NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 49

OPEN-GRADED FRICTION COURSES FOR HIGHWAYS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
- PAVEMENT DESIGN
- BITUMINOUS MATERIALS AND MIXES
- CONSTRUCTION
- GENERAL MAINTENANCE
- HIGHWAY SAFETY

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1978

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

FOREWORD

By Staff
Transportation
Research Board

This synthesis will be of special interest and usefulness to pavement designers, materials and construction engineers, those responsible for highway safety, and others seeking information on the advantages of open-graded friction courses. Detailed information is presented on construction and maintenance techniques presently in use.

Administrators, engineers, and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information often is fragmented, scattered, and unevaluated. As a consequence, full information on what has been learned about a problem frequently is not assembled in seeking a solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of synthesizing and reporting on common highway problems. Syntheses from this endeavor constitute an NCHRP report series that collects and assembles the various forms of information into single concise documents pertaining to specific highway problems or sets of closely related problems.

Open-graded friction courses have been used increasingly in recent years for pavement surfaces throughout the United States. This report of the Transportation Research Board contains currently available information on mixture design procedures, material selection and evaluation, construction procedures, cost effectiveness, maintenance, safety aspects, and pavement performance.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researchers in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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This synthesis was completed by the Transportation Research Board under the supervision of Paul E. Irick, Assistant Director for Special Projects. The Principal Investigators responsible for conduct of the synthesis were Thomas L. Copas and Herbert A. Pennock, Special Projects Engineers. The synthesis was edited by Judy Wall.

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Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Grant Allen, Engineer of Materials Services, Arizona Department of Transportation; John J. Carroll, Construction Specialist, Construction Standards and Operations Branch, Federal Highway Administration; Al Donofrio, Assistant Chief of Materials and Research, Delaware Department of Highways and Transportation; Don M. Harriott, Staff Engineer, The Asphalt Institute; Roy W. Jump, Maintenance Supervisor, Division of Highways, Idaho Transportation Department; Norman W. Loeffler, Pavement Design Engineer, Federal Highway Administration; G. W. Maupin, Jr., Research Engineer, Virginia Highway and Transportation Research Council; Raymond Pavlovich, Highway Research Engineer, Federal Highway Administration; Richard W. Smith, Director, Research and Development, National Asphalt Pavement Association; and John Trumbull, Chairman, Emulsified Asphalt, Inc.

Bob H. Welch, Associate Engineer of Materials and Construction, Transportation Research Board, assisted the Special Projects Staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance was most helpful.

OPEN-GRADED FRICTION COURSES FOR HIGHWAYS

SUMMARY

Open-graded asphalt friction courses have been found to provide pavement surfaces with a number of desirable characteristics, the most important one being the surface's ability to virtually eliminate the danger of hydroplaning under usual conditions of rainfall and at normal operating speeds.

Forty-nine states plus the District of Columbia and Puerto Rico have constructed open-graded asphalt surfaces. In 23 states, such construction has been limited to relatively recent experimental sections. Of those 23, a number have made no decision concerning the general applicability of this type of construction for the conditions in their state. Fifteen states have made extensive use of open-graded surfaces for several years, and 7 others have more recently begun using open-graded construction as a part of their standard practices for either new construction or reconstruction.

Open-graded asphalt friction course construction began as a plant-mix seal coat, but almost all states now view the major purpose of the surfacing to be the construction of an improved skid-resistant surface and the elimination of dangers from hydroplaning during severe rainstorms. Consequently, the term *open-graded asphalt friction course* or, as used in this report, *open friction course* (OFC) is now recognized as the preferred term. Sixteen states, however, still consider the surface a seal coat as well as a friction course. Reports summarized for presentation here strongly indicate that a complete watertight seal is not provided by the usual construction techniques for OFC and that, in high-rainfall areas where water infiltration into the base could create structural weakness, independent sealing with dense mixtures should precede the construction of the open friction course. In drier climates, where surface oxidation, or drying out, is the most prevalent type of deterioration, the open friction course does provide a sealing action to prevent raveling of the previous surface.

Although a number of states have expressed considerable concern about the durability of open friction courses, widespread failure of such surfaces has not been reported. A large proportion of the mileage constructed is less than six years old, and no good estimate of the expected life of OFC can as yet be made. However, some projects constructed as plant-mix seals are still providing good service after six to eight years.

Most failures reported by states can be attributed to poor construction practices that are now carefully avoided in new projects. In particular, flushing resulting from too high an asphalt content is now generally controlled by proper design and construction techniques. Likewise, the dangers of asphalt drain-down in the trucks that can lead to "fat spots" in the road after laydown is now universally recognized. To prevent asphalt drain-down, mixing temperatures are carefully controlled and limitations are placed on hauling and standing times.

Failures of OFC because of closing up of the surface and loss of permeability to water are of legitimate concern. However, the relationship of loss of permeability to loss of potential for reducing hydroplaning has not been fully established. Some evidence exists to show that a high friction number and a fair potential to resist hydroplaning are retained after considerable clogging of the surface occurs, although increased splash and spray from a clogged surface is a definite disadvantage. Closing up of the surface generally means only that the surface has been changed to a dense surface and that therefore overall durability is not adversely affected. The concern here is the loss of cost-effectiveness when a premium price has been paid for constructing the OFC.

The cost-effectiveness of OFC in comparison with that of the more conventional, dense surfaces could not be established by the data collected for

this synthesis. In many cases, the costs reported for open-graded mixtures were for short, experimental projects and were as much as three times the cost of dense-graded mixtures. In cases based on more extensive use, the costs per ton were about equal. The majority of states reporting indicated cost ratios of around 1.3 to 1.5 on the ton basis. Cost ratios per square yard of surface are more favorable for open-graded mixtures because of the greater amount of voids present and therefore the greater volume of material. Also, OFC is generally applied at a course thickness of 5/8 to 3/4 in. (16 to 19 mm), whereas dense-graded surfaces are applied at a thickness of 1 to 1.5 in. (25 to 38 mm). Data on the average life of OFC are not yet available, so comparisons between the two types of surfaces with respect to average life under similar conditions cannot yet be made. Where overlays are concerned, the cost of upgrading the structural capability of the existing pavement is also a consideration in judging overall costs of improvement.

There are no criteria available that can be applied universally when a decision must be made about whether or not to use an open-graded asphalt friction course. The decision for each project must be made on the basis of expected traffic demands, availability of materials, overall costs, and effects on maintenance of traffic during snow and icing conditions.

For states making early use of plant-mix seal, the design of the mixture evolved primarily from experience, and those states still rely to a major extent on their own procedures. However, states that have constructed sections more recently on an experimental basis generally use the procedure recommended by the Federal Highway Administration (FHWA) or one based on a modification of that procedure.

At first glance, there appears to be a wide discrepancy with respect to aggregate gradations used, inasmuch as the master ranges of gradation permitted vary from state to state. Approximately 35 different specifications are in use. However, the reported gradation of typical aggregates shows that, except for a few states that are experimenting with a larger aggregate, all states use a nominal top size of 3/8 in. (9.5 mm) and 35 of the 40 typical gradations reported fall within the master range recommended by FHWA. The most significant difference is in the amount passing the No. 8 (2.36-mm) sieve. Some states keep this fine-aggregate fraction at a minimum to preserve the openness of the surface under traffic, whereas others accept the premise that sufficient fine aggregate must be present to provide a chocking action for the larger stone and consequently to create greater stability and holding power. The optimum amount of such fine material has not yet been fully established.

Further research is needed primarily to determine the degree of openness required for the surface's continued ability to function as a means of eliminating hydroplaning. If it is determined that less permeable mixtures can continue to function properly, then the way is opened for increasing the durability of the pavement as well as increasing its usefulness in preventing water from entering the base.

