQUID ASPHALT WITH SPECIAL REFERENCE TO SURFACE TREATMENT PRACTICE. Proc., Association of Asphalt Paving Technologists, Vol. 27, p. 1, 1958.

The effect of humidity on the rate of evaporation of solvent from cutback asphalts has been investigated under controlled humidity conditions. It was concluded that the humidity has significant effects. As the humidity is increased, the required curing time is also increased.

58-4 Creamer, W. M., and Brown, R. E. APPLICATION OF A NEW NON-SKID SURFACE TREATMENT ON CONNECTICUT STATE HIGHWAYS. Bull. 184, Highway Research Board, p. 10, 1958.

This report describes a method of application and the usefulness of thermosetting epoxy resin as a new material for surface treatments. The treatment consists of an application of sharp, hard aggregate bound to the underlying concrete by thermosetting epoxy resin. It provides a good skid-resistant surface even on dangerously slippery concrete.

58-5 Coulter, T. M. THE DESIGN OF BITUMINOUS PAVEMENTS. Main Roads, Vol. 24, No. 2, p. 42, 1958.

In New South Wales, the most common form of bituminous pavement used is the light surface treatments. A primer-binder is added in most cases to insure a denser surface, better affinity of the seal coat binder and the road surface, and to hold the gravel pavement in shape for some time. The rate, grade, and type of binder depend on the road conditions. Cover gravel should meet Los Angeles Abrasion test requirements (20-35%) and Flakiness Index of British standards. The aggregate should also be uniformly graded with size depending on traffic. For ½-in. aggregate or more, a filler course of one-half the size of the main aggregate should be applied and embedded in the interstices to reduce noise. The best value of the rate of spread was found to be the average least dimension of the aggregate divided by 22.

58-6 Lee, A. R. RECENT RESEARCH ON SOME PROBLEMS IN CONSTRUCTION AND MAINTENANCE OF ROADS. Roads and Road Construction, Vol. 36, No. 424, p. 98, April 1958.

Serious failures can occur very shortly after laying surface treatments on roads carrying medium or heavy traffic if wet weather occurs within about 24 hours after completion of work. Fast, intense traffic may fling aggregates off the roads exposing a layer of binder that may be slick. This problem has been solved by use of surface active chemicals—cationic materials consisting of a long-chain hydrocarbon soluble in tar or bitumen and a positively charged section which is attracted by the negatively charged surfaces of siliceous aggregates. Ways of using the chemical are described; all of which were reported to be effective. The "Immersion Tray Test" is described for testing the likelihood of suitable performance of a chemical.

58-7 Lovering, W. R. SELECTING ASPHALT BINDERS FOR SEAL COATS. Western Construction, June 1958.

Determination of the type and grade of the asphalt binder for seal coats is considered to be dependent on: (a) pavement and air temperature, (b) size of chippings, and (c) traffic and alignment of the highway. On cold surfaces, RC cutbacks are preferred over MC cutbacks; while on hot surfaces emulsified asphalt is more suitable. Viscosity of the asphalt used for wetting the aggregates is independent of chipping size; whereas for retention of aggregates the viscosity should increase with chipping size. Heavier grades of asphalt are needed for heavier traffic. The binder must harden in a short time and develop strength in order to hold the chippings.

58-8 Snyder, V. R. SEALING BITUMINOUS CONCRETE PAVEMENTS. Public Works, p. 86, July 1958.

Approximately 110 miles of cracked pavements have been seal coated in Iowa by an application of 200-300 AC, MC-4 or -2, RS-2, and ½-in. size cover aggregate. The aggregate quantity was determined by finding the spread ratio and effective mat thickness. The quantity of the binder was determined by the Kearby method and assuming 35 percent embedment for ½-in. aggregate. Also included are the methods of construction and a specification requiring a specific viscosity of the binder at the time of application.

58-9 RECOMMENDATIONS FOR TAR SURFACE DRESSING. Road Research Laboratory, Department of Scientific and Industrial Research, Road Note 1, 1958.

This note contains recommendations for construction of tar surface treatments over five different types of pavements. It is emphasized that the most important factor determining the life of surface treatments is the amount of tar and the degree of uniformity in its application. Also included are the recommendations for selection of proper type and amount of binder as well as the selection of proper gradation and size of aggregate for surface treatments suitable for each type of the underlying pavement.

58-10 SURFACE TREATMENT MANUAL. American Bitumuls and Asphalt Co., 1958.

This 57-page pamphlet covers surface treatments rather thoroughly except for design. "Why" and "when" to seal coat are two parts of the publication. The major portion, however, is related to construction techniques and equipment. This is a fairly excellent section and would be good for the construction engineer.

59-1 Coulter, T. M., and Punch, J. J. DESIGN, CONSTRUCTION AND MAINTENANCE OF ROADS AND RUNWAYS. Permanent International Association of Road Congress, XIth Congress, Rio de Janeiro, 1959.

In Australia, thin sprayed surface treatments are used for low-cost roads. It is the general practice to use straight run 80/100 penetration grade bitumen that is cutback in the field with kerosene or other light flux oil to a viscosity suited to the conditions needed on each particular job. The amount of flux used depends principally on the nature of the coverstone, the volume of traffic, and also the expected changes in weather conditions.

To protect newly constructed surfaces against stripping caused by rainfall during the early life of the pavement, either antistripping agents are added to the binder, or aggregates are precoated with creosote or with a light petroleum tar. A method used in the state of Western Australia for improving initial adhesion of cover aggregates is to spray the spreaded cover aggregate with a light application of kerosene or creosote prior to the final rolling. Tests for determination of aggregate polishing are given in the Appendix.

59-2 Johnson, J. C. LOADING DESIGN FOR ASPHALT PAVEMENTS. Public Works, Vol. 90, No. 1, p. 77, January 1959.

Primarily the article deals with the design of all types of surfaces. However, it is recommended that surface treatments be used only for light and medium traffic.

59-3 McLeod, N. W. ASPHALT SURFACE TREATMENTS AND SEAL COATS. Proc., Fourth Annual Conference of Canadian Technical Asphalt Association, Vol. IV, p. 49, 1959.

Critical construction practices and the design of surface treatments are discussed. While many new ideas related to surface treatments are presented in this article, the author covers the subject in more detail in Reference 60-3. For an idea of what is covered to a less extent in this article, see the annotation to Reference 60-3.

59-4 Wood, T. K. DOUBLE ASPHALT SURFACE TREATMENTS. Rural Roads, Vol. 9, No. 2, March-April 1959.

The design and construction of double asphalt surface treatments as practiced in Texas are described. The amount of binder is determined by the application of the theory of absolute volumes. Close control of rate of application of binder and aggregate, and rolling and brooming are required during construction.

59-5 Zube, E. SEAL COATS: LABORATORY CONTRIBUTIONS TOWARD PERFORMANCE. Highway Research Board, Bull. 215, p. 14, 1959.

A number of field tests were developed to provide means for evaluating the quality of work being performed on a seal coat construction job. They were (a) method for checking transverse and longitudinal spread of asphalt distributor, (b) temperature study of bituminous binder from time of application of binder to rolling of screenings, (c) degradation of screenings due to rolling and traffic, (d) absorptiveness and permeability of pavements, (e) rate of curing of bituminous binder and adherence of screenings, and (f) seasonal effects on performance of seal coats.

59-6 THE REPORT OF THE ROAD RESEARCH BOARD FOR 1959. Road Research, Department of Scientific and Industrial Research, p. 66, 1959.

It was reported that two full-scale experiments were started in 1959 to investigate if rubberized bitumen would improve the durability of a surface treatment carrying light traffic and also if a crazed and cracked road would be improved if sealed with it. Two percent natural rubber was added to the asphalt cement and cutback binders.

Experiments were also carried out on coated chippings for surface treatments. Cold wet chippings can be easily coated with a very fluid binder made from a hard asphalt base and a volatile fluxing oil to which is added five percent of a commercial cationic adhesion agent.

60-1 Bower, H. C. CATIONIC ASPHALT-EMULSION FOR SURFACE TREATMENTS. Roads and Engineering Construction, Vol. 98, No. 2, p. 90, February 1960. Also presented at Canadian Technical Asphalt Assoc., 4th Annual Conv., Vol. IV, 1959.

This article discusses in detail the utilization of asphalt emulsions in surface treatments. In order that an early bond between the cover aggregate and the binder may develop, the emulsion should break. Breaking of emulsions is produced by evaporation of water, absorption of water, and pressure of the roller. Both cationic and anionic type emulsions are discussed. It appears that there is no difference in the quantity of application required, regardless of the type of the emulsion used.

60-2 Dewhurst, J. R. THE SETTING OF ROAD TAR IN SURFACE DRESSING. Jour. of Applied Chemistry, Vol. 10, Part II, p. 470, November 1960.

"Tar has been recovered from a number of surface dressings at intervals during the first year of their life and the changes in viscosity determined. A method is described for determining the contributions of oxidation and loss of oils to the observed hardening, and the results for one pair of dressings are given. The hardening of the tar was mainly due to loss of oils, oxidation accounting for about one-quarter of the effect. Tars derived from a high-aromatic crude only have been examined; other tars are to be tested in a similar way."

60-3 McLeod, N. W. BASIC PRINCIPLES FOR THE DESIGN AND CONSTRUCTION OF SEAL COATS AND SURFACE TREATMENTS WITH CUTBACK ASPHALTS AND ASPHALT CEMENTS. Proc., Association of Asphalt Paving Technologists, Supplement to Vol. 29, p. 1, 1960.

This is a very comprehensive article (150 pages including discussion) dealing with seal coats and surface treatments. It covers failures, construction, techniques, and a thorough design procedure. The design is based on Hanson's work (35-1) and some modification to this basic work as made by the County Roads Board of Victoria, Australia. The quantity of aggregate and binder are related to an "average least dimension" of the aggregate, and the quantity of the binder is further related to the voids between the compacted aggregates. Charts are also given that allow the selection of an appropriate type and grade of asphalt for the size of aggregate used and the road surface temperature at the time of application of the binder.

60-4 Nevitt, H. G. CAREFUL DOES IT; ASPHALT SURFACE TREATMENTS. Roads and Streets, Vol. 103, p. 199, April 1960.

This article discusses the importance of the materials, the proportioning of the materials, and construction control in obtaining a desirable surface treatment. Remarks are also made that surface treatments are both an important component part in stage construction and a low-cost method of paving for light traffic.

60-5 Nevitt, H. G. COMMON ERRORS IN SURFACE TREATING. Roads and Streets, Vol. 103, p. 174, May 1960.

The most common error in constructing surface treatments, as considered by the author, is the lack of good engineering in the planning and carrying out of the work. Other common errors mentioned are insufficient amount of asphalt, aggregate, unsatisfactory aggregate, unsuitable weather, and poor traffic control. The latter errors are all related to a lack of understanding of how surface treatments and seal coats function and of their engineering.

60-6 THE USE OF ROAD TAR—RECENT DEVELOPMENTS WITH SPECIAL REFERENCES TO DENSE TAR MACADAM BASE AND WEARING SURFACE. Roads and Road Construction, Vol. 38, No. 447, p. 91, March 1960.

A portion of this article is devoted to a discussion about the suitability of tarred (precoated) chippings in surface treatments. It was noted that the amount of tar, needed as the binder, should be the same as if untarred chippings were used. These tarred chippings have made the use of surface treatments on main roads carrying fast traffic practical. For emergency treatments of slippery roads in the winter, the tarred chippings should be hot (over 120 F).

60-7 THE ASPHALT HANDBOOK. The Asphalt Institute, College Park, Md., Manual Series No. 4, September 1960.

This book covers many phases of asphalt construction and one of its sections is on "Surface Treatments and Seal Coats." Construction, types of materials and suggested quantities are given. However, no design method is suggested.

60-8 PROCEDURE FOR CONDUCTING CONDITION SURVEYS OF CHIP SEAL COATS. Research Division, Department of Highways, State of South Dakota, December 9, 1960.

This report deals extensively with the procedures established for the rating of seal coats. Five major factors influencing the overall performance of seal coats are evaluated independently and numerical values ranging from 0 to 20 are assigned to each factor. These factors are chip retention, skid resistance, uniformity of application, cracking, and bleeding. The summation of all of the numbers assigned to each factor is an indication of the overall performance and condition of the rated seal coat. A similar method is reported for rating the condition of underlying surfaces prior to the application of the seal coats. Also included are two typical forms that are used to record the results of the rating.

61-1 Dickinson, E. J. THE WETTING OF "AIR DRY" STONE BY BITUMINOUS BINDERS IN THE ROAD SURFACE DRESSING OPERATION. Jour. of the Institute of Petroleum, Vol. 47, No. 445, p. 22, 1961.