Although some experimental pavements have been constructed with cold emulsion mixtures, essentially all present construction uses paving grade asphalt as the binder material in hot plant mixtures. The general use of emulsions has been promoted as an energy-saving procedure. However, for areas of high traffic density, the overall saving of energy has been questioned because of associated traffic delays and differences in construction techniques. This question has yet to be resolved. The more attractive possibility for emulsion mixtures is the ability to use them in remote locations where hot-mix plants are not readily available for aggregate heating. In particular, equipment for on-site emulsion mixing shows promise for this type of construction. Experimental construction and research are under way to further develop optimum types of emulsion for OFC mixtures and construction techniques for OFC surfaces.

CHAPTER ONE

INTRODUCTION AND HISTORY OF DEVELOPMENT

INTRODUCTION

This synthesis is concerned with open-graded asphalt friction courses used on new or old highway pavements to provide a high-quality skid-resistant riding surface. This surface is basically a refinement of open-graded plant-mix seals, which are referred to in different states by a variety of names, such as plant-mix seal coats, asphalt friction courses, and popcorn mix. The term *open-graded asphalt friction course* is used by the Federal Highway Administration (FHWA). However, because the simpler term *open friction course* (OFC) adequately describes the type of surface, this term and its abbreviation are used throughout this synthesis.

In the early preparations for this synthesis, it was intended that a distinction be made between OFC and plant-mix seals of the older type, because the initial purpose of the two types of overlay appeared to be different. It was found, however, that a clear-cut distinction between them could not be drawn with respect to specifications, construction techniques, and performance records. Although states now generally recognize the primary purpose of the overlay to be improvement of skid resistance of the pavements, and although some modifications of earlier techniques have occurred, there have been no sharp or easily definable changes in state specifications. Accordingly, the discussions here are directed toward the design and construction techniques that will optimize the performance of the surface with respect to its skid-resistance characteristics. However, the performance records cited must be recognized as including projects that were constructed as plant-mix seals as well as open friction courses.

The synthesis is concerned with highway surfaces only, and complete consideration is not given to the similar development of porous friction courses (PFC) for airport runways.

Published papers concerning research studies and state practices have been considered in the development of the synthesis, as has a review of present practice and performance records. The chapters on design, construction, and maintenance are intended to present a consensus of what is now considered good practice rather than to completely document all previous procedures.

Although hot mixtures using asphalt cement binders and cold mixtures using emulsions were considered to be within the scope of the synthesis, it was found that very little use is being made of emulsion friction courses and that interest among the states is limited primarily to the use of such mixtures where hot-mix plants are not readily available. It was also found that special considerations and techniques are necessary for cold emulsion mixtures. Consequently, a separate chapter (Chapter Eight) is included on emulsion mixtures. The balance of the synthesis is concerned with hot asphalt mixtures.

HISTORY OF DEVELOPMENT

One can best understand the overall promise and purpose of OFC by reviewing its historical development and evolution from an alternative to chip seals to the present open friction course.

In the 1930s Oregon began experimenting with open-type asphaltic concrete wearing surfaces (41). The surface adopted as the standard had a maximum aggregate size of 1/2 in. (12.5 mm) and was laid at a thickness as small as 3/4 in. (19 mm) on a dense, impermeable base. Tests showed high skid resistance, less glare from headlights of oncoming vehicles, and better visibility of the centerline stripe.

Substantial use of plant-mix seal coats began in the western states in the late 1940s and 1950s. Eager in 1967 reported on the construction and performance of this type of surface course (1). These seal coats were the open-graded type, the aggregate being essentially the same as that used in normal chip seals (max. size about 3/8 in.—10 mm). This was mixed with a relatively high percentage of paving-grade asphalt in a hot-mix plant and placed with a paver at a thickness of 5/8 to 3/4 in. (16 to 19 mm). According to Eager, California used this type of construction as early as 1944. It appears that Arizona and Nevada began using OFC in 1954 and that FHWA began its use in federal parks in 1961. Eager also reported that Indiana used a "retread" construction similar in composition to plant-mix seals as early as the 1930s.

Several authors who presented the early experience with this type of construction pointed out that initial interest in open-graded plant-mix seals grew out of efforts to avoid the disadvantages of chip-seal construction (1, 2, 3). Two major disadvantages overcome by the plant-mix seal were (a) the problems resulting from a sudden rainstorm before the aggregate had had time to become firmly set with the binder material and (b) the danger of broken windshields from flying stones. The 5/8- to 3/4-in. (16- to 19-mm) thickness of the plant-mix seal also may improve ridability over irregular pavement surfaces.

Although the first objective in using plant-mix seals was to get a better seal coat, other advantages soon became apparent. Open-graded plant-mix seals were found to provide highly skid-resistant surfaces with a minimum potential for developing a hydroplaning condition (1, 2, 3). It was the discovery of these properties that led to the realization of the usefulness of such construction for urban areas and high-density traffic.

A May 1968 Circular Memorandum issued by FHWA

was the first nationwide encouragement to states to use plant-mix seal coats (4). This memorandum cited the advantages as being: "(1) a durable surface with good skid-resistant characteristics, (2) a strong wearing course capable of withstanding high-speed traffic and heavy axle loads, and (3) a smooth surface with uniform appearance." The protection from hydroplaning afforded by such surfaces was also cited.

The superiority of plant-mix seals in providing high friction numbers* became evident in many studies conducted in the 1960s. Of particular interest is "A Skid Resistance Study in Four Western States" (5). The purpose of this study was to compare skid-resistance values of plant-mix seals with those of other, conventional surface types and to show trends of skid resistance with regard to average daily traffic, age of pavement, asphalt content, and type and grade of aggregate. The types of surfaces tested were portland cement concrete, asphalt concrete, chip seals, and plant-mix seals. The study showed that, among the surfaces tested, bituminous plant-mix seals gave the highest skid-resistance coefficients.

With increased awareness of the danger of skidding accidents, the state highway agencies and FHWA undertook greater efforts to reduce such accidents to a minimum. Many recognized that open-graded plant-mix seals offered the best available potential for providing not only a high level of skid resistance throughout the life of the surface but also protection against hydroplaning. In May 1973, FHWA issued a Notice that again encouraged states to use this type of mixture on all resurfacing projects to reduce the dangers of skidding accidents (6). OFC was also recommended for use on all new pavements having high skid-resistance requirements, such as those with high traffic volume and high operating speeds. The Notice also recognized the advantages of less splash and spray from truck tires on open-graded plant-mix seals as compared with dense-graded surfaces. The relatively quieter and smoother ride was also noted.

Attached to the Notice were two reports. One report, by the Pavement Design Branch of the Highway Design Division of the Office of Engineering, FHWA, was primarily a review of state practices and experiences in constructing open-graded seal coats and contained general recommendations for material characteristics and for design and construction procedures. The other report, by Brakey of the Colorado Highway Department, was based primarily on that state's experience with plant-mix seal coats, the term used by Colorado (7). Type A of the Colorado specifications is the open-graded type that is of concern in this report. Brakey's report discusses the Colorado "super compaction" design procedure, which up to that time represented the most complete design procedure reported in the literature.

Despite the encouragement by FHWA and the favorable reports by a number of states, many states were slow to investigate OFC construction as a means for improving pavement skid resistance. This attitude resulted partly from a belief by many that their usual dense-graded construction had overall superiority in structural benefits and pavement durability and afforded greater protection to the base and subbase because of better waterproofing characteristics. With good design and good aggregates, friction numbers of the dense surfaces appeared to be completely satisfactory. In addition, the difficulties sometimes encountered with open-graded plant-mix seals and reports of raveling, peeling off, or flushing from excess asphalt contributed to the reluctance of many to use open-graded plant-mix seal construction.

Recognizing this reluctance, the FHWA Office of Research and Development initiated a study that ultimately led to the introduction of a design method based on a new approach to the problem. The FHWA report recommended abandoning the dual-purpose focus on open-graded seal coats, that is, on the ability to seal the old pavement as well as renew the skid-resistance characteristics of the surface (8). Instead, the report took the position that the most important property of the open-graded asphalt surface course is its ability to improve the skid-resistance characteristics of the surface, which is accomplished by the provision of both a high friction-number speed gradient and a low friction-number speed gradient. Consequently, the name *open-graded asphalt friction course* was recommended as the designation for the type of construction desired. As indicated previously, the designation *open friction course* (OFC) is used in this synthesis.