Factors affecting the retention of stone on a surface treatment laid under dry conditions on a lightly traveled road carrying fast traffic have been investigated. To insure permanent retention of the stone, two conditions that must be fulfilled are (a) the surface viscosity of the sprayed binder film must be low enough so that the stone is rapidly wetted, and (b) the binder film viscosity during the 24 hours following application should be low enough so that traffic on the surface can arrange the stone into an interlocking mosaic. Cutback bitumens, although suitable for cold conditions, are not as effective as would be expected from their low viscosity because evaporation of oil from the top of the sprayed film gives an increase in surface viscosity.

61-2 Mackintosh, C. S. RATES OF SPREAD AND SPRAY IN BITUMINOUS SURFACE DRESSING OF ROADS. Civil Engineer of South Africa, Vol. 3, No. 10, p. 183, 1961.

This article contains a design method for surface treatments developed for use in South Africa. It is reported to be a fast, easy, and economical method of design. Basically, a pan, similar to a test board, is used to obtain the quantity of aggregate. The aggregate, instead of being weighed, is passed into a cylinder and the aggregate spread ratio is determined directly by reading a graduated dipstick. Thus the aggregate shape is taken into account automatically. A nomograph is also given for use in determining the binder requirement. (See the Appendix for further detail.)

61-3 Stewart, S. A. HIGH SPEED ROAD SURFACING UNIT. Surveyor, London, Vol. 120, p. 820, 1961.

A description is given of a machine which is capable of surface treating a road in one operation at speeds between 3 and 15 mph. The machine can operate without interruption of traffic. The self-contained unit has an aggregate capacity of 11 tons and a binder system of 700-gal capacity. The rate of spread is determined by a six-speed gear box which gives application rates of 3½, 4½, 5, 5½, 6, and 7 sq yd/gal. These rates are constant within 0.25 sq yd/gal regardless of vehicle speed.

A specially designed spray-bar is used for binder application. It consists of three rows of 12 jets each. At vehicle speeds up to 7 mph, only one bank of jets is used; the second row comes into operation at speeds between 7 and 12 mph, and the third row at higher speeds.

62-1 Kari, W. L., Coyne, L. D., and McCoy, P. E. SEAL COAT PERFORMANCE. Proc., Association of Asphalt Paving Technologists, Vol. 31, p. 1, 1962.

In this paper, one quantity design method is presented for use. Empirical design formulas are given as are the assumptions made in their derivations. In addition, a number of factors that influence the performance of surface treatments are discussed. (See the Appendix for additional detail.)

62-2 Walker, R. N., and Rigden, P. J. SURFACE TREATMENT EXPERIMENTS WITH MIDDLE EAST AND VENEZUELAN BITUMENS. Proc., Australian Road Research Board, Paper No. 86, Vol. 1, Pt. 2, p. 793, 1962.

Due to observed differences in performance of road bitumens manufactured in South Africa from Middle East crude petroleum and from other (imported) sources when resealing under cold or wet conditions, a full-scale road experiment was conducted to investigate the causes of these differences. The performance of various types of bitumen is described and the results of inspections of the road experiment are given. The conclusion is drawn that although the Middle East bitumen has in certain respects inferior physical and chemical properties, the effect of these properties on performance is probably masked by other factors when on the road.

62-3 GRAVEL SURFACE DRESSING. Cement, Lime, and Gravel, Vol. 37, p. 117, April 1962.

The article reports on gravel surface dressing (surface treatments) in Great Britain. A test for binder distribution is presented and the importance of uniform distribution is emphasized. A discussion of surface dressing with gravel is given and it is reported that much of the trouble with such construction arises by use of too large an aggregate. Gravel size should vary with the amount of traffic expected (½ in. for heavy traffic to ¼ in. for light traffic). The conclusion was made that, in general, the reasons for failure

of surface dressings are poor binder application and wrong aggregate size. If these two factors are properly accounted for, "the resultant road surface should be as good as any."

62-4 CHIPPING SIZES A CRITICAL FACTOR IN GOOD SURFACE DRESSING. Surveyor, Vol. 121, p. 373, March 1962.

The article reports that chipping (aggregate) size is a critical factor in good surface dressings (surface treatments). "Most surface dressing failures are caused because surveyors are using too large a chipping." It is reported that the current trend is to use a reduced top size, i.e., ⅜ in. instead of ½ in., to improve surface treatment performance. Further, good surface treatments depend on the right balance of three factors: (a) size of aggregate, (b) amount of binder, and (c) even distribution of aggregate and binder.

63-1 Bohn, A. O. THE BREAKING OF ASPHALT EMULSIONS FOR SURFACE TREATMENTS. Proc., Association of Asphalt Paving Technologists, Vol. 32, p. 353, 1963.

The problem of predicting the breaking time of asphalt emulsions for surface treatments construction when the climatic conditions are known (with basis on laboratory experiments) is discussed. A scratch strength method is used to determine the time dependent aspects of the material. Conclusions are drawn based on a knowledge of such factors as the (a) cloud situation, (b) road roughness, (c) breaking activity of the aggregate and the emulsion, (d) wind velocity, and (e) humidity of the air.

63-2 Letters, K. UEBER EINE GUENSTIGE BEEINFLUSSUNG VON OBERFLACHEN BEHANDLUNGEN DURCH DIE GEGENWART VON WASSER. Bitumen-Terre-Asphalte, Vol. 14, No. 12, p. 626, December 1963. (In German)

The results of an investigation into the advantageous influence of moisture on the retention of surface treatment aggregate by a bituminous binder material is reported. In practice, the aggregate particles are "always" coated with a dust layer in amounts from 0.2 to 1.0 percent. When the aggregate is placed on a bituminous layer, the dust which is present prevents the development of good retention characteristics. The addition of small amounts of water wets the dust and does allow good adhesion of binder to aggregate. It is reported that for an aggregate with dust contents of 0.5 to 1.0 percent and for water additions of 1.0 to 2.0 percent the adhesion properties on both the bottom and side surfaces of the aggregate are substantially improved (greater than a 50 percent increase in retention due to moisture addition).

64-1 Eager, W. L. EFFECT OF MOISTURE ON BITUMINOUS PAVEMENT IN ROCKY MOUNTAIN AREAS. Highway Research Board, Research Record No. 51, p. 100, 1964.

Stripping of asphalt films from aggregate surfaces in the presence of moisture and the resultant loss of mat stability and raveling of the aggregate from the surface are discussed. It is reported that the stripping phenomena is more pronounced with the lighter types of asphaltic materials (cutbacks). Seal coats can be used to retard this action. Types of seal coats used are described.

64-2 Leeming, J. J. LIVES OF SURFACE DRESSINGS. Surveyor, London, Vol. 123, p. 33, March 1964.

Cost records were used to carry out a statistical analysis of the lives of surface treatments in Dorset County, England. The analysis includes the

results for 15 years, ending with the 1963 construction season. Several tentative conclusions are drawn and the methods of analysis are described. A major conclusion is that the life of the treatment depends more on the type and size of aggregate than on the kind of binder material used.

64-3 Robinson, D. A. ROADS SURFACE DRESSING IN SWEDEN. Roads and Road Construction, Vol. 42, p. 360, November 1964.

The results of observations made during a comprehensive program of inspection of surfacing work in progress and previously completed, and of a routine and test section nature, are reported. In Sweden, the most popular method of "building-up" a road surface is by multiple surface treatments. The construction procedure for this method is outlined in the article. In general, a low viscosity tar is used in the first pass, a medium voscosity tar is used in the second pass, and the surface layer is constructed with a cutback bitumen. Where single-coat surface dressings are employed, cutback bitumen is always used rather than tar as the binder material. The quality of the surfacing work is reported as being "high." The most common fault was reported as being "fattening-up" rather than a loss of aggregate.

64-4 Swaminathan, C. G., and Shulka, R. S. FLUXING OF BITUMEN FOR SURFACE DRESSING. Indian Roads Congress, Road Research Bull., No. 9, p. 41, 1964.

The paper is concerned with the problem of cutting an 80 to 100 penetration asphalt cement with a kerosene oil cutterstock to account for differences in placement temperatures while insuring proper adhesion of the binder with the aggregates. Use of the cutback material enables bituminous surface dressing work to be conducted throughout the year in India. Laboratory and field data have been correlated and a chart developed to indicate the quantity of cutterstock required as a function of atmospheric temperature. Also included are rate of curing and application temperature results.

64-5 "NEW" MATERIALS USED IN SEAL COAT EXPERIMENTS. Minnesota Highway News, p. 1, November 6, 1964.

The use of a "new" aggregate in place of sand for seal coat construction is discussed. The new aggregate is produced from boiler slag. It possesses the quality of glistening in daylight and night hours and thus provides a built-in reflectorizing effect. In addition, the aggregate is competitive in price with the sand. The material has been used in experimental sections of highway subjected to all types of traffic. "Although it has not been in use long, early results are impressive."

64-6 ASPHALT SURFACE TREATMENTS AND ASPHALT PENETRATION MACADAM. The Asphalt Institute, Manual Series No. 13, 1964.

The manual contains information that can be used as a guide to the Asphalt Institute Method of design and construction of surface treatments. It describes the materials and equipment used in surface treatment construction and explains the surface treatment processes. Appendices are included which contain details of the design method and suggested specifications.

65-1 Herrin, M., and Saner, J. L. VOIDS IN ONE-SIZE SURFACE TREATMENT AGGREGATES. Highway Research Board, Research Record No. 104, p. 60, 1965.

The results of a laboratory study performed to determine the influence of aggregate characteristics on the void space in a one-size surface treatment aggregate layer are presented. The void space was investigated as a measure of the quantity of bituminous material needed in the surface treatment

construction. It was reported that: (a) the volume of the voids did not vary in direct proportion with the depth within the aggregate, (b) rounded aggregates had a smaller volume of voids than the more angular crushed stone, and (c) smaller aggregates had greater percent voids than the larger aggregates.

65-2 Major, N. G. BASIS FOR SELECTION OF BINDERS FOR CHIP SEALING. New Zealand Engineer, Vol. 20, No. 12, p. 521, December 1965.

The article proposes a rational basis for the selection of binders for road surface sealing work. In addition, criteria are presented for different properties which are required for seal binders at various stages of construction and service life. Examples of the application of asphaltic binder materials to field sealing operations are also given.

65-3 Schweyer, H. E., and Gartner, W. A STUDY OF TENACITY OF AGGREGATES IN SURFACE TREATMENTS. Highway Research Board, Research Record No. 104, p. 18, 1965.

The article reports the results of a tenacity test developed for measuring chip retention in surface treatments. Aggregate was embedded into a layer of asphalt cement under standard test conditions and then pulled away in mass so that the strength of bond between the aggregate and a laboratory roadbed could be determined. Variables in the study were limited to aggregate and asphalt spread quantity, the type, size and size distribution of the aggregate, and the consistency of the asphalt binder.

65-4 Swami, S. A. AUSTRALIAN METHOD OF SURFACE DRESSING. Jour. of the Institution of Highway Engineers, Vol. 12, p. 22, January 1965.

In this article a quantity design method for surface treatments is presented for use. The method employed takes into consideration the following factors: (a) size of aggregates; (b) grade of binder; (c) binder-aggregate relationships (application rates and allowance for surface texture); (d) pretreatment of aggregates; (e) fluxing of the binder; and (f) spraying, spreading and rolling requirements. A chart is presented to enable the determination of basic quantities of binder and aggregate based on the principle of the average least dimension of the cover aggregate. Tables of correction values are also given to take into account factors such as: (a) condition of old surface, (b) type of aggregate, and (c) climatic conditions, etc. (The design method discussed by Swami is almost identical to McLeod's method even to the extent of employing the same numerical correction factors. However, the method uses a slightly different procedure for correcting for the condition of the underlying surface.)

65-5 PRINCIPLES AND PRACTICE OF BITUMINOUS SURFACING, VOLUME 1—SPRAYED WORK. National Association of Australian Road Authorities, 1965.

This paper is concerned with sprayed bituminous treatments. It was prepared as an aid to people who are responsible for: (a) specifying the type of treatment to be used and/or (b) the actual construction of the surface treatment. Included are items pertaining to: (a) the issuing of specifications, (b) the ordering of materials, (c) the stockpiling of aggregates, (d) surface preparation and condition insofar as this influences design, and (e) field practice for work control.