The FHWA report stated that OFC could be considered a plant-mix seal without excess asphalt cement, which under the earlier concept was thought to flow down to the pavement-overlay interface and thus "seal" the pavement. The distinction recommended by FHWA makes it possible to eliminate some of the uncertainties faced by the engineer who is attempting to "seal" the pavement as well as to provide a new skid-resistant riding surface. Under this concept, a more definite design procedure for the surface course can be adopted. It is necessary, however, to correct any serious deficiencies of the existing pavement. The recommendation is that the existing surface be evaluated separately from the new surfacing material. A dense, impermeable surface requires only a tack coat. If the old pavement is dry, porous, and permeable, a prime coat may be needed. If the pavement is flushed, it may be necessary to remove the excess asphalt or take other measures to prevent such excess from bleeding through the new surface. Under some circumstances, an overlay of dense-graded material is required. (This is discussed further in Chapter Four.)

FHWA instituted Demonstration Project No. 10, "Improved Skid Resistant Pavements," to demonstrate the effectiveness of the open friction course and to provide technical assistance to states constructing this skid-resistant pavement overlay for the first time. Twenty-nine states participated in this project in some manner. Twelve states constructed demonstration projects, and the others participated in mix-design demonstrations or received other technical assistance from FHWA. A report of the results of this project is now available (9). The findings of the report and FHWA's design procedure are discussed in more detail later in this synthesis; suffice it to say here that the findings support the usefulness of the concept introduced and the design procedure used. Although other concepts or design procedures will most likely provide satisfactory surfaces, the FHWA procedure has eliminated a number of previous uncertainties that could lead to failures. The FHWA procedure is believed to be

*The literature most often uses the term "skid number" rather than "friction number." However, in view of the fact that a high number indicates good friction, in 1976 the AASHTO Subcommittee on Materials recognized "friction number" as the preferred term. That recommendation is followed in this synthesis.

particularly useful where a performance history of the materials to be used is not available.

A close parallel exists in the use of this construction for airport runways, where hydroplaning is of paramount importance. The Federal Aviation Administration (FAA) has generally adopted the designation *porous friction surface course* (PFC) for its recommended surface overlay. The design and performance of such overlays are adequately discussed in two Waterways Experiment Station reports of a study made for FAA. The first of these reports covers the laboratory investigation of material requirements and mix-design development and discusses a field study of construction control and construction processes (10). The laboratory results were correlated, where possible, with field observations. The report shows that satisfactory performance was obtained with the aggregate gradation and mixture design studied. The report also describes a procedure for obtaining a design asphalt content, gives a field mixing temperature, gives minimum field permeability values, and describes laboratory procedures for conducting permeability tests. A standard recommended guide specification is also included in the report.

The second report includes the final results of a field performance survey described in the first report and discusses construction experience and validation of a design procedure with a desired mixing viscosity range (11). Long-term PFC performance is recorded and combined with laboratory test results that provide data for a new recommended PFC gradation, water permeability requirements, and requirements for the initial voids in the total mixture.

These reports, as well as others (12, 13, 14, 15), document the design and performance of PFC, which closely resembles the recommended OFC. The two designs have very much in common, with some differences because of use. A detailed consideration of the differences is beyond the scope of this synthesis; those concerned with the study of all aspects of such surfaces should read the aforementioned references and consider their relationship to the highway problem.

Another type of construction, the porous pavement, is also of general interest but as yet has no application to normal highway construction and thus is not considered here. This pavement was developed for the Environmental Protection Agency by the Franklin Institute and is designed to permit rainwater to pass through the pavement surface and be stored in the base for eventual percolation into the subgrade. This type of construction requires a thick aggregate base course (approx. 12 in.—300 mm) with large void spaces to provide the storage reservoir for the water. The first reported application of this principle was in the construction of a parking lot at the University of Delaware (16). The surface was designed with a permeability coefficient of 70 in. (1 780 mm) of water per hour. The principle, if successful, will relieve storm sewers of runoff during rains and at the same time permit renewal of the ground water. Its greatest potential application appears to be in parking lots in areas having permeable soils.

CHAPTER TWO

ADVANTAGES AND LIMITATIONS OF OPEN FRICTION COURSES

The existing literature and reports of states' experience record the desirable characteristics of OFC and support most of the claims of the advantages to be gained by its use. Following is a list of the claims made, with a short discussion of each. (More detailed discussion is presented elsewhere in this synthesis as indicated.)

1. *Hydroplaning potential during rainstorms is minimized.* This is the major advantage of OFC. The open-graded aggregate of the friction course provides drainage channels so that water flows from the surface below the highest asperities of the aggregate. Consequently, good tire-pavement contact is maintained in the presence of large volumes of water. (See Chapter Seven for additional discussion.)

2. *Skid resistance at high speeds during wet weather is improved.* Figure 1 shows this characteristic. Because of the macrotexture of OFC, the friction numbers of such surfaces do not decrease as rapidly with increasing speed as do the friction numbers of dense-graded surfaces. Thus, although an OFC and a dense-graded surface may have equal friction numbers measured at 40 mph (60 km/h), the measured friction number of OFC at 60 or 70 mph (100 to 115 km/h) would be significantly higher than that of a dense-graded surface.

3. *Splash and spray during wet weather is minimized.* Figures 2 and 3 show this characteristic of OFC. With OFC, much of the water generally is flowing below the highest points of the surface; thus, between the tire and the pavement, there is initially less water present that must be removed, or splashed, to retain tire-pavement contact. In addition, the water can be forced downward into the channels of OFC without necessarily being removed laterally, as is the case with dense-graded surfaces.

4. *Road smoothness is improved (due to correction of minor surface irregularities).* This advantage is generally discussed in early reports dealing with plant-mix seals. The improved road smoothness is in comparison with chip seals. As discussed in Chapter Four, care must be exercised that the open-graded mixture not be used to correct severe rutting or depressions in the

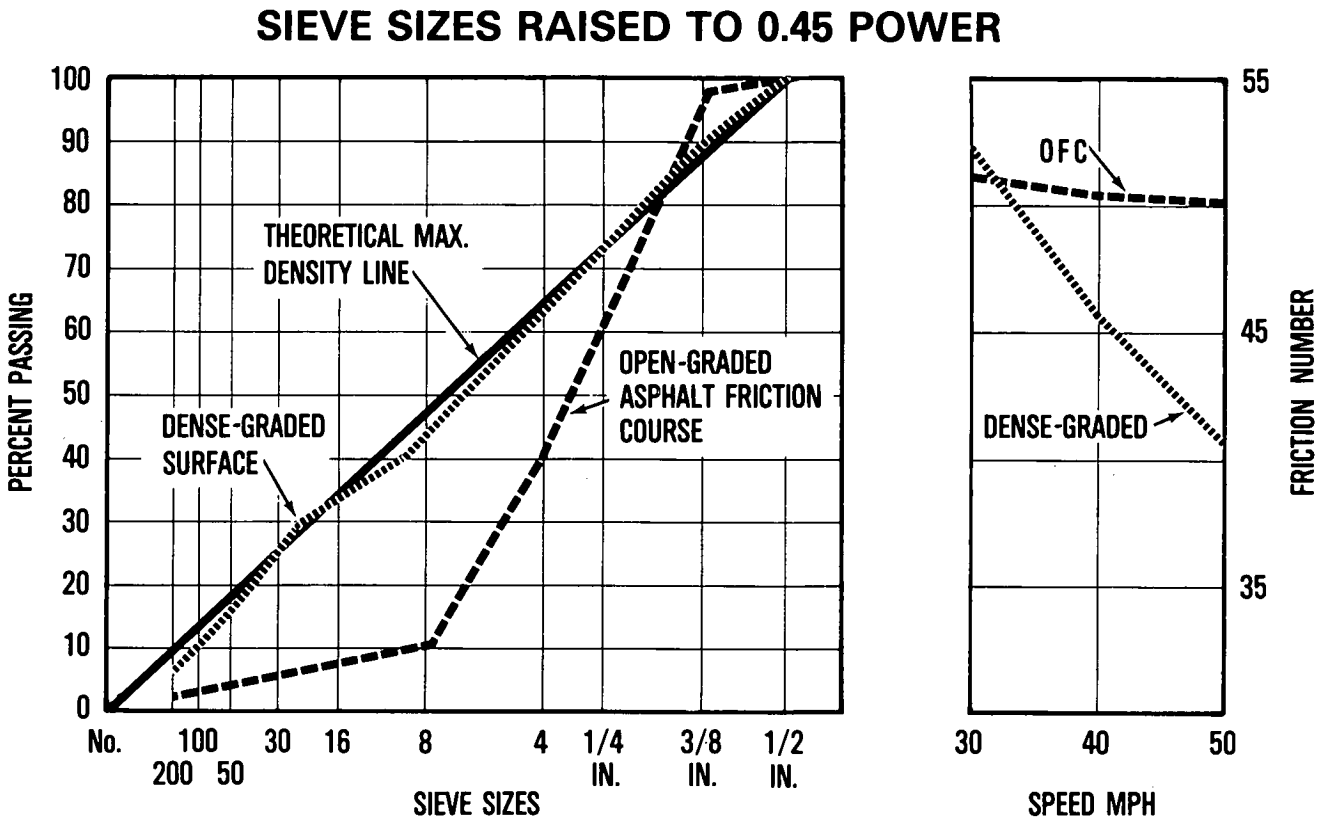


Figure 1. Comparison of friction-number gradient of dense-graded mixtures and open-graded mixtures (FHWA).

underlying pavement, because such action could create a basin for the accumulation of water, which would eventually seep into the base and accelerate structural damage to the pavement.

5. *Wheel-path rutting is minimized.* OFC depends on the aggregate interlock for its stability and is generally placed at a thickness of approximately 3/4 in. (19 mm). Consequently, rutting is minimized because there is no visco-elastic flow in the surface layer. However, movement within the underlying pavement or base would result in rutting of pavements overlaid with either OFC or dense-graded surfaces, although a small amount of rutting in OFC will not result in ponding of water in the wheel paths.

6. *There is less glare at night during wet weather.* This is a well-established and significant advantage of OFC. Because most of the water is flowing below the surface, the mirror effect of the water film that occurs on the surface of dense-graded pavements does not occur on OFC. Reflected light from oncoming vehicles and light from objects adjacent to the highway are dispersed by the angularity of the OFC surface. The driver's decreased annoyance and increased ability to discern signs and lane markers under adverse weather conditions are decided safety benefits of OFC.

7. *Riding surfaces are quieter (because of less noise from tires).* Despite early concerns that OFC might be noisier than a dense-graded surface, research has shown that OFC is generally as quiet as or quieter than most conventional pavements. (See "Noise Levels for OFC" in Chapter Seven for further discussion.)

8. *There are cost savings because lesser amounts of high-quality skid-resistant aggregate are used.* Inasmuch as OFC is generally laid at thicknesses of 5/8 to 3/4 in. (16 to 19 mm) and dense-graded mixtures at thicknesses of 1 to 1.5 in. (25 to 38 mm), the difference in amount of aggregate used is obvious. This consideration is important where the supply of good skid-resistant aggregate is limited and the costs are high.

9. *Traffic can use the surface almost immediately after placement.* The relatively thin section of the overlay and the openness of the surface permit rapid cooling. In addition, because stability results largely from point-to-point contact of the coarse aggregate, less reliance is placed on the cooling and setting of the asphalt than is the case with either dense-graded overlays or chip seals.

10. *There is better wet-night visibility of traffic stripes.* This is related to number 6 above, in that the removal of glare results in better ability to discern traffic stripes. There is an additional benefit: because the paint stripes are not covered with water, the light from a vehicle's headlights is reflected from the paint stripe back to the driver in the desired manner. Also, because of the texture of surfaces, paint covers portions of the coarse aggregate not subject to continuous wear from tires. After the paint stripe has become worn, this residual is particularly effective in providing night visibility, even though the daytime effectiveness may be well below that desired.

11. *Painted markings have a longer life.* All states do not agree on this point. Some report that paint stripes do not last as long on OFC as they do on dense-graded surfaces. As discussed in Chapter Six, many states report that the first paint applied soon after the overlay is placed wears away quickly but that thereafter no difference in painting difficulty is discernible. Those reporting longer life take into account the

Figure 2. Effect of OFC on truck spray. The top photo shows typical spray surrounding trucks during rainstorms when the trucks are traveling over dense-graded asphalt or portland cement concrete pavements. The lower photo shows a truck traveling over OFC during a rainstorm. Note absence of any spray. (Photos courtesy of the Rhode Island Department of Highways.)

Figure 3. Drainage characteristics of OFC photographed during rain of about 1/2 in./h (13 mm/h). Water is draining through the mat and out the edge of the surfacing. (Photo courtesy of the Texas Transportation Institute, 21.)

portion of the paint that is below the surface and thus protected from wear, as discussed in number 10 above.

12. Ice formation on the surface is retarded. Disagreement also exists with respect to this point. Some states report that icing or frosting occurs earlier on OFC than on dense-graded surfaces. As discussed in Chapter Six, whether or not ice formation (or snow entrapment) occurs sooner or later on OFC as compared with dense-graded mixtures depends greatly on the atmospheric conditions and temperatures existing during the storm. It should be noted, however, that even when snow is trapped in the OFC, slipperiness is often not as great as would appear, inasmuch as traction is maintained by the high points of the aggregate.

13. Safety is increased (because of reduced stress on the operator during rainstorms). This advantage is not listed in published reports. It is often mentioned, however, when OFC is discussed with highway personnel. During rainstorms, the combination of a drier surface, reduced splash and spray, and less glare at night gives the driver a feeling of confidence. Fewer distractions permit the driver to give more attention to the normal traffic conditions.

These advantages are generally supported by the performance of a number of installations throughout the country. However, certain limitations of and restraints on OFC also must be considered before a decision is made to use this type of construction in any specific case.

One basic requirement for OFC is the availability of a high-quality nonpolishing aggregate. A high friction number cannot be maintained with aggregates that do not have adequate microtexture and resistance to polishing and degradation under traffic. If such aggregates are unavailable, combinations of several available materials in dense-graded surfaces might provide better skid-resistant surfaces in the long run.

OFC should not be used directly over structurally inadequate pavements. Little structural strength is added with OFC, and a pavement in structural distress must be upgraded or rehabilitated prior to the application of OFC. Obviously, an open-graded asphalt friction course may be applied as the final surface to such reconstructed pavements.

Temperatures for placing OFC are more critical than they are for placing dense-graded overlays (17). Placement at temperatures below 60 F (16 C) can lead to poor adhesion and subsequent bond failure. Placement at ambient temperatures above 100 F (38 C) may lead to nonuniformity and flushed areas in the finished pavement because of excess asphalt flow in the haul trucks or pavers.

Costs per ton of mixture are generally higher for open-graded mixtures than they are for dense-graded mixtures, which may lead to higher total project costs. However, the greater coverage in square yards per ton of OFC because of higher void content and thinner course thickness offsets this factor to a great extent. (This is discussed further in Chapter Six.)

A report by the AASHTO Sub-Committee on Maintenance (18) identified the following maintenance problems associated with OFC:

1. The use of chemicals for snow and ice control is increased.
2. Reflection cracking occurs faster under certain conditions.
3. Petroleum product spills cause rapid deterioration of the materials.
4. Handwork in placement creates a different surface texture.
5. The expected service life may be shorter than that of dense pavements.
6. Patching is difficult.
7. Early preventive maintenance is necessary.
8. The pavement remains wet longer.
9. Provision must be made in the shoulder area to allow free flow of water collected in the OFC.