APPENDIX

The major methods of designing seal coats and surface treatments that have been published in existing literature are summarized in this appendix. Each method is covered in a separate section and usually consists of two parts. The first part contains a written summary of the design method and generally some comments regarding procedures used and conclusions drawn. The second part of this section, when present, consists of an example of the design by the particular method. In some of the methods, an example is not given as either the design method was not suitable for preparation of an example or the design procedure was very simple and an example was not needed.

For reference purposes, the authors of this publication have given titles to each of the design methods. Where one person seemed principally responsible for developing or reporting the design, his name was used in the title. When more than one person was involved, the title was related to the organization for which these people worked. Since these titles were assigned for use in this publication, they may not be the same as used in a locality that designs surface treatments by one of these methods. Engineers in these areas, though, should readily recognize the design procedures they use regardless of the title.

HANSON'S DESIGN METHOD

The classic work on the design and construction of surface treatments was published by F. M. Hanson in 1935 (35-1). This New Zealand engineer made numerous tests and observations in the field regarding the construction of seal coats and surface treatments. From his studies he established a number of principles related to the bituminous binder and the size and amount of the aggregate. So fundamental were these principles, that they have been used by a number of engineers in developing other methods of designing seal coats and surface treatments (49-2), (54-4), (60-3). The principles set forth by Hanson were slow to be recognized in many parts of the world. Perhaps this was because he published this important paper in the Proceedings, New Zealand Society of Civil Engineering, which did not have widespread distribution. In any case, it was 10 to 15 years before some of the principles were realized and utilized in other design methods in the United States and other parts of the world.

In his article, Hanson did not specifically set forth a method of design of surface treatments. However he did give some general principles that he used in the design of this type of surface.

1. A one-size aggregate is the best gradation of aggregate to be used for seal coats and surface treatments.
2. The thickness of cover aggregate, one stone thick, will depend on the compaction that the aggregate has received. During compaction and even while under traffic loads, the aggregate will tend to reorient itself until it presents its least dimension in the vertical direction. Thus the average thickness of the aggregate is less after compaction than when first applied to the surface of the road.
3. The average compacted thickness of the aggregate can be assumed to be equal to the least dimension of the aggregate. Hanson suggests this average least dimension be determined by measuring at least 100 particles of the aggregate with a pair of calipers and averaging the results.
4. There is a definite relationship between the average least dimension of the aggregate and the quantity of spread of the aggregate. Hanson presents a chart relating the least dimension of the chips and the area in square yards that would be covered by 1 cu yd of the aggregate with an allowance for whip-off. Although he does not give the equation for this relationship, it is:

$$Q = 19.5/ALD$$

where

Q = quantity of spread, in sq yd/per cu yd of aggregate.
ALD = average least dimension of the aggregate, in in.

5. To allow for inadequate spreading during construction and for whip-off, the aggregate should be at least 10 percent greater than would be required to just cover the surface of the road.

6. The amount of voids in the aggregates before compaction is 50 percent, whereas the voids in the compacted aggregate will be 20 percent.

7. To hold the aggregate adequately in place, the voids should be filled 50 to 70 percent with bituminous material.

8. In order that the aggregate will extend far enough above the surface of the bituminous material and provide satisfactory skid resistance, the aggregate should protrude at least 0.11 to 0.185 (avg. 0.15) in. above the bituminous surface.

9. There should be little absorption of the bituminous material by the underlying pavement surface. If this surface does absorb part of the binding material, then (a) the surface may not be fit to be sealed, or (b) the surface may need to be primed first, or (c) the binder may be too thin (in which case it will not hold an appreciable amount of cover aggregate).

10. Correction should be made to the basic amount of bituminous material needed to account for the volume change that will take place as the material is heated to spraying temperature.

Although Hanson did not exactly list a step-by-step method for designing bituminous surface treatments, the principles that he suggested can be used in designing a surface treatment.

Example of Design Procedure

1. Assume the measured average least dimension of a cover aggregate to be 0.482 in.

2. The spread of the cover aggregate would be 19.5/ALD = 19.5/0.482 = 40 sq yd/cu yd of stone (this quantity includes an allowance for whip-off of 10 percent).

3. Since there are 20 percent voids in the compacted aggregate, the volume of the voids is equal to 0.20 x 0.482 = 0.0964 in., i.e., a layer of bituminous material of 0.0964 in. on the surface of the road will rise just to the average height of the aggregate (0.482 in.) and would appreciably fill all of the voids in the aggregate.

4. The minimum thickness of the bituminous material (before aggregate is added) that is needed to hold the aggregate chips adequately in place must be between 50 and 70 percent of the amount needed to just cover the aggregate. Thus it should be between (0.70 x 0.0964) = 0.0675 in. and (0.50)(0.0964) = 0.0482 in.

5. Similarly, the maximum height to which the bituminous material should rise between the aggregate so as to have satisfactory skid resistance is 0.482 - 0.15 = 0.332 in. Thus, the maximum thickness of bituminous material (before aggregate is added) so as to have adequate skid resistance is 0.0964 x 0.332/0.482 = 0.0664 in.

6. The binder thickness of 0.0664 in. is within the range needed to adequately hold the aggregate chips. Thus, 0.065 in. of bituminous material will be used (see step 4).

7. The quantity of bituminous material needed is 0.065 x 7.48 x 9/12 = 0.36 gal/sq yd.

CALIFORNIA DESIGN METHOD

Realizing that existing methods for designing seal coats and surface treatments were unsatisfactory, Hveem, Lovering, and Sherman, of the California Division of Highways, were one of the first groups in the United States to analyze the surface treatment design problem. In an article in the "California Highways and Public Works" (49-2), they presented a number of factors that they thought ought to be considered in a definite engineering approach to arrive at a solution to this problem. The authors did not believe that all of the conclusions and inferences drawn in their article were supported by complete field data, but stated "... as more information becomes available, procedures can be adjusted or modified as found to be necessary." They wanted the engineer

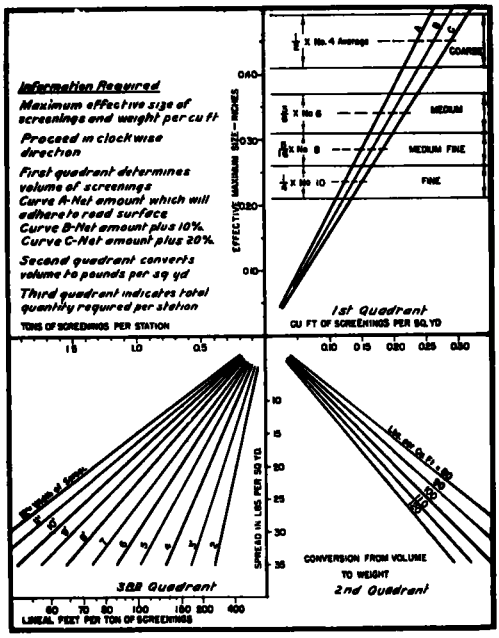

Figure 8. Chart for estimating the quantity of screenings to be applied for seal coat construction (data taken from Hveem, et al 49-2).

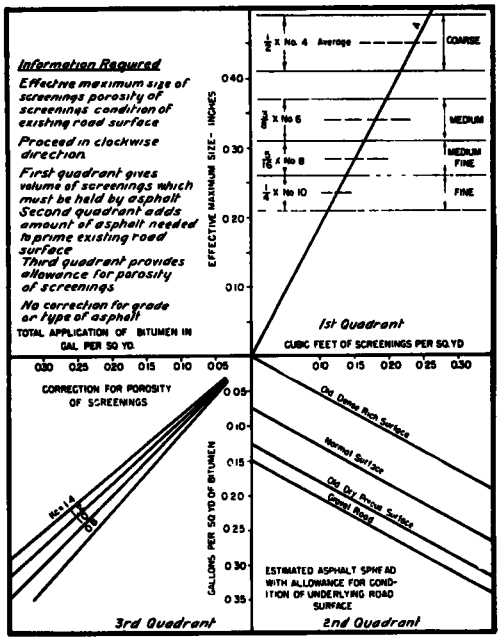

Figure 9. Chart for estimating the quantity of asphalt required for a seal coat (data taken from Hveem, et al 49-2).

to be provided with an orderly and logical procedure for designing surface treatments so that the design could be made with greater assurance than was possible at the time the article was written.

These authors not only had made a study of Hanson's work (35-1), but also carried out a series of investigations that tended to verify many of his conclusions (however, few of the actual data were reported). They also concluded that, with the graded aggregates commonly used in California, the method of determining the average mat thickness as suggested by Hanson (measuring individual aggregate particles with a calipers) was not feasible. They learned that the loose volume of the screens which would produce a layer one-stone thick could be related to an "effective maximum size," so long as closely sized aggregates containing no appreciable fine material were used. The "effective maximum size" is determined as the theoretical sieve size in inches which would allow 90 percent of the aggregate to pass through the sieve openings. Although realizing that other aggregate factors should be evaluated and considered, the authors state that the effective maximum size gives sufficiently accurate results for this work when the present limitation of construction methods and equipment is considered.

It is interesting to note that the "spread modulus" as used by Lovering later in the development of another method was first introduced by these authors. They determined that better correlation existed between the spread modulus and the loose volume of the screenings than between the effective maximum size and the loose volume. However, it was decided to use the effective maximum size in their design, since screenings from different sources gave somewhat different values in the spread modulus. In addition, they conclude from this that not all variables are considered in sieve analysis and that other variables, such as surface and shape of the aggregate, should be considered.

The relationship between the effective maximum size and the quantity of screens needed on the road surface is given in Figure 8, which is fairly self-explanatory. Beginning in the upper right quadrant with the effective maximum size of the aggregate, one progresses in a clockwise direction. The quantity of aggregate needed can be determined for various percentages of whip-off, aggregates of different unit weights, and for different widths of spread.

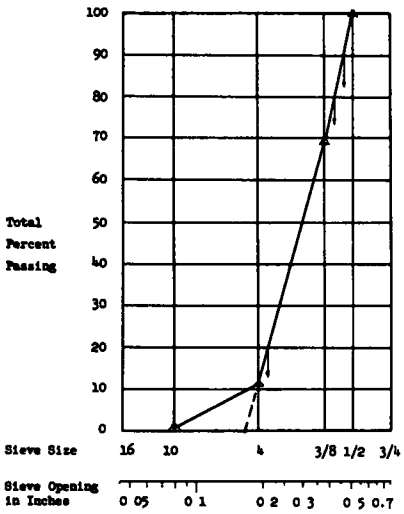

Figure 10. Gradation of aggregate used in the example of the California design method.

The allowance for various percentages of aggregate whip-off is fairly unique with this design procedure. Hanson had tentatively concluded that an allowance of approximately 10 percent should be made to the cover aggregate to account for whip-off. Many of the other design methods use this amount. The authors of the California method, however, estimated that under some conditions, depending primarily upon the construction conditions, at least 20 percent allowance should be made. They believed that the whip-off allowance factor should not be constant, but should be based on the type of spreading equipment and other factors.

The quantity of bituminous material to be applied, like the cover stone, is based upon the maximum effective size of the aggregate (Fig. 9). Use of the chart is explained in the figure and is similar to that for determining the quantity of cover stone (Fig. 8). In addition to the effective maximum size of the aggregate, the quantity of bituminous material is influenced by two main factors:

1. Condition of underlying surface. The basic quantity of asphalt needed for a normal surface should be reduced by approximately 0.075 gal/sq yd if the underlying surface is an old, dense, rich surface. However, if the road is an old, dry, porous surface, the quantity should be increased by approximately 0.05 gal/sq yd and if the road is a gravel road it should be increased be approximately 0.075 gal/sq yd.

2. Porosity of the aggregate. The additional amount of asphalt that an aggregate will absorb is related in this design method to a surface factor (K_c) of the aggregate. (The centrifuge kerosene equivalent test is used to determine the surface factor (K_c) by measuring the amount of No. 10 lubricating oil retained by the cover aggregate after it has been soaked in oil and then drained under specified conditions.) The authors note that the amount of bituminous material that will be absorbed by the aggregate depends on the consistency of the bituminous binder which in turn depends on the temperature. If a porous surface aggregate does not absorb the bituminous material initially because of low temperatures, then sand should not be applied to the surface of the seal coat to blot the apparent excess bituminous material. Later, when the temperature increases, the bituminous material will be absorbed by the aggregate and the surface will have less bituminous material than is needed. "It is probable that the best solution is to avoid porous aggregate when possible."