These disadvantages were listed as reported by individual states, but they do not in all cases represent a consensus. There are differences of opinion concerning some of them, and more recent evidence indicates that earlier opinions may have been in error. Following are some comments on each of the items listed above.

1. The use of chemicals for snow and ice control is increased. Experiments conducted during the winter of 1976-77 show that, in general, OFC does not require increased use of salt to provide adequate traction. (See Chapter Five for further discussion.) Some variations in behavior were observed, depending on atmospheric conditions. OFC often retains trapped snow in the voids, which leads to an appearance of slipperiness even when traction is satisfactory. More information is needed to determine the optimum use of salt for OFC.

2. Reflection cracking occurs faster under certain conditions. This disadvantage is recognized by most states. Problems have been particularly bad for overlays over portland cement concrete. Raveling also often occurs at the cracks. (See Chapter Five for further discussion.)

3. Petroleum product spills cause rapid deterioration of the materials. This disadvantage is inherent in the open texture of OFC. Because of it, some states have used dense material at intersections where such spills are most likely to occur. Areas damaged from spills at accident sites are unsightly but do not adversely affect overall performance of the OFC to a great extent.

4. Handwork in placement creates a different surface texture. This disadvantage is not difficult to overcome. Much of the handwork can be eliminated by

a skilled crew, and increased experience tends to reduce problems from hand-raking.

5. *The expected service life may be shorter than that of dense pavements.* This is an opinion held by some states, based primarily on knowledge that hardening of the asphalt in OFC occurs at a more rapid rate than it does in a dense surface. However, most OFC pavements have performed as expected. At the present time, data are insufficient to predict the average expected life of this type of surface.

6. *Patching is difficult.* This is a recognized disadvantage. (See Chapter Five for further discussion.)

7. *Early preventive maintenance is necessary.* Preventive maintenance does appear to contribute to prolonging the life of OFC. However, most OFC now in use has not been treated in any way and performance is considered generally satisfactory. (This is discussed further in Chapter Five.)

8. *The pavement remains wet longer.* Because water flows in the voids of the pavement, it takes longer for OFC to appear dry after a rain. However, the points of contact between the surface and the tire are actually dry much sooner on OFC than on dense surfaces.

9. *Provision must be made in the shoulder area to allow free flow of water collected in the OFC.* This is not necessarily a disadvantage. It is, however, an important design consideration, and maintenance crews should be alerted to maintain adequate drainage at the shoulders and at the gutter line where curb and gutter are used.

With the present state of knowledge, no criteria can be applied universally when a decision must be made about whether or not to use an open-graded asphalt friction course. The evidence is very strong that the use of some type of open-graded surface providing good lateral water drainage offers the best available type of construction for minimizing the problems of hydroplaning and splash and spray from other vehicles. For pavements where speeds are low or in situations where problems from lack of easy water drainage are not likely to occur, other types of surfaces may provide equally adequate and more economical performance. The decision for each project must be made on the basis of the expected traffic demands (volume and speed), the availability of materials, overall cost, and effects on maintenance of traffic during snow and icing conditions.

Several states have adopted criteria based on expected amounts of traffic and speed permitted. In Georgia, for example, OFC is used in construction of all new Interstate highways that are asphalt and all Interstate resurfacing where the existing pavement is asphalt. In addition, OFC is used in other projects, according to the following guidelines, as listed in Georgia's response to the questionnaire discussed in Chapter Six:

"Recommended for multilane roadways with uncontrolled or limited access and posted speed limits of 40 mph or greater where rapid lane change movements and sudden deceleration or acceleration of the vehicle is to occur.

"Recommended for two-lane roadways where the traffic level is moderate to high and frequent passing movements or sudden stops are likely to occur. Posted speed limits should be 40 mph or greater and shoulders or ROW provide for limited or inadequate space for refuge or recovery. Particular consideration should be given to roadways with sudden changes in alignment or grade.

"Consideration is also recommended for localized problem areas where increased traction under wet conditions is desired. OFC should also be considered for corrections of intersections or other localized areas where accident experiences indicate a need."

In Louisiana, the adopted policy (19) requires the use of asphaltic concrete friction course (that state's term for OFC) on highways that carry daily traffic volumes from 2000 to 2999 per lane and that have speed limits greater than 45 mph (72 km/h). In this situation, either slag, stone, or expanded clay may be used for the aggregate. OFC must also be used for highways with traffic volumes in excess of 3000 vehicles per lane and with speed limits greater than 45 mph. In this situation, only slag or stone may be used as the aggregate. Also, the underlying pavement in this situation must be dense-graded asphaltic concrete.

CHAPTER THREE

DESIGN OF OPEN FRICTION COURSES (Hot Mixtures)

A review of the literature and of the states' responses to the questionnaire discussed in Chapter Six indicates that initially most plant-mix seal coats were designed by judgment. The engineer tried what seemed to be about right for the intended purpose and adjusted gradation and asphalt content as work progressed. By learning through experience, those dealing with the same aggregates all the time eventually arrived at a design that provided adequate performance, and a number of states are continuing practices that have proven satisfactory through experience.

Dependence on such a procedure, however, is considered hazardous for those with less experience. In particular, the arbitrary changing of asphalt content to adjust for drainage in delivery trucks is questionable. Drainage for a selected asphalt cement is a function of the mixing temperature and hauling time as well as of the amount of asphalt. As mentioned previously, the FHWA procedure was a new approach, in that the desirable characteristics of the finished product were recognized and the properties of the materials and the combination of materials needed to provide such characteristics were determined in the design procedure. Although the original FHWA procedure (8) failed to recognize the adjustments needed for aggregates of unusual specific gravity, a later correction factor was established and issued to all states (20). This synthesis uses the updated FHWA procedure as the basis for the design considerations and discussions. The recommended step-by-step procedure provided in Appendix A is the updated FHWA procedure based on the two aforementioned references (8, 20).

MATERIAL REQUIREMENTS

Coarse Aggregate Selection

The physical properties of the coarse aggregate in OFC are the controlling factors with respect to the attainment and maintenance of high friction numbers and a low friction-number speed gradient.

Highway designers now know that pavement skid resistance is a function not only of the large-scale texture (macrotexture) but also of the small-scale texture (microtexture), which can barely be felt. In a dense-graded asphalt mixture, the pavement macrotexture is provided by the coarse aggregate, but the microtexture is provided by both the coarse and fine aggregate. In the open friction course, however, the coarse-aggregate fraction must provide the necessary microtexture without assistance from the fine aggregate. It is therefore very important that this characteristic be considered in the selection of the coarse aggregate. A number of aggregates derive their excellent microtexture properties through the process of attrition, but in some cases this can be excessive in terms of abrasion loss.

FHWA recommends that relatively pure carbonate aggregates or any aggregates known to polish be excluded from the coarse-aggregate fraction of OFC (material retained on the No. 8—2.36-mm—sieve). FHWA also recommends that the coarse-aggregate fraction have at least 75 percent (by weight) of particles with at least two fractured faces and 90 percent with one or more fractured faces; the abrasion loss, as determined by AASHTO T 96, should not exceed 40 percent.

Gallaway and Epps recommended a specific polish value requirement for aggregate, based on expected traffic volumes of the roadway (21). A value of not less than 35, as determined by Texas Method 438-A, is recommended for traffic volumes of 4000 vehicles or less per day per lane. For traffic volumes of more than 4000 vehicles per day per lane, a value of not less than 40 is recommended. Texas Method 438-A, based on the British polishing wheel, is a modification of ASTM Method E 303. The procedure is given in Appendix B.

The 40 percent abrasion loss recommended by FHWA is generally accepted by state highway agencies as a suitable maximum. However, the FAA guide specification for overlays of airfield runways limits this loss to 25 percent. Many consider abrasion loss in OFC especially important because of the need to maintain an open texture in the pavement. Traffic abrasion, which generates fine particles that could be trapped in the surface and eventually fill the voids, cannot be tolerated.

Both the percentage and the shape of fractured faces in the coarse-aggregate particles must be taken into account in the determination of how to provide the necessary aggregate voids and the interlocking, which imparts much of the stability and load-carrying capacity to the mixture. The requirement for a high percentage of fractured faces is found in nearly all state specifications for OFC. Smith cautioned against the use of materials such as chert, which, because of their hardness and the sharpness of their edges, may perform exceptionally well in dense-graded mixtures but, because of the smooth microtexture, have performed poorly in open-graded asphalt friction courses (22).

Relatively few comparative field tests using different types of aggregate have been conducted. However, the report by Ortgies of the Iowa Department of Transportation describes tests with several types of aggregates and combinations of them (23). His tests used quartzite, fine-grained limestone, coarse-grained limestone, and lightweight expanded shale. In general, the results of this work confirm the coarse-aggregate selection criteria suggested by FHWA. The quartzite with a good

performance record in dense-graded mixtures also performed better than the other three aggregates in OFC. The coarse-grained limestone, although lower in friction number than quartzite, also gave acceptable friction-number values, as did a 50-50 blend of the two materials. Fine-grained limestone, known to polish under traffic, did not perform satisfactorily when used alone. However, acceptable friction numbers were obtained with 50-50 blends of the fine-grained limestone and either quartzite or expanded shale. Tests were not made in Iowa on 100-percent expanded shale, but material from the same source gave excellent performance in Louisiana.

Slags and Lightweight Aggregate

Slags have been shown to provide surfaces with good friction numbers and excellent performance in OFC. Where available, they are usually competitive with natural aggregates and in some cases are preferred. In areas where suitable natural aggregates or slags are not available, significant success has been obtained with lightweight manufactured aggregates such as expanded clay.

Louisiana has used slags with success. Both Louisiana and Texas have made considerable use of sintered and expanded materials. The same gradation requirements generally apply for such materials, but slightly higher abrasion losses, as determined by laboratory tests, are permissible. The Louisiana test for abrasion (La. TR 111) is a modification of the standard Los Angeles abrasion test (AASHTO T 96). In the Louisiana test, the weight of the charge is adjusted to represent a volume of charge equivalent to that used in the standard test for aggregates of normal density. The development of this test is discussed in a report issued by the Louisiana Department of Highways (24). The procedure is given in Appendix C.

Louisiana recognizes that significant wear does occur in its OFC constructed with lightweight aggregate, but because of the nature of the aggregate, a high friction number is maintained. (The continual exposure of new surface material with excellent microtexture avoids loss of friction number.) Louisiana also reports that the fines from such wear are for the most part swept to the side of the road and are not trapped in sufficient quantity to create a closing-up problem.

In Iowa, a 50-50 blend (by volume) of fine-grained limestone and expanded shale was tested; after 16 months the friction number remained satisfactory, although there were reservations as to whether expanded shale had adequate resistance to the action of studded tires (23).

Because asphalt requirements are controlled by volumetric parameters (even though they are normally expressed as percentages by weight), adjustment for asphalt content on the basis of the aggregate's density is required when either slag or lightweight aggregate is used. Absorption also may be of concern with mixtures composed of these aggregates. (This is discussed later in this chapter.)

Aggregate Gradation

The attainment of the desired macrotexture property and internal drainage characteristics is primarily a function of the gradation of the mixture. As shown in the replies to questions 5 and 6 of the questionnaire on state practices (see Chapter Six), a wide variety of master gradation ranges are specified by the states—35 different gradation specifications for the 49 states reporting. It is likely that many of these differences reflect a state's efforts to match the ranges with its usual sources of supply and to maintain some uniformity in the void structure of aggregates being supplied at different times. Despite this diversity of master ranges specified, the typical gradations reported by the states present a much more uniform picture. Although in several cases a larger size (nominal 1/2 in.—13 mm) is being tried, almost all states are using a nominal maximum size of 3/8 in. (9.5 mm), with different allowances for oversize material. Essentially all the typical 3/8-in. material falls within the master ranges suggested by FHWA (Fig. 4). Consequently, adoption of these ranges is recommended. The recommended master ranges for gradation are given in Table 1.

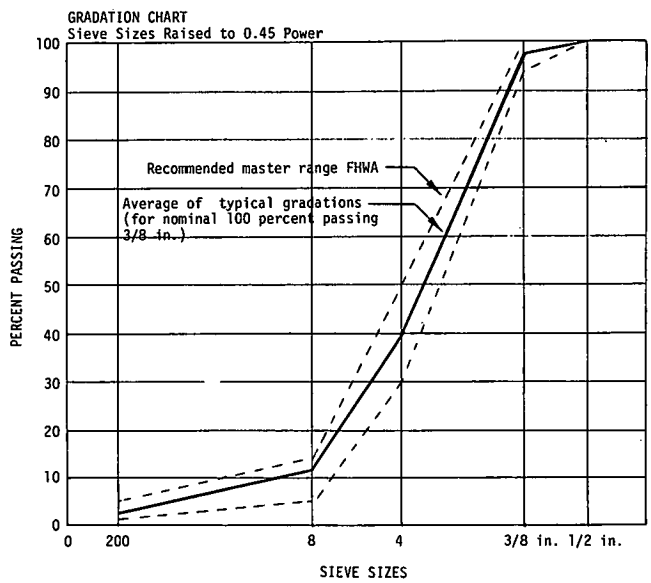


Figure 4. Average of typical gradations in use by states for open-graded asphalt friction courses.

TABLE 1
RECOMMENDED MASTER RANGES FOR GRADATION

Sieve Size[a]	Percent Passing[b]
1/2 in. (12.5 mm)	100
3/8 in. (9.5 mm)	95 - 100
No. 4 (4.75 mm)	30 - 50
No. 8 (2.36 mm)	5 - 15
No. 200 (75 μm)	2 - 5

[a]U.S.A. Standard Series.
[b]By volume. Most specifications use percent passing by weight. There is no significant difference in percent by volume or percent by weight when all fractions of the aggregate have similar characteristics. However, if two or more components having different densities are being blended, adjustment to proper volume percentage may be needed.

The gradation originally recommended in FHWA RD 74-2 (8) required 100 percent passing the 3/8-in. (9.5-mm) sieve, but subsequent experimentation verified that small quantities of oversize material did not significantly affect the desired mixture properties. The revised specification generally allows more economical use of standard-size aggregates. The limits on the amount passing the No. 8 (2.36-mm) sieve are provided primarily as a guide. The overriding consideration, which dictates the actual amount, is the level of interstitial void capacity provided by the coarse-aggregate fraction. The uniformity of the grading between the No. 8 and No. 200 (75-μm) sieve was an important consideration in the establishment of the limits for the No. 8 sieve. The upper limit of 15 percent passing the No. 8 sieve was the maximum amount of *uniformly graded* minus No. 8 sieve material that could be incorporated into the interstitial voids of the coarse aggregate without bulking the coarse aggregate. Preventing the bulking of the coarse aggregate was considered important for maximizing coarse-aggregate interlock and thus internal friction.

Differences of opinion exist as to the amount of fine aggregate that should be used in the mixture. Some states prefer a single aggregate with very few fines to assure greater openness. On the other hand, the need for at least some fine aggregate has been greatly emphasized by FHWA and others, because the fine aggregate provides a chocking action for the stabilization of the coarse-aggregate fraction. However, the need for such chocking action decreases with increasing angularity of the coarse aggregate. Therefore, the importance of the fine aggregate also decreases as angularity increases, and in some instances lowered quantities of fine aggregate may be justified.