Example of Design Procedure

Determination of Quantity of Cover Stone

1. Assume the loose unit weight of the cover stone to be 86 lb/cu ft, and the specific gravity to be 2.65, and that the allowance for whip-off will be 10 percent. The gradation of the aggregate is to be:

Sieve	1/2 In.	3/8 In.	No. 4	No. 10
% Passing	100	69	12	1

2. Plot the gradation on semilog aggregate grading chart and draw a smooth curve through the points (Fig. 10).

3. From the grading chart, determine the effective maximum size of the aggregate as the theoretical sieve size in inches which would allow 90 percent of the aggregate to pass that opening. The effective maximum size of this aggregate is 0.46 in.

4. Enter Figure 8 in the first quadrant with an effective maximum size of 0.46 in. At the 10 percent whip-off (line B), move downward and read the quantity of screenings as 0.27 cu ft/sq yd.

5. In the 2nd quadrant, the quantity when converted from volume to weight is 23 lb/sq yd for an aggregate with a loose unit weight of 86 pcf.

6. If it is desired, the quantity of screening per 12 ft width of spread can be determined in the 3rd quadrant as 64 lineal feet per ton of screenings.

Determination of Quantity of Bituminous Binder

1. Assume the screenings have a $K_c = 1.2$ and are to be placed on a normal surface.

2. Since the effective maximum size is 0.46 in., enter the left side of the 1st quadrant of Figure 9. Go to the right until line A is reached. Drop toward the bottom of the page until the line "normal surface" is intercepted. Move to the left and read at the left side of the 2nd quadrant 0.21 gal/sq yd of bitumen, this is the amount required before correction is made for the porosity of the screening.

3. The correction for the porosity is made in the 3rd quadrant. Beginning at the right side of this quadrant at 0.21 gal/sq yd, move until the line $K_c = 1.2$ is intersected. Above this point at the top of the 3rd quadrant, the corrected quantity of bitumen is read to be 0.23 gal/sq yd.

NEVITT'S DESIGN METHOD

In 1951, H. G. Nevitt set forth his ideas for a seal coat design method (51-1). Nevitt stressed the point that materials requirements should be predicted as accurately as possible because of the ever-increasing costs, waste without benefit, and the poor appearance that can result from poor design.

Nevitt derived several equations for the "correct" determination of aggregate and bitumen quantities. In so doing, he made several assumptions which influence his design quantities. These assumptions are included in this summary with the general discussion of the design method.

Nevitt's derived formulas for aggregate quantity determinations, in general form, are as follows:

$$A = \frac{1}{CKD}\left(\frac{100 - U}{100 + O}\right)$$

$$A_1 = Kg\ CKDG\left(\frac{100 + O}{100}\right)$$

where

- A = application rate, in units of area per unit volume of loose aggregate;
- A_1 = application rate, in weight per unit area;
- C = coverage or spread factor denoting the proportion of highway surface covered by aggregate regardless of bitumen level (Nevitt does not suggest a method for the determination of this factor; however, several other authors have presented methods which could possibly be used);
- K = an aggregate-shape constant which accounts for use of either rounded or angular aggregate particles—numerical values range from 1.000 to 0.333;
- D = principal size of the aggregate; that is, it is the size of the majority of the particles that are at or very close to the intended "one-size" aggregate (Nevitt assumed the principal size—the size to be used with the previous formula derivations—to be given by the 50 percent point on the aggregate gradation analysis curve);
- U = percentage of voids in the cover aggregate (Nevitt suggests the approximate values of U to be U = 47.7 percent for crushed aggregates, and U = 41.7 percent for uncrushed aggregates;

O = the "overage factor," the average percent of the aggregate to be applied to the surface in excess of the calculated retained amount to compensate for losses (Nevitt suggests using a value of 20 percent);
G = ratio of the specific gravity of the aggregate to 2.65; and

Kg = a constant equal to the weight of water per unit volume times 2.65.

In all of the formulas for aggregate quantity determination, the product CKD is equal to the volume of the aggregate. The value of 100 - U is the percentage volume of aggregate in a given volume.

The assumptions made by Nevitt in his derivations for aggregate quantity are as follows:

1. The principal size is given by the 50 percent point on the aggregate gradation analysis curve.
2. One-sized, symmetrical particles are used. Nevitt believes the errors introduced by these first two assumptions for closely graded aggregate are not serious. For wide gradation the errors must be compensated for by adjustment factors. Values for these factors were not given.
3. An "overage factor" of 20 percent was used; however, Nevitt states that this was only a tentative value.
4. Bulking of the aggregate was not considered to be a problem.

When the previous equations are converted to a more suitable form by expressing them in usual terms and/or substitution of numerical values for such factors as permit this, the results are

$$A = \frac{36}{CKD}\left(\frac{100 - U}{100 + O}\right) \text{ sq yd/cu yd}$$

$$A_1 = 124\ CKDG\left(\frac{100 + O}{100}\right) \text{ lb/sq yd}$$

These equations are in consistent units.

In general form, Nevitt's derived formulas for the residual bitumen quantity are as follows:

$$B = 0.55\ D(K_h - CK)$$

$$b = 0.055\ D(K_h - CK)$$

where

B = required residual bitumen volume per unit of area;
b = bitumen tolerance or allowable variation which is approximately 10 percent of the residual embedment bitumen;
K_h = height constant of the aggregate, equivalent to the ratio of the average height of the layer to the principal size of the aggregate;
C = spread factor; and
K = the shape constant for the aggregate.

The assumptions made by Nevitt in his derivations for bitumen quantity are as follows:

1. The bitumen quantity given by his formulas refers only to the embedment residue. The diluting agent needed to give viscosity and the quantity of bituminous material which will penetrate into the old mat are not considered. Nevitt considers the calculation of the total bitumen content as a three-step affair: "The embedment residue should be determined by formula; the proper application viscosity, through selection of the suitable cutback grade, should be decided upon, and the embedment total volume found to correspond; then to this volume should be added that estimated as the amount of this

grade the old surface will absorb." In his paper, Nevitt places emphasis only on the first step because he thinks the second step should be determined by construction conditions, while the third step is dependent on the character of the old surface and the grade of asphalt selected for the particular job.

2. No allowance is made for aggregate surface characteristics such as absorption. Nevitt states that "the methods so far proposed to aid this calculation do not appear to have gained any popularity," and he, therefore, would rather ignore the factor.

3. One-sized symmetrical particles are considered as the aggregate to be used.

4. A bitumen level at the centerline of the aggregate particle plus a tolerance of 10 percent is thought to be desirable. Differential penetration into the underlying material makes the attainment of the bitumen level with any accuracy very difficult.

5. Particle volume below the centerline equals that above the centerline. In practice, this is hardly the case. Usually one side of the particle is larger than the other, and when placed, the particles orientate themselves so that the larger base is on the bottom of the layer.

6. The presence of fine aggregate particles has been neglected. When present, these particles tend to fill the lower portion of the voids and as such reduce the bitumen content required.

When the equations presented to this point are put into a form appropriate for American engineering usage, the following relationships result.

$$B = 3.09\ (K_h - CK)D \text{ gal/sq yd}$$

$$b = 0.309\ (K_h - CK)D \text{ gal/sq yd}$$

To further simplify his equations, Nevitt included the numerical values of U and O he had assigned to these factors.

For crushed aggregate:

$$A = \frac{15.7}{CKD}$$

For uncrushed aggregate:

$$A = \frac{17.5}{CKD}$$

$$B = 3.09\ (K_h - CK)D$$

All variables are as previously defined.

Nevitt's formulas depend on many factors which are difficult to evaluate. In some instances, no procedure has been established to provide a numerical value that can be used in the design equations. Because of this, the workability of the equations is such that the formulas are not desirable for practical design use.

Nevitt strongly stresses the fact that his equations are rational in form and that the constants given in his article are theoretical values which are "probably" too high. The actual constants to be used in practice require determination. Use of these equations is said to give accurate estimations of the required quantities. Nevitt concludes his paper by remarking that it is doubtful that any other approach can offer more than his since the same difficulties will be encountered by others.

MODIFIED KEARBY DESIGN METHOD

One of the most common methods for designing seal coats and surface treatments is based on the work of Jerome P. Kearby (52-3) (53-2). Although this method is widely used, its applicability is primarily limited to one-size aggregates—ratio of maximum to minimum size should be 2:1 with a reasonable tolerance for undersize or oversize

(58-1). The principle on which the design is based is that best results are obtained by "... using the coarser grades of aggregate of nearly uniform size with just sufficient aggregate to slightly more than cover the surface one stone in depth and by limiting the asphalt to an amount sufficient to embed only a portion of the thickness of the loose mat of aggregate" (53-2).

Kearby thought, as have others, that the required quantity of aggregate should be the amount that is needed to form an aggregate cover, one stone in depth, over the entire pavement surface. In this respect, the quantity of aggregate is definitely fixed. The average thickness of the aggregate when placed so as to form this mat is termed by Kearby as "effective or average mat thickness." Kearby suggests two methods for determining the average mat thickness.

1. One procedure is based on the sieve analysis of the aggregate. The percentage of aggregates for each individual screen size is multiplied by the average screen size. The sum of the products is the average mat thickness of the aggregate; in other words, it is the computed average size of the aggregate. The average mat thickness, when divided into 36 in., gives the number of square yards of area which may be covered by 1 cu yd of aggregate. This quantity is termed "the spread ratio." If desired, the spread quantity (in lb sq yd) can be determined from the spread ratio if the loose unit weight of the cover stone is known.

2. The other method recommended for determining the average mat thickness is the "test-board" method. A board, usually one yard square, is covered with a sufficient quantity of aggregate so that full coverage of the area with one stone in depth is obtained. The weight of the aggregate on the board divided by the area of the board is the "spread quantity." Using the loose unit weight of the material, the spread ratio and the average mat thickness can be computed.

In relating the average mat thickness to the spread quantity or the spread ratio, an assumption is made that the aggregate in the one-stone thick layer will have the same arrangement and voids as it will have when compacted in the mold for determining the loose unit weight. Unquestionably, this assumption is not correct. However, Benson (58-1) states that such an assumption "... provides a good theoretical method for determining average surface thickness...," which in turn can be used in computing the proper quantity of bitumen needed.

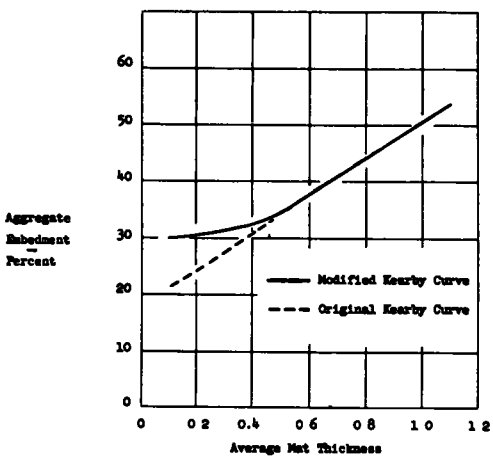

Figure 11. Relation of percent embedment to average mat thickness for determining quantity of asphalt (data taken from Benson 58-1).

The quantity of bitumen required was related by Kearby to the amount needed to embed the aggregate sufficiently in the asphalt so as to hold the aggregate firmly in place. Kearby further related the amount or percent of embedment to the average mat thickness. This relationship, as originally proposed by Kearby, is shown in Figure 11. Later investigations by Benson and Gallaway (53-1) (58-1) indicated that the relationship between the average mat thickness and the amount of embedment required, as proposed by Kearby, was accurate except at the smaller average mat thicknesses. They proposed a modification to the original Kearby curve. The modified curve is also shown in Figure 11. It is interesting to note that after this change Kearby used the modified curve in design. However, Peyton (57-4) in reporting on the Kearby design method as used in Kansas, indicated that the original relationship between the average mat thickness and the percent embedment should be used.

The percent embedment, as suggested by the modified Kearby curve, is applicable only

to regions with relatively hot summer weather (58-1). In cooler areas, the depth of embedment may be increased since there is less possibility of bleeding occurring during the summer months. However, no suggestion has been made as to the amount of increase that would be permissible.

Once the percent embedment is determined from the modified curve, the required amount of bituminous material can be computed from the average mat thickness and the voids in the aggregate (the latter quantity is calculated from the loose unit weight and specific gravity of the aggregate). Although the required volume of bitumen can be determined by appropriate mathematical computations, Kearby has devised a nomograph for these calculations (52-3) (53-2).

The quantity of bitumen as determined by the Modified Kearby Method, is applicable only to single surface treatments. However, limited studies (58-1) indicate that the required amount of bituminous material for a double surface treatment is 130 to 140 percent of that required for the single surface treatment. For a triple surface treatment, the required amount of bituminous material would be between 140 and 150 percent of that required for the single surface treatment. Benson (58-1) indicates the manner of distribution of the bituminous material between the various courses is not particularly significant. He suggests, though, that the application rates for the first course of a double surface be slightly greater than that used for the second course.