Experience has also demonstrated that some material passing the No. 200 (75- μm) sieve is required. A portion of this fine material tends to blend with the asphalt and thus increase the effective viscosity of the binder and reduce asphalt drainage in the mixture. The recommended minimum is 2 percent. This requirement also helps assure a continuous grading of the fine aggregate for better stability and prevention of raveling. It is interesting that, although 17 states had requirements permitting 0 percent passing the No. 200 sieve, the typical materials used almost always contained amounts equal to 2 percent or more passing the No. 200 sieve.

In general, most states permit the material passing the No. 200 (75- μm) sieve to be the natural fines but allow the addition of mineral filler if necessary. As indicated in Chapter Six, a few states require the addition of 1 to 1-1/2 percent hydrated lime, limestone, or portland cement to promote adhesion.

Binder Selection

The grades of asphalt cement used for hot mixtures are AC-10, AC-20, AC-40, AR-40, and AR-80 of AASHTO Specification M 226. The requirements given in Table 2 of Specification M 226 are recommended for AC-10, AC-20, and AC-40 when such asphalts are normally available in the area. The requirements given in Table 3 of M 226 apply for AR-40 and AR-80. Where penetration grading is still used, either 85-100 or 60-70 grades of AASHTO Specification M 20 are specified.

Some states use the AC-10 or 85-100 grade asphalts primarily on the premise that, because the final surface is open and is accessible to air and water infiltration, hardening tends to occur faster than it does in dense-graded mixtures. Thus, it is reasoned, starting with the softer material increases durability because it takes longer to reach a critical hardness of the binder. On the other hand, use of the harder grades (AC-20 or AC-40) tends to permit higher mixing temperatures without drainage, and the higher viscosity (at equal temperatures) provides for thicker films that are more resistant to hardening. Consequently, the overall hardening of AC-20 or AC-40 during the life of the pavement may be less than that occurring with AC-10, which would offset the apparent advantage of an initially lower viscosity for the AC-10 material. More specific data are needed on this point, but because many factors enter into the hardening of the asphalt in a pavement, it is reasonable to assume that the asphalt grade providing the most convenient combination of drying, mixing, and placement temperatures with suitable mixture workability should be used. For most states, this appears to be the AC-20 or the AR-40 grade. The AC-40 grade has been found useful mostly in southern states subject to high pavement temperatures during the summer months and relatively mild winter conditions. This grade of material may be too hard for areas subject to severe winters, however.

THE MIXTURE DESIGN

Preliminary Data

It is necessary that adequate quantities of all the individual components of the actual aggregates proposed for use be submitted to the mixture design laboratory, together with any information on the proportions of each that the contractor prefers to use. The design engineer must be able to construct the proposed job-mix in the laboratory, not only in gradation but also in the exact proportions of the various components. If mineral filler is submitted as a separate item, it should also be tested for specification compliance. Where modifications in the job-mix formula are deemed necessary, the designer must assure that such modifications can be made with the supply of commercial materials available.

The FHWA design process requires that separate specific gravity values be determined for the coarse aggregate and fine aggregate (material retained and passing the No. 8—2.36-mm—sieve) of the job-mix blend. One approach is to prepare a sample having the job-mix gradation in accordance with the proportions proposed by the contractor and then to separate the sample into two fractions by splitting on the No. 8 sieve. Each fraction can then be tested separately for specific gravity.

Although the above approach requires only two specific gravity determinations, it leaves the designer with little flexibility if an adjustment to the job-mix gradation must be made. It is therefore desirable to determine specific gravities of the coarse- and fine-aggregate fractions (retained and passing the No. 8—2.36-mm—sieve) for each type of material submitted.

The asphalt cement should be subjected to the routine tests to verify specification compliance. Information should be provided regarding the intended use or presence of additives in the submitted sample. Typical additives are antistripping agents and silicone. When kerosene or fuel oil is used as the diluent for the additive, the dilution proportion should also be given. It is preferred that the sample of asphalt cement received at the laboratory be a representative sample from the plant, already containing the additives.

Asphalt Content

In the FHWA design procedure, the method of selecting the asphalt content consists of two steps. The first is measuring the surface capacity of the aggregate fraction retained on the No. 4 (4.75-mm) sieve. Surface capacity includes absorption, superficial area, and surface roughness, all of which affect asphalt cement requirements. The surface capacity is represented by K_c, which is determined by using a modified oil equivalent test developed in California (25). This test, described in Appendix A, is basically a measure of the amount of SAE No. 10 lubricating oil retained by the sample after drainage under controlled temperature conditions for a specific time. The surface constant (K_c) is empirical and is determined from a chart provided in the California publication (25) (also provided in Appendix A).

After K_c is determined, the second step consists of calculating the asphalt content by use of an equation based on field experience with similarly graded mixtures. The FHWA procedure uses this equation:

$$\text{Percent asphalt} = 2.0(K_c) + 4.0 \qquad (1)$$

In the FHWA procedure, the result obtained by this test is considered the final design asphalt content, except where adjustments are needed for aggregates having specific gravities significantly different from 2.65 (which is assumed to be the apparent specific gravity of the aggregates from which the field experience was derived in establishing the equation).

When specific gravity differs significantly from 2.65, corrections in the weight percentage of asphalt are needed, because the required coating (based on K_c) is fundamentally a volumetric factor and asphalt content is expressed as a weight percentage of the aggregate. Smith (20) developed this modified equation:

$$A\,(cor) = A\ orig \times \frac{2.65}{(SG)ca} \qquad (2)$$

where

A(cor) = Corrected asphalt content (by weight of aggregate)

A(orig) = Original asphalt content (by weight of aggregate) ($2.0\ K_c + 4.0$)

(SG)ca = Apparent specific gravity of coarse aggregate

The procedure recommends applying this correction whenever the specific gravity of the coarse aggregate is greater than 2.70 or less than 2.60.

In Appendix A, equations 1 and 2 above have been combined into one so that the apparent specific gravity of the aggregate is automatically taken into account. The combined equation is:

$$A = (2.0\ K_c + 4.0) \times \frac{2.65}{(SG)ca}$$

where

A = Design asphalt content (by weight of aggregate)

K_c = Surface capacity constant

(SG)ca = Apparent specific gravity of coarse aggregate

It should be noted that the procedure developed in Colorado by Brakey (7) for determining the asphalt content uses the surface constant but differs from the FHWA approach in that the estimated optimum asphalt (EOA) is determined by this equation:

$$EOA = 1.5\ (K_c) + 3.5$$

The EOA is then used as the basis for trial mixtures in the laboratory. Generally, four mixtures are made: one at 0.5 percent asphalt below EOA, one at EOA, one at 0.5 percent above EOA, and one at 1.0 percent above EOA. After laboratory examination of the mixtures, the final asphalt content is selected. In general, it is reported that most final asphalt contents using the Colorado procedure are above the initial EOA determined by the equation. As shown in Chapter Six, several variations of the equation for estimating asphalt content are in use by other states, but in each case adjustments are made by observation of laboratory specimens. Consequently, the final asphalt contents obtained by using the different procedures do not differ greatly. The FHWA procedure is recommended because it is more specific and requires less laboratory work.

Void Capacity of Coarse Aggregate

One of the basic requirements of OFC is that the final mixture after compaction have adequate void capacity to serve as lateral water drainage channels during rainstorms. Such channels also must have adequate capacity to handle normal rainfall without flooding. This property of the mixture is controlled mostly by the compactibility of the coarse aggregate, which in turn is primarily a function of the particle shape and crushed faces. The interstitial voids of the coarse aggregate must be large enough to accommodate the total volume of asphalt plus the volume of fine aggregate and still leave adequate void space in the completed mixture. The FHWA procedure assumes that 15-percent design voids is minimum. However, as discussed later, some question exists as to the optimum amount.

To measure the interstitial void capacity of the coarse-aggregate fraction (material retained on the No. 8—2.36-mm—sieve) of the proposed job-mix gradation, a vibratory unit-weight determination is conducted using a special procedure developed originally by FHWA for compaction control of granular materials. Appendix A explains this test procedure. A desirable feature of the test is the high degree of densification achieved without causing a significant amount of aggregate degradation. The test result thus provides an indication of the minimum level of interstitial voids that could exist in the friction course after long-term densification under high traffic volumes (assuming no aggregate degradation).