The required amount of bituminous material, as determined by this method, is based on an underlying surface that will have no effect on the amount of bituminous material needed. Accordingly, correction to the required basic amount of bituminous materials must be made when the underlying surface is "non-average." Although Kearby did not suggest any amount, Benson (58-1) suggests that no corrections be made for freshly primed bases or seal coats on normal bituminous surfaces. However, if the surface is porous and cracked, an allowance of 0.05 to 0.10 gal/sq yd should be made for absorption. Similarly, on an existing rich surface or on a very heavily primed surface, a reduction of up to 0.05 gal/sq yd in bitumen should be made.

A final correction must be made to the required amount of bituminous material needed if cutbacks or emulsions are used. This is to allow for the volatiles or water in the liquid bituminous material. Thus, the amount of asphalt cement in the liquid asphalt must be known and the amount of the liquid asphalt to be sprayed on the road must be increased over the basic requirement accordingly.

Kearby also indicates that some variation in the amount of bituminous materials and aggregate size should be made, depending on the amount and type of traffic. Although he does not indicate any specific values, he says, "For highways carrying high traffic counts and heavy vehicles, the percentage embedded should be reduced and larger aggregates used. For highways carrying light traffic counts and light vehicles, the percentage embedded should be increased and medium size aggregates may be used" (53-2). In almost all of his writings, Kearby noted that the average mat thickness, as computed by this method, may vary somewhat under actual construction procedures. In these cases, appropriate steps should be taken to increase or reduce the amount of bitumen.

Example of Design Procedure

Determination of Quantity of Cover Stone

A. Average aggregate size method:

1. Assume the loose unit weight of a cover stone aggregate to be 86 pcf, the specific gravity to be 2.65, and the gradation of the aggregate to be:

Passing sieve	1/2 In.	3/8 In.	No. 4	No. 10
Retaining sieve	3/8 In.	No. 4	No. 10	Pan
Avg. size	0.438	0.281	0.133	0.040
Percent (wt. basis)	31	57	11	1

2. The average aggregate particle size is the weighted average of each individual sieve size.

$$\begin{aligned} 0.31 \times 0.438 &= 0.1358 \\ 0.57 \times 0.281 &= 0.1602 \\ 0.11 \times 0.133 &= 0.0146 \\ 0.01 \times 0.040 &= \underline{0.0004} \\ \text{Avg. particle size} &= 0.3110 \text{ in.} \end{aligned}$$

3. Average mat thickness of a one-stone cover = the average size of the aggregate particle = 0.311 in.

4. Theoretical spread ratio = 3 x 12/0.311 = 115.8 sq yd/cu yd of aggregate.

5. Field spread ratio (10 percent greater than theoretical spread ratio) = 115.8/(1.00 + 0.10) = 105.3 sq yd/cu yd of aggregate. Field spread quantity = 86 x 27/105.3 = 22.0 lb/sq yd.

B. Test-board method:

1. The cover aggregate is spread to a thickness of one cover stone over a 1-sq yd test-board. The amount of aggregate on the board is weighed. Assume the weight to be 34.5 lb; also assume the aggregate has a loose unit weight of 88 pcf and a specific gravity of 2.67.

2. Spread quantity = 34.5/1 = 34.5 lb/sq yd.

3. Field spread quantity = 34.5 x 1.1 = 38.0 lb/sq yd. (an increase of 10 percent). Field spread ratio = 88 x 3 x 3 x 3/38.0 = 62.5 sq yd/cu yd.

4. A mat of this cover stone, 1 in. thick on a surface of 1 sq yd would weigh 1/12 x 3 x 3 x 88 = 66 lb/sq yd. The average mat thickness using the given aggregate therefore is 34.5/66 = 0.52 in.

Determination of Quantity of Bituminous Binder

1. The quantity of bituminous binder will be determined for the cover aggregate given in the preceding "average aggregate size" method. Assume the bituminous material is a cutback containing 15 percent cutterstock, and is to be placed on a fairly rich, existing surface.

2. The average mat thickness, as previously determined, is 0.311 in. From Figure 11, the percent embedment for this aggregate is 33 percent.

3. Depth to which aggregate must be embedded in asphalt is 0.311 x 0.33 = 0.103 in.

4. The percentage of the voids in the aggregate is equal to the total volume (1 cu ft) minus the solid volume of the aggregate:

$$\left[1 - \frac{86}{2.65 \times 62.4}\right] 100 = 48.0 \text{ percent}$$

5. Volume of bitumen required is 0.103/12 x 3 x 3 x 0.480 = 0.0371 cu ft/sq yd, or 0.0371 x 7.48 = 0.278 gal/sq yd. (Note: This quantity of bitumen is the amount of "basic" bitumen needed; if a cutback or emulsion is used, this volume needs to be corrected for the loss of volatiles or water that will occur.)

6. Since the surface treatment is to be placed on a rich existing surface, the quantity should be reduced by 0.05 gal/sq yd: 0.28 - 0.05 = 0.23 gal/sq yd.

7. The final corrected quantity, allowing for the 15 percent cutterstock, is 0.23/(1 - 0.15) = 0.27 gal/sq yd.

8. If a double surface treatment is to be placed, the quantity of cutback needed is approximately 0.27 x 1.35 = 0.37 gal/sq yd.

Use approximately half of this quantity, or 0.19 gal/sq yd for the first course and 0.37 - 0.19 = 0.18 gal/sq yd for the second course.

LOVERING'S SPREAD MODULUS DESIGN METHOD

Although strongly influenced by the research of Hanson, W. R. Lovering (54-4) decided that the direct measurement of individual aggregate particles for determing the average mat thickness was not very feasible. In addition, one-size cover aggregates used by Hanson had been found to be quite costly to produce. Accordingly, grading tolerances were established which permitted a small amount of both oversized and undersized aggregates in the cover-stone materials. A gradation such as this, required a method of calculating the average mat thickness that was different from the method that could be used when the aggregate is one-sized. Primarily this is because direct measurement cannot be used with the small particles of a graded aggregate (i.e., less than No. 10 sieve).

In order that a graded aggregate might be used as a seal coat cover aggregate, Lovering determined that there was a satisfactory correlation between the loose volume of cover stone required to produce a layer one stone thick and the "mean particle diameter," defined as the weighted average of the mean size of the largest 20 percent of the aggregate, the middle 60 percent, and the smallest 20 percent. The mean particle diameter was called by Lovering the "spread modulus."

Lovering realized that, due to normal fluctuation in the operation of the spreading equipment, slightly more cover stone than just a one-stone thick layer was actually needed. From observation and available data (which was not included in the paper), he concluded that a factor of 0.85 to 0.95 times the spread modulus would provide the proper quantity of screening in cubic feet per square yard with a reasonable allowance for both compaction and whip-off. Accordingly, he suggested that the quantities of screenings be calculated by

$$S = 0.9M$$

where

S = cubic feet of screening per square yard, and
M = spread modulus.

Lovering was also influenced by Hanson's work in regard to the amount of voids in the cover aggregate and the amount of the voids to be filled with bituminous material. Lovering decided that an average value of 0.075 cu ft of binder should be used for each cubic foot of loose screening before the allowance is made for whip-off. Thus, he concluded, the quantity of bituminous material required (in gal/sq yd) is equal to 0.56 (0.075 × 7.5) times the cubic feet of cover stone per square yard exclusive of the allowance made for whip-off. When the spread modulus is used instead of the actual quantity of cover stone, Lovering says that the required amount of bituminous materials can be calculated from

$$A = 0.4M + V$$

where

A = required amount of asphalt, in gal/sq yd;
M = the spread modulus; and
V = the quantity of bituminous material, in gal/sq yd, to allow for absorption by the underlying surface; the suggested values for V are 0 gal/sq yd for rich or fat surfaces and 0.1 gal/sq yd for average surfaces—these values should be increased or decreased depending on the dryness and the denseness of the underlying surfaces.

Care should be taken in comparing the required basic amount of asphalt as determined by Lovering's equation and that determined by other methods, i. e., in comparing the amount of asphalt before correction is made due to the condition of the underlying surface. From the quantities of V suggested by Lovering, the basic amount given by

Lovering's equation should give less quantity. A rich or fat surface is used as the basis of determining the basic amount instead of a normal or average surface as in the other methods.

Example of Design Procedure

Determination of Quantity of Cover Stone

1. Assume the loose unit weight of the cover stone to be 86 pcf and the gradation of the aggregate to be:

Sieve	1/2 In.	3/8 In.	No. 4	No. 10
% Passing	100	69	12	1

2. Plot the gradation on the semilog aggregate grading chart and draw a smooth curve through the points. Inasmuch as this is the same aggregate as used in the example for the California design method, the plot of this aggregate gradation is shown in Figure 10.

3. Extend the grading curve at low percentage. Do not take into account the very fine aggregate sizes. This extension is shown by the dash line in Figure 10.

4. From the grading chart, determine the aggregate size at 100, 80, 20, and 0 percent passing: 100 percent size = 0.50 in., 80 percent size = 0.42 in., 20 percent size = 0.21 in., and 0 percent size = 0.16 in.

5. Calculate the spread modulus as the weighted average of the mean sizes.

$$0.20 \times \frac{0.50 + 0.42}{2} = 0.092$$

$$0.60 \times \frac{0.21 + 0.42}{2} = 0.189$$

$$0.20 \times \frac{0.16 + 0.21}{2} = 0.037$$

Spread modulus (M) = 0.318 in.

6. The quantity of screening is S = 0.9M = 0.9 × 0.318 = 0.286 cu ft/sq yd = 0.286 × 86 = 24.6 lb/sq yd.

Determination of Quantity of Bituminous Binder

The quantity of bituminous binder needed, assuming the underlying surface to be a dense, dry surface, is A = 0.4M + V = 0.4 × 0.318 + 0.05 = 0.125 + 0.050 = 0.177 gal/sq yd. (Note: 0.05 is the suggested quantity of bituminous material, in gal/sq yd, that will be absorbed by the dense, dry surface.)

EUROPEAN DESIGN METHODS

A brief summary of the surface treatment design methods developed in France, Sweden, and the Netherlands, as reported in various published articles, follows. The major articles (53-5) (55-5) were in many cases short and lacking in detail. Often just the basic design formulas were given without mention of how they were obtained or data to support their development. Pertinent information that could be gained from the various articles has been summarized herein.

In most of the methods, the prime objective of the designs seems to be to provide a mosaic-like appearance on the finished product and to create a surface treatment that is "relatively permanent so that the road maintenance department for the duration of

some three to four years would be out no further expenses" (53-5). In some of the articles it was mentioned that these design methods will not, by any means, produce the ultimate answer for all of the combined questions that may arise. The authors believe that many new situations must be handled more with a sense of feeling and experience rather than with scientific knowledge.

Kuipers' Method

In 1955, a paper was presented by J. P. Kuipers (55-5) in which he summarized a design method developed in the Netherlands. The following section contains the pertinent information acquired from an English translation. This information includes only basic quantity design formulas and discussions of some of the factors which influence the final quantities to be determined.

The quantity of aggregate of cubic shape with dimension d, in mm, required to cover an area of 1 sq m should be $d/100 \times 100 = d$ liters. This relationship exists, however, only for ideally shaped aggregate. Since in practice an ideal aggregate is not available, allowance must be made for the presence of the voids which are present. The author specifically notes that the void spaces in a surface treatment are noticeably larger than those obtained whenever the aggregate is compacted in thick layers because, in the latter case, there is better chance for reorientation to a better position.

With consideration given to the aggregate shape the author believes that the needed aggregate quantity can be given by the relationship

$$S = dvK$$

where

- S = needed aggregate quantity, in kg/m^2;
- d = mean size of aggregate particles, in mm;
- v = unit weight of the aggregate (for double crushed gravel 1.45, for stone 1.43, and for blast furnace slag 1.51); and
- K = a factor for the type of surface to be treated: for a normally sealed surface (asphaltic concrete or an old road) K = 1; if the surface has many openings such as would occur on a road in which large crushed stone is used, the value of K is reduced down to ¾.

The author recommends for wearing surfaces that carry high volumes of traffic an aggregate which is 8 to 12 mm (0.315 to 0.472 in.) in size. For wearing surfaces on roads that carry smaller volumes of traffic a finer aggregate can be used.