This element of the FHWA design procedure is employed by only a few states, probably because the test procedure has not yet been standardized by either ASTM or AASHTO and the equipment has not been acquired by many states. Most states now assume that when gradations within the master range are specified and when the aggregates have the required number of crushed faces and usual particle shape, the coarse-aggregate void system will be satisfactory. Experience has indicated, however, that in some cases aggregates that have the proper gradation range but too much

sphericity do not have adequate void capacity and do not perform well in OFC.

Optimum Content of Fine Aggregate

The optimum amount of the fine-aggregate fraction is that which permits the required quantity of the interstitial (coarse-aggregate) voids to remain unfilled after the total volume of the asphalt cement and fine aggregate is added. A requirement of the design method is that the coarse aggregate may not be bulked; that is, the interstitial void system of the coarse-aggregate fraction may not be made greater by the addition of the fine-aggregate fraction. This ensures the needed internal void system with large voids for water drainage purposes.

The FHWA procedure assumes that the above requirement will be satisfied if the fine-aggregate fraction is limited to a maximum of 15 percent (by volume) of the total aggregate. The FHWA procedure also assumes that it is desirable to use as much fine aggregate as possible (up to the maximum of 15 percent) while still satisfying the requirement for a 15-percent minimum in design air voids because of the chocking action the fine aggregate imparts to the coarse-aggregate particles. This is considered most important for preventing raveling of the mixture in service.

As mentioned previously, there is some question as to the optimum design air-void content. Although it has been well established that design voids of appreciably less than 15 percent result in surfaces that do not maintain optimum water drainage characteristics, design voids greater than 15 percent may be desirable. Kandhal, Brunner, and Nichols reported that a design void content of 20 percent would be better because the OFC would maintain its open texture for a longer period of time (27).

Gallaway and Epps provided procedures for designing mixtures with different percentages of voids but made no recommendations as to which would be considered optimum (21).

Additional information also is needed on the relationship of the designed voids to the actual voids in the pavements. A study of the field performance of selected projects has been conducted by FHWA, but the report is not yet available. That report should provide needed information concerning this point.

The detailed procedure explained in Appendix A determines the percent of fine aggregate (material passing the No. 8—2.36-mm—sieve) needed to assure the attainment of a minimum air-void content of 15 percent in the compacted mixture. The amount of fine aggregate added must be less than 15 percent. In the void analysis, the procedure does not take into account the absorption of the asphalt by the aggregate. However, any absorption that occurs would result in higher voids than the design; thus the difference is in a favorable direction and serves as a safety factor with respect to void content.

The requirement of the FHWA procedure to modify the proposed job-mix gradation because of a difference of a few percentage points between it and the computed job-mix gradation on the No. 8 (2.36-mm) sieve may seem inconsequential from a practical standpoint. However, the FHWA report calls attention to the fact that the procedure is dealing with a "target value concept." Normal variability in gradation during batching operations may be as much as several percentage points on any one sieve size, and this could add to any initially allowed deviation to produce a significantly different aggregate gradation with unacceptable characteristics. It is therefore desirable to determine the target value as precisely as possible.

Optimum Mixing Temperature

The optimum mixing temperature is based on the concept that the aggregate should be heated so as to be reasonably dry to facilitate coating and adhesion yet not be so hot that the viscosity of the asphalt binder is reduced to a level that causes drainage and segregation of the asphalt from the aggregate during transit from the mixing plant to the job site. According to FHWA, the recommended target mixing temperature is that which will provide asphalt cement viscosities in the range of 700 to 900 centistokes (7 to 9 cm^2/sec). However, Kandhal, Brunner, and Nichols reported that in Pennsylvania the optimum range for asphalt cement viscosity is 1400 to 1700 centistokes (14 to 17 cm^2/sec) (27). This difference indicates that Pennsylvania normally uses a target temperature about 15 F (8 C) lower than FHWA does for the same conditions.

Both Pennsylvania and FHWA run the asphalt drainage test described in Appendix A to verify the suitability of the target mixing temperature. Under normal field control conditions, temperature variations equal or exceed the difference in the target mixing temperatures, so there is no significant difference between the two viewpoints.

Temperature must be sufficient to adequately dry the aggregate and place the mixture at the paving site. Should the maximum suitable mixing temperature determined by the drainage test be inadequate to dry the aggregate properly, a higher-viscosity asphalt cement should be selected and a new mixing temperature should be established by tests with the new binder.

It is important to note that in the FHWA procedure the purpose of the asphalt drainage test is not to determine asphalt content, as has been its purpose in the past, but rather to determine the mixing temperature at which the recommended quantity of asphalt may be used.

Resistance to Effects of Water

Because the interior of the OFC is accessible to water, it is important to investigate OFC's tendency to lose strength in the presence of moisture. The FHWA design procedure therefore includes the determination of the percentage of retained strength after four days of immersion at 120 F (49 C), in accordance with AASHTO Methods T 165 and T 167 (modified). The requirement is that the retained strength be not less than 50 percent. Note that the level of strength in this test is not considered an important criterion—only the percentage of retained strength. A number of states now require the use of an antistrip additive in the asphalt cement as a standard practice for OFC rather than make the immersion test. As indicated by the replies to question 13 of the questionnaire on state practices (see Chapter Six), several states use antistrip additives not only to promote adhesion but also to counteract the asphalt's tendency to drain from the aggregate during hauling.

CHAPTER FOUR

CONSTRUCTION TECHNIQUES (Hot Mixtures)

Open-graded asphalt friction courses can be mixed and placed with the same types of mixing plants and laydown equipment as are used for dense-graded mixtures. However, open-graded mixtures differ from dense-graded mixtures in appearance and handling and therefore require special consideration. This chapter is based on a number of reports, conversations with highway engineers, and the comments received in reply to the questionnaire discussed in Chapter Six. The information presented is believed to represent a general consensus of the opinions of those contacted.

TRAINING OF CREWS

Discussions with highway engineers in several states have indicated that an understanding by the contractor and laydown crew of the differences between OFC and the normal, dense asphalt mixture is a must. Open-graded mixtures tend to look much richer and behave differently in handling. Therefore, when contractors and crews undertake an OFC project for the first time, it is important that someone familiar with OFC work explain the intent of the mixture and caution them about the differences to expect. This is generally an easy task and requires about half a day.

SURFACE PREPARATION

Open friction courses should be placed only on structurally sound pavements, and the overlay should not be relied on to correct structural deficiencies. Where the surface of the existing pavement or base is irregular, it should be brought to uniform grade and cross section by use of a dense-graded leveling course. Such a leveling course should be thoroughly compacted prior to placement of the OFC overlay. Open-graded material should not be used for this purpose because of the danger of entrapping water in low spots. In discussing the need for complete water drainage from the pavement, Allen, Peters, and Longfellow (28) stated:

"The theory behind porous open-graded friction courses is that they allow for [water] drainage through the mix and if the transverse geometrics are correct, this drainage will be off the traveling surface by transverse movement. One can note the effectiveness of this drainage by observing traffic movements during periods of heavy rainfall. Dense mixtures will tend to create, to a large degree, splashing or whipping of surface water off the roadway surface and onto the traveling vehicles etc., while surfaces that are open reduce this tendency considerably.

"Following periods of rainfall one can observe the continuation of drainage for extended periods of time.

"The importance of transverse geometrics cannot be overstated. The true effectiveness of an open-graded friction course requires adequate movement of the water off the roadway. When surface slopes are inadequate or subsequent densification of underlying pavement courses creates rutting a 'collection basin' can be formed which can create more problems than the ones you hoped to solve by the use of an open-graded friction course. In areas of freezing the 'collection basin' could become a hazard if the collected water does freeze. It cannot be overemphasized that surface distortion and slope