The approximate quantity of binder material to use can be determined by

$$B = 0.008\,(sd + f)\,av$$

where

- B = quantity of binder, in kg/m^2, of road surface;
- s = a factor related to the shape and the kind of surface of the aggregate: for most types of crushed stone, s is equivalent to one; for very porous material such as slag, this factor is increased to 1.3, and for rounded material such as "pearl" size gravel, the value = 1.1.
- d = average particle size of the material, in mm;
- f = a factor related to the type of road as follows:

Road Type	f
Tar	0
Dense old asphalt	1
Open asphalt concrete or binder course	2
Base course	5
Brick road or cobble stone (no allowance is made for cracks between bricks)	2 to 10

v = a factor related to the intensity of traffic; the following table is given by Kuipers as a means of evaluating v:

Traffic condition	Veh./Day	v
Heavy	>15000	1.0
Much	7000-15000	1.1
Average	2000-7000	1.25
Little	100-2000	1.5
Very little	<100	2.0

When the road surface is expected to be in the shade continuously, the value of v can be increased by approximately 10 percent.

a = a factor related to the type of binder to be used. The following table is to be used for evaluating this factor:

Binder type	a
Asphalt cement 180/200	1.0
Asphalt cement 280/320	1.05
Cutback 150/250	1 1
Road tar 100/200	1.4
Asphalt emulsion	1.5

The article (53-5) did not explain how the values of f, v, and a were determined for the various situations given. It is presumed that sufficient information was obtained from the field to substantiate these values.

Linckenheyl's Method

A design method that was developed for use in France was reported by G. Linckenheyl (53-5). The aggregate quantity is based on the mean particle dimension, whereas the binder quantity is based on the average thickness of a single-grain aggregate layer.

For the design of aggregate quantity for a one particle mosaic-like layer, the following relation is controlling:

$$g = 0.9\ \Delta$$

where

g = aggregate amount in liters/square meter (l/m^2); and

Δ = mean particle dimension, in mm; its calculation is based on a round holed sieve of size $(D + d)/2$ that allows at least one-third but not more than two-thirds of the aggregate to pass through it—D is the greatest aggregate diameter and d is the least aggregate diameter.

The author states that this formula is applicable only for coarse aggregate particles of 10 to 15 mm (0.394 to 0.590 in.) and upward. In the case of smaller aggregate particles, the relation is $g = 3.0 + 0.7\ \Delta$.

According to Linckenheyl, the relationship between the diameters of aggregate particles in a particular gradation should be $d = \frac{5}{8} D$; $D - d = \frac{3}{8} D$.

To determine the binding agent requirement, the following formula was presented:

$$Q = 0.10\ g$$

where

Q = amount binding agent, in l/m^2;
g = average thickness of a single grain aggregate layer and also equals the aggregate amount, in l/m^2; g is determined in a manner similar to that used by Kearby, that is, it is determined by "means of multiplication of the middle sieve size with the percentage constituent of the retained aggregate upon the concerned sieves" and then summing the resulting products (53-5).

Frijiling's Method

A design method developed for use in the Netherlands before that of Kuipers was reported by J. J. Frijiling (53-5). This method is very similar to Linckenheyl's since the aggregate quantity formulas are almost identical. The only difference is a slight variation in the numerical value of the constant used in the quantity equations. The relation given by Frijiling is

$$g = 0.8\ \Delta$$

where

g = aggregate quantity, in l/m^2; and
Δ = the mean particle dimension, in mm.

In this method, Δ is also determined by the use of a round-holed sieve as in Linckenheyl's method.

Frijiling concluded from his previous experience that the coarsest grains should be at the most $1\frac{1}{2}$ times as large as the smallest. That is, the following equation should be used for gradation control: $d = \frac{2}{3} D$.

The necessary amount of binding agent for a surface treatment, when cutback asphalt is used with an aggregate over 10 mm in size, is given by

$$Q = a + h/b$$

where

Q = binder requirement, in l/m^2;
h = average aggregate size; and
a and b = factors dependent on the surface condition of the old layer, on the hardness of the paving, the traffic and the weather.

Values of a and b can be readily obtained from the following table:

Factor	a	b
Hardness of road covering.		
Hard	—	+9
Relatively soft	—	+10
Condition of road surface		
Dense and rich	-0.2	—
Dense	0	—
Coarse or porous	+0.2	—
Very porous	+0.4	—
Type of traffic:		
Very light	—	-2
Light	—	-1
Medium	—	0
Heavy	—	+1
Very heavy	—	+2

Factor	a	b
Construction time and weather		
Before Sept. 1 hot	—	+1
Before Sept. 1 warm	—	0
Before Sept. 1 cold	—	-1
After Sept. 1 cold	—	-1
Foundation		
Good to moderate	—	0
Poor	—	-1
Very poor	—	-2

Although Frijiling does not tell precisely how to combine the various values of b as obtained for the various factors considered, it appears that the "sums" of the b-values are used in the given equation.

When aggregate <10-mm size is used, somewhat more cutback asphalt is required. The author again does not report by how much the asphalt quantity should be increased.

Gyllsjo's Method

By experimental construction during the years 1948-1950, Sven Gyllsjo of Sweden found the following formula to be applicable for use in determining the amount of binding agent in his country (53-5):

$$Q = C + KS$$

where

- Q = total binding agent quantity required in l/m^2;
- C = amount binding agent necessary for moistening of the base which depends on the condition of the old surface, in l/m^2—for a 250 penetration asphalt, C is ascertained to be 0.4;
- S = thickness of the aggregate covering, in mm—this corresponds approximately to the larger aggregate particles; and
- K = a factor dependent on the amount, shape, and size of the aggregate—for an asphalt of 250 penetration, K is ascertained to be 0.078. (Note: C and K are experimental values and are different according to the type of binder used.)

No mention was made by Gyllsjo as to how the aggregate quantity was to be determined.

Conclusions

In conclusion, it can easily be seen that all of these European methods are about the same as the current design methods used in the United States. It is beneficial, however, to have knowledge of these methods because "the adapted suggestions from foreign countries can contribute and assist essentially in the improvement of construction techniques of surface treatements and can add a conclusive clarification of the intricacies of this construction type" (53-5).

McLEOD'S DESIGN METHOD

This method of designing seal coats and surface treatments was given in an article by Norman McLeod (60-3). His procedure, however, is based principally on Hanson's work (35-1). The Country Roads Board of Victoria, Australia, has also used Hanson's Method for many years. However, that agency has refined it somewhat, and McLeod has included these modifications into his design procedure.

This design method is the most comprehensive of all existing methods and incorporates a number of ideas that do not exist in the other design methods. For example, McLeod discusses and gives a method by which the type and grade of the asphalt binder

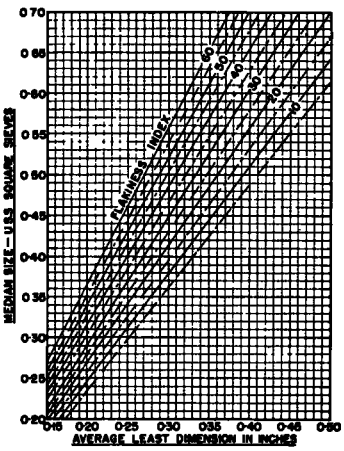

Figure 12. Determination of average least dimension of cover aggregate (data taken from McLeod, 60-3).

can be determined by using the size of the cover aggregate and the road surface temperature. The method for designing surface treatments and seal coats with one-size cover aggregate is fairly comprehensive. However, the methods that he presents for designing surface treatments with graded aggregates and for designing double surface treatments are much more empirical and are not covered in quite as much detail as the method for designing surface treatments with one-size cover aggregate.

McLeod suggests that different design procedures be used depending on the type of cover aggregate (one-size or graded). A one-size aggregate is defined as those aggregates that have a gradation 60 to 70 percent by weight of the aggregate passing the specified sieve size and retained on a sieve having an opening that is seven-tenths of the specified size. For example, if the nominal size of the aggregate is ½ in., then from 60 to 70 percent of the cover aggregate must pass a ½-in. sieve and be retained on the ⅜-in. sieve, which has openings that are approximately 0.7 x 0.5 in. This requirement for one-size cover aggregate for seal coats and surface treatments is much more stringent than the specified gradations for cover aggregate as given by ASTM Designation: D 1139. In fact, McLeod refers to the aggregate specified in ASTM Designation: D 1139 as "graded aggregate." McLeod flatly maintains that the one-size cover aggregates have outstanding advantages over the graded aggregates since they have been used to build the "consistently best surface treatments and seal coats to be found in the world."

Design of Surface Treatment and Seal Coats with One-Size Cover Aggregates

The quantity of cover aggregate and bituminous material is related to the "average least dimension," or ALD, of the cover aggregates. Although Hanson obtained the ALD of the cover aggregate by measuring the least dimension of a number of individual pieces of aggregate with calipers, the Country Roads Board of Victoria, Australia, has developed a much more rapid method. First, the median size of the aggregate is obtained from a plot of the aggregate gradation by determining the size of the aggregate which will have 50 percent by weight smaller than it. Each aggregate size fraction is then tested to determine the quantity of material that passes a specified elongated and slotted opening. For example, a particle passing a ½ in. and retained on a ⅜-in. square opening sieve is tested particle by particle for its ability to pass through a slot opening 0.263 in. in width. The amount of the specified size fraction passing through the appropriate slotted openings is expressed as the percentage of the total weight of these sizes and is referred to as a "flakiness index" of the aggregate. The slotted sieve for testing elongated, flat particles and for determining the flakiness index is covered by British Standards Institution 812. Once the flakiness index of the cover aggregate and the median size is determined, the ALD of the cover aggregate can be determined from Figure 12.

Hanson found that one-size cover aggregates in a loose or freshly spread condition contain 50 percent voids between the aggregate particles. However, after they have been rolled and after they have been subjected to an appreciable volume of traffic, the aggregate particles tend to become oriented in a position so that they lie on their flattest sides with their least dimension vertical. In this state, the aggregate contains approximately 20 percent voids. This void space of 20 percent is independent of the size of the one-size cover aggregate. Since the aggregate particles are finally oriented so that their least dimension is in the vertical direction, the quantity of aggregate and bituminous materials is related to the ALD of the cover aggregate.

TABLE 3

PERCENTAGE OF 20 PERCENT OF VOID SPACE IN ONE-SIZE COVER AGGREGATE TO BE FILLED WITH RESIDUAL BINDER

(Country Roads Board of Victoria, Australia, 1960-1961)

Aggregate	Percentage of 20 percent of void space in one-size cover aggregate to be filled with residual binder				
	Surface Condition Primed, Smooth, or Black				
	Traffic (vehicles per day)				
	Under 100	100 to 500	500 to 1000	1000 to 2000	Over 2000
Recognized good types of aggregate	85	75	70	65	60
Quartz aggregates	90	80	80	75	75
Other aggregates	90	80	75	70	65
Absorptive limestone aggregates	Two application procedure				

NOTE The quantities of residual binder specified above do not make allowance for absorption by the road surface or by an absorptive cover aggregate (after McLeod, 60-3).

Since the percent of voids between the compacted aggregate is 20 percent and the amount between the loose aggregate is 50 percent, the average loose depth of the cover aggregates can be determined by multiplying the ALD by 1.6. This average loose depth is further increased to allow for wastage and loss by whip-off. Although the Country Roads Board has learned that the amount of whip-off varies with the ALD of the cover stone, it is never greater than 10 percent; McLeod recommends that an average wastage loss of about 5 percent be used. Thus, the average loose depth of the aggregate should be increased by 15 percent.

The number of square yards that can be covered by 1 cubic yard of the cover aggregate can be determined by dividing 36 (in./yd) by the average loose depth of the cover aggregate, in in. (Allowance is not made for aggregate loss.) If a quantity is desired in the number of square yards that can be covered by 1 ton of the aggregate, it can be computed by dividing 46.45 by the bulk specific gravity of the aggregate times the average least dimension of the cover aggregate. (The constant 46.45 is a conversion factor with allowance of 15 percent for whip-off and wastage.)

Hanson not only determined that the void between the cover aggregate when it is compacted to its densest state is 20 percent but also concluded that the optimum amount of bituminous binder needed for such a surface treatment or seal coat should be just enough to fill approximately two-thirds of the 20 percent of the void space between the aggregate particles. However, the Country Roads Board of Victoria has learned from experience that the portion of the 20 percent voids between the aggregate particles that must be filled with binder to the optimum height is not a constant value, but must be varied with the volume of traffic and the type of the cover aggregate.

The amount of the 20 percent void space between the one-size aggregate to be filled with residual binder is given in Table 3. The percentage of the 20 percent void space in the one-size cover aggregate to be filled with residual binder varies between 60 and 90 percent. Although the type of aggregate influences the percent of the void space to be filled, the amount is primarily influenced by the traffic to be carried on the road. As the traffic on the road becomes heavier, large amounts of asphalt cannot be tolerated, as flushing and bleeding will occur. Thus the amount of asphalt that is used must be reduced. The thickness of the layer of the residual bituminous material needed can be computed by multiplying the volume of the required material per square yard times 7.48 to obtain the quantity, in gallons per square yard, of the bituminous material needed.

The quantity of the residual bituminous binder as computed needs to be corrected for that portion of the binder that might be absorbed into the road surface or into the pores of the aggregate. Usually no allowance is made for the absorption of the bitu-

TABLE 4

RATES OF APPLICATION OF GRADED AGGREGATES AS COVER MATERIALS FOR SURFACE TREATMENTS AND SEAL COATS OF THE SINGLE APPLICATION TYPE

(Country Roads Board, Victoria, Australia)

Size of Aggregate		Rates of Application of Graded Aggregate 1 Cubic Yard—Square Yards		
		Road Surface Condition		
Nominal Size (graded)	Trade Size or Number	Hungry	Smooth	Black
1 In.	56	1 to 50	1 to 50	1 to 45
3/4 In.	6	1 to 60	1 to 60	1 to 55
3/4 In.	67	1 to 65	1 to 65	1 to 60
3/4 In.	68	1 to 75	1 to 75	1 to 70
1/2 In.	7	1 to 90	1 to 90	1 to 85
1/2 In	78	1 to 90	1 to 90	1 to 85
3/8 In.	8	1 to 110	1 to 110	1 to 105
3/8 In.	89	1 to 115	1 to 115	1 to 110
No. 4	9	1 to 140	1 to 140	1 to 130
		1 to 170	1 to 170	1 to 160
Sand	Coarse	1 to 130	1 to 130	1 to 110
		1 to 180	1 to 180	1 to 170

NOTE· The above rates of application of graded cover aggregate are the quantities to be actually applied for the surface treatment or seal coat (after McLeod, 60-3).

minous binder into the cover aggregate. However, if the aggregate is very porous, such as a soft limestone, then the quantity of required bituminous material should be increased by not more than 0.03 gal/sq yd. The correction to be applied to the amount of residual binder to allow for the quantity that might be absorbed into a bituminous surface is dependent on the basis of the appearance of the surface in the wheelpath. When excessive binder has flushed to the surface, the bituminous surface is rated "black." A surface is rated "smooth" when it is a normal surface and is rated as 1H, 2H, or 3H, when it is "hungry" and has different degrees of dryness and will absorb different quantities of binder. The suggested correction for the different surface conditions is given in the following table:

Rating of Existing Bituminous Surface	Quantity of Bituminous Binder To Be Added or Reduced (gal/sq yd)
Black	Reduce 0.03
Smooth	No correction
1H	Add 0.03
2H	Add 0 06
3H	Add 0.09

The type and grade of bituminous material to be selected for the bituminous binder on surface treatments and seal coats in Canada were shown in Figure 6, which indicated that the type and grade of bituminous material needed for surface treatment work depend on the road surface temperature and the size of the aggregate. For instance, if a road surface temperature is 90 F and a one-eighth to one-fourth size aggregate is used, an RC-2 is the appropriate type of bituminous material to be used in the construction. McLeod indicates that Figure 6 is for Canadian conditions and would, in all likelihood, not be applicable to very warm climates. He suggests that highway engineers in various localities prepare similar diagrams that will be suitable to their own areas. However, Figure 6 should be applicable to the northern parts of the United States as well as Canada.

TABLE 5

RATES OF APPLICATION OF ASPHALT BINDER FOR SURFACE TREATMENTS AND SEAL COATS OF SINGLE APPLICATION TYPE WHEN USING GRADED COVER AGGREGATES

(Country Roads Board, Victoria, Australia)

Size of Aggregate		Rates of Application of Asphalt Binder Residual Binder. Gallons per Square Yard					
		Road Surface Condition					
Nominal Size (graded)	Trade Size or Number	Hungry		Smooth		Black	
		Imperial Gal.	U S Gal	Imperial Gal.	U S Gal.	Imperial Gal	U. S Gal.
1 In.	56	0.35	0.42	0.33	0 396	0.33	0.396
3/4 In.	6	0.3	0.36	0 275	0.33	0.275	0.33
3/4 In.	67	0.275	0.33	0.25	0.30	0.25	0 30
3/4 In	68	0 225	0.27	0.2	0 24	0.2	0 24
1/2 In.	7	0.2	0.24	0 175	0 21	0.175	0 21
1/2 In.	78	0.2	0.24	0.175	0.21	0.175	0 21
3/8 In.	8	0.175	0.21	0 15	0 18	0.15	0.18
3/8 In.	89	0 15	0.18	0.125	0 15	0.125	0.15
No. 4	9	0.15	0.18	0.125	0.15	0 125	0.15
		0 125	0.15	0.1	0 12	0.1	0 12
Sand	Coarse	0.175	0.21	0.15	0.18	0 15	0 18
		0.125	0.15	0.1	0 12	0.1	0.12

NOTE The above rates of application for residual binder do not make allowance for absorption by the road surface or by an absorptive cover aggregate (after McLeod, 60-3)

If a cutback is used, the amount of bituminous material needed must be corrected for the amount of solvent in the cutback. That is, the correct amount of residual bituminous material must be divided by the percent of the the residual bituminous material in the cutback in order to determine the amount of cutback that is needed at 60 F.

Since all of the calculations up to this point are for the bituminous material at a volume at 60 F, a final correction must be made to determine the rate of application of the bituminous material at the spraying temperature. This can be done by using the common temperature-volume correction tables for asphalt materials or by assuming a coefficient of expansion of the material to be approximately 0.00035 per deg F.

Design of Seal Coats and Surface Treatments Using Graded Aggregates

Although the one-size cover aggregate produces the best surface treatments, it is sometimes necessary to use a graded aggregate. The design of seal coats and surface treatments using graded aggregates cannot be based on the average least dimension, as is used with the one-size aggregate. Accordingly, when the cover aggregate for seal coats must be a graded aggregate, the required quantity of cover stone and bituminous binder cannot be calculated but must be determined by experience. Suggested quantities are given in Tables 4 and 5.

Design of Double Surface Treatments

When double surface treatments are constructed, the first layer can be designed by Hanson's method, based on the cover aggregate's average least dimension. However, for the second application of bituminous binder and cover aggregate, there is no design method for determining their quantities.

From experience, however, it has been determined that the second cover aggregate should be finer than the top size of the bottom layer and that the quantity needed should range from 1 cu yd/120 sq yd to 1 cu yd/150 sq yd. The quantity of bituminous binder suggested for both layers is given in Table 6.

When a double surface treatment is constructed on the basis of this design, the first application of the binder and aggregate should be heavily rolled and traffic should be allowed on the first layer for some time until the one-size cover aggregate has been thoroughly compacted and oriented so that the average least dimension of the aggregate is approximately vertical. This is because the first layer is designed according to

TABLE 6

RATES OF APPLICATION OF ASPHALT BINDER FOR EACH APPLICATION OF A DOUBLE SURFACE TREATMENT

(Country Roads Board, Victoria, Australia)

Application	Type of Aggregate	Percentage of 20 Percent Void Space in Cover Aggregate To Be Filled With Residual Binder																							
		Condition of Existing Surface. Primed, Smooth, or Black																							
		Traffic Volume (vehicles per day)																							
	One-size coarse aggregate	Less than 250								250 to 1000								Over 1000							
First application[a]	Gravel																								
	Round	65								65								65							
	Partly crushed	65								65								65							
	Wholly crushed	60								60								60							
	Crushed stone																								
	Other than limestone	60								60								60							
	Limestone	80								80								80							
	Size of aggregate first application	½ In., "G", or larger				Smaller than ½ In., "G"				½ In, "G", or larger				Smaller than ½ In, "G"				½ In, "G", or larger				Smaller than ½ In, "G"			
	Size of aggregate second application	Fine Crushed Stone ¼ In or No 4		Coarse Sand Passing ⅛ In		Fine Crushed Stone No 4		Coarse Sand Passing ⅛ In		Fine Crushed Stone ¼ In or No 4		Coarse Sand Passing ⅛ In		Fine Crushed Stone No 4		Coarse Sand Passing ⅛ In.		Fine Crushed Stone ¼ In		Coarse Sand Passing ⅛ In		Fine Crushed Stone No 4		Coarse Sand Passing ⅛ In	
Second application[b]		Imp Gal	U S Gal	Imp Gal	U S Gal	Imp Gal	U S Gal	Imp Gal	U S Gal	Imp Gal	U S Gal	Imp Gal	U S Gal	Imp Gal	U S Gal	Imp Gal	U S Gal	Imp Gal	U S Gal	Imp Gal	U S Gal	Imp Gal	U S Gal	Imp Gal	U S Gal
	Both courses of aggregate not limestone	0 125	0 15	0 10	0 12	0 10	0 12	0 075	0 09	0 10	0 12	0 075	0 09	0 075	0 09	0 075	0 09	0 10	0 12	0 075	0 09	– –	– –	– –	– –
	First course not limestone second course limestone	0 15	0 18	0 125	0 15	0 125	0 15	0 10	0 12	0 125	0 15	0 10	0 12	0 10	0 12	0 10	0 12	0 125	0 15	0 10	0 12	– –	– –	– –	– –
	First course limestone second course not limestone	0 15	0 18	0 125	0 15	0 125	0 15	0 10	0 12	0 125	0 15	0 10	0 12	0 10	0 12	0 10	0 12	0 125	0 15	0 10	0 12	– –	– –	– –	– –
	Both courses limestone	0 175	0 21	0 15	0 18	0 15	0 18	0 125	0 15	0 15	0 18	0 125	0 15	0 125	0 15	0 125	0 15	0 15	0 18	0 125	0 15	– –	– –	– –	– –

[a]First Application Percentage of 20 percent void space in compacted cover aggregate to be filled with residual binder

[b]Second Application Rate of application of residual binder in gallons per square yard

NOTES 1 The limestone referred to above represents any porous absorptive aggregate

2 The quantities of residual binder specified above for the first application, do not make allowance for absorption by the road surface

3 When traffic exceeds 1500 vehicles per day, each project is considered separately

(Data taken from McLeod, 60-3)

Hanson's method. After this, the second application of bituminous binder and cover aggregate can be made according to the quantities given in Table 6.

Example of Design Procedure

Determination of Quantity of Cover Stone

1. Assume the gradation of a good cover stone for a surface treatment is as follows:

Sieve	1/2 In.	3/8 In.	1/4 In.	No. 10
% Passing	100	87	12	1.0

This aggregate meets the requirement for 3/8-in. one-size cover aggregate (Trade Name - H) specified by the Country Roads Board of Victoria (60-3). Its gradation is plotted in Figure 13.

Also suppose there will be 10 percent loss due to whip-off, 5 percent loss due to wastage, that the bulk specific gravity of the aggregate is 2.68, and that the results of testing the aggregate in the slotted sieves are:

Sieve Size (in.)	Total Weight (gm)	Width of Slotted Sieve (in.)	Weight Passing Slotted Sieve (gm)
1/2 to 3/8	456	0.263	97
3/8 to 1/4	2624	0.184	742
	3080		839

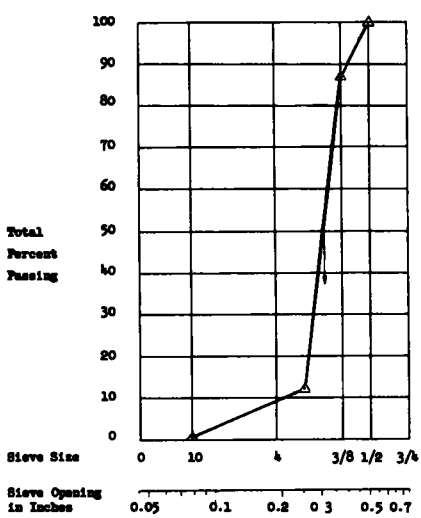

Figure 13. Gradation of aggregate used in the example of the McLeod design method.

2. From Figure 13, the median size of the aggregate (50 percent by weight smaller) is read to be 0.31 in.

3. The flakiness index is (using data from Step 1,): 839 × 100/3080 = 27.2.

4. The ALD of the cover aggregate, as determined from Figure 12 is 0.217 in. (Median aggregate size is 0.31 in. and the flakiness index is 27.2.)

5. The average loose depth of the aggregate is: 1.6 × ALD = 1.6 × 0.217 = 0.35 in.

6. The average loose depth of the cover aggregate with allowance for 10 percent whip-off and 5 percent wastage is 1.15 × 0.35 = 0.40 in.

7. The number of square yards that one cubic yard of the aggregate will cover is: 36/0.40 = 90 sq yd.

8. The number of square yards that will be covered by one ton of the aggregate (with 50 percent voids in the aggregate) is

$$\frac{2000}{2.67 \times 62.4 \times 0.40/12 \times 3 \times 3 \times 0.5} = 80 \text{ sq yd/ton}$$

Determination of the Quantity of Bituminous Material

1. The existing road surface is assumed to be very dry (very hungry) and will carry 1200 vehicles per day. The temperature of the road surface at time of construction is 80 F.

2. Since there is 20 percent void space in the compacted cover aggregate, the equivalent height of the layer of the residual bitumen to fill these voids is 0.2 × ALD = 0.2 × 0.217 = 0.043 in.

3. From Table 3, the percent of the voids in the compacted aggregate to be filled (good aggregate and 1200 vpd) is 65 percent. Thus the thickness of the layer of bituminous material needed is 0.65 × 0.043 = 0.028 in.

4. The uncorrected quantity of residual bituminous binder is 0.028/12 × 3 × 3 × 7.48 = 0.16 gal/sq yd.

5. A correction to the 0.16 gal/sq yd must be made because of the very dry condition of the underlying surface, which will absorb 0.09 gal/sq yd. Thus, the amount of the residual binder needed is 0.16 + 0.09 = 0.25 gal/sq yd (Note: An additional correction would have to be made if the aggregate absorbed an appreciable amount of binder.)

6. Using the temperature of the road surface and the size of the aggregate, the recommended type and grade of the asphalt can be determined from Figure 6. Since the road surface temperature is 80 F and the cover aggregate is ⅜ to ½-in. size, Figure 6 indicates that an RC-3 should be used.

7. If the RC-3 contained 22 percent solvent, the amount of cutback needed at 60 F is 0.25/(1.00-0.22) = 0.32 gal/sq yd.

8. The average temperature for spraying an RC-3, as determined from Figure 3 is 225 F. Assuming a coefficient of expansion for the cutback to be 0.00035 per deg F, the rate to apply the RC-3 on the road surface at the spraying temperature of 225 F is 0.32 + 0.32 × 0.00035 × (225 - 60) = 0.34 gal/sq yd.

9. Thus 0.34 gal/sq yd of RC-3 is needed at a spraying temperature of 225 F.

MACKINTOSH'S DESIGN METHOD

A foreign design method developed for use in South Africa was reported by C. S. Mackintosh in 1961 (61-2). This method introduces several new concepts to quantity design which appear to have great merit.

Mackintosh's method utilizes the average least dimension concept first introduced by Hanson in 1935 (35-1). Instead of requiring the independent measurement of several aggregate particles however, he makes use of a thickness gage which registers the distance between two parallel plates in thousandths of an inch and thus determines the average least dimension direct. This instrument is more accurate, less fatiguing and much quicker to use than the vernier calipers initially used by Hanson.

Mackintosh emphasizes the fact that the aggregate spread ratio can be measured directly by one of two alternative methods.

"Box-and-Tray" Method

A standard volume of chips, 0.1 cu ft, is spread on a hardboard tray, 24 in. wide and from 36 to 42 in. long, which has three fixed walls and one end wall movable. Aggregate chips are placed in the tray until a one-chip thick layer with no bare patches has been achieved. If the one-chip thick layer cannot be achieved the first time, the movable wall is shifted 1 in. (corresponding to a change of 5 sq yd/cu yd in the spread ratio) and the process of chip placement is repeated until all aggregate particles are placed on the tray. The tray is calibrated so that when the one-chip thick layer has been formed, the spread ratio can be read directly.

"Pan-and-Cylinder" Method

This method makes use of a steel pan with known base area, a steel cylinder with an internal diameter of 5 in., a calibrated dipstick and a glass measuring cylinder. Aggregate chips are placed in the steel pan in such a way as to form a single layer with no bare patches. The aggregate mat, one chip thick in the pan, is then poured

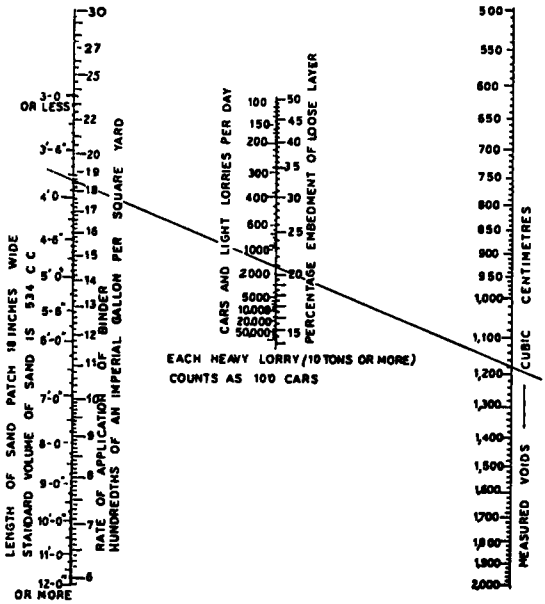

Figure 14. Nomogram for determining the rate of application of bituminous binder in surface treatments (data taken from Mackintosh, 61-2).

into the steel cylinder and compacted by dropping the cylinder 10 times from a height of 3 in. This compaction shakes the chips into a stable position.

The calibrated dipstick is next placed in the cylinder with its foot resting on the surface of the chips. The spread ratio in square yards of road per cubic yard of chips is then read off directly at the brim of the cylinder.

After recording the spread ratio, water is poured from the glass measuring cylinder into the steel cylinder to determine the amount of voids present in the compacted aggregate. The volume of water required to fill the voids represents "the amount of binder required to completely embed the loose chips on a circle of road surface" of the area equal to that of the base of the original steel measuring pan. This value will be used to determine the exact binder quantity requirement.

The rate of application of binder required is composed of two portions. These are as follows:

1. "The amount required to fill the cracks and surface voids of the existing road surface."
2. "The amount required to embed the chips so that they are held securely."

Mackintosh states that "even with years of experience, it is not always possible to estimate accurately the amount of binder needed to allow for existing surface texture." Because of this inadequacy, Mackintosh suggests use of a sandpatch test to measure accurately the amount of binder that is required to fill cracks in the existing surface. (Note: This test does not indicate the amount that will soak into the underlying surface.)

The sandpatch test consists of marking two parallel lines 18 in. apart and about 12 ft long on a truly representative section of the surface to be treated. A standard volume of fine sand, 534 cc, is spread over the full width of the marked strip and then is pushed along with a rubber-bladed rake so as to fill cracks but not to leave any loose sand on the surface. The length of the patch is then recorded. "The sand represents the amount of bitumen required to fill the voids in the old surface under the lower limit of the new surface treatment."

Use is then made of a nomogram (Fig. 14) to determine the magnitude of the two portions of the asphalt binder requirement. The center scale relates the percentage of embedment of the loose aggregate to the volume of traffic expected on the road. "The left-hand scale of the nomogram is double-sided. On the left are gradations for the length of the sand patch, and on the right the corresponding rate of application of binder required to fill the existing surface voids."

"An index line is placed across the three scales of the nomogram linking the measured voids and the percentage embedment. Where this line cuts the lefthand scale, the rate of application of binder is read off again. This is added to the figure found in the sandpatch test to give the total rate of application desired."

Mackintosh feels that the above method gives results of great accuracy and, compared to earlier methods, takes only a fraction of the time. He reports that rates for both chips and binder can be determined in six minutes by this method.

One of the most contradictory concepts reported by Mackintosh concerns his theories on allowances for aggregate losses and whip-off. He reports that surplus chips are not

only whipped off by traffic, but their presence actually causes the loosening of some chips already held by the binder. Because of this, Mackintosh states that "excess chips should not be applied as an allowance for whip-off. The aim should be such accurate rates of spread and spray that there is practically no whip-off." He goes on to report though, that "a maximum allowance of six percent, though four percent is usually enough, should be made for handling losses and imperfect workmanship" (61-2).

AMERICAN BITUMULS' DESIGN METHOD

One of the more recent quantity design methods for surface treatments was presented by W. L. Kari, L. D. Coyne, and P. E. McCoy of the American Bitumuls and Asphalt Company of California in 1962 (62-1). In their method the following formulas are theoretically derived.

Binder quantity

$$B = 0.708\ D + P_C$$

Aggregate quantity

$$W_A = 80D$$

where

- B = binder quantity to be applied, in gal/sq yd;
- D = average stone diameter, in in., as obtained from the gradation analysis on the aggregate being used—it appears that the value used is the 50 percent passing size;
- P_C = pavement rating factor which is an adjustment factor dependent upon the existing pavement surface condition, in gal/sq yd; and
- W_A = weight of applied stone cover lb/sq yd.

Several assumptions were made in arriving at these formulas which cause the results to be only approximate estimations of the quantities desired. The assumptions are listed below with reasons, as given in the paper, as to why they were made. In some cases it appears that the assumptions are quite inadequate.

1. An aggregate specific gravity of 2.65 was used for all calculations.
2. The aggregate particles were assumed to be of a spherical shape. This situation occurs only with some well worn gravels.
3. The maximum aggregate size considered was ½ in. This value influences the values of the constants used in the derivation of the binder quantity. As can be seen from the modified Kearby Curve, for aggregate sizes up to ½ in. the variation in the percentage of embedment is relatively small. Above ½-in. maximum size, however, the variation in the embedment percentage increases rapidly. This indicates a greater bitumen requirement for aggregate sizes larger than ½ in. If appropriate corrections in the design are not made when using larger size aggregates to compensate for the increased requirement, a "weak" seal coat will result and the cover material will not adhere well to the old surface.
4. It has also been assumed that the spherical particles reorient and become embedded into the existing surface at some future time and thereby cause a reduction in the void content. To account for this decrease, use has been made of Hanson's observations (35-1). The authors say that Hanson found the value of the ratio of final voids to initial voids to vary between 0.4 to 0.6. The authors state that experience dictates the use of the larger value and this value is used by the authors in the derivations herein.
5. The pavement surface has been assumed to be smooth and nonabsorptive. To compensate for this condition which may or may not occur in the field, the pavement rating factor, P_C, has been included in the formulas. Kari et al suggest use of the following table for numerical evaluation of the P_C factor.

Pavement Condition	Pavement Rating, P_c (gal/sq yd)
Smooth, non-porous	0.00
Slightly porous, oxidized	0.05
Slightly pocked, porous, oxidized	0.10
Badly pocked, porous, oxidized	0.15

To determine an equation for the quantity of aggregate to use, Kari and his co-authors based their work on laboratory results. The weight of screenings required to form a layer one stone in thickness uniformly distributed over a specified area was determined. The linear relationship between average stone size, D, and aggregate cover spread, W_A, resulted. This relationship is $W_A = 68D$, where D is in inches, and W_A is in pounds per square yard. To allow for spreading inequalities and losses, they suggest the aggregate quantity be increased by 15 percent. Incorporation of this allowance into the previous formula results in $W_A = 80D$.

The authors say that as long as the loose dry unit weight, d_A, of the aggregate remains between 90 and 100 pcf the above expression is reasonably reliable. For other values of d_A the last equation should be multiplied by the ratio $d_A/100$.

Example of Design Procedure

Several assumptions must be made regarding the materials to be used and the surface to be treated. These are:

1. The aggregate to be used for cover material is the same as that described in the California method. (The aggregate will therefore have the gradation analysis curve shown in Figure 10).
2. The existing pavement condition is described as slightly pocked, porous, and oxidized.

From the aggregate grading chart the value of the average stone diameter, D, given by the 50 percent point is determined to be $^5/_{16}$ in. With this value the aggregate quantity is readily determined by use of Kari's relationship: $W_A = 80\ (5/16) = 25$ lb/sq yd.

The value of the pavement rating factor, P_c, for the existing surface condition is now obtained from the suggested table. For the conditions described above, P_c equals 0.10 gal/sq yd. The binder quantity is calculated using Kari's relationship for the determination of B. This relationship results in $B = 0.708\ (5/16) + 0.10 = 0.321$ gal/sq yd.

ASPHALT INSTITUTE DESIGN METHOD

The Asphalt Institute design method is one of the more recently published methods for surface treatment design. Basically the method is the same as specific methods previously presented in this appendix.

The method utilizes design procedures for one-size aggregate surface treatments that were developed from the Australian investigations in this area. Thus, this design method is essentially the same as McLeod's method (60-3) with slight variation.

For surface treatments constructed with graded aggregates, use is made of design procedures which enable the determination of a spread modulus, the quantity of aggregate and the quantity of asphalt required. The method of design employed is essentially the same as Lovering's method (54-4) with only slight modification.

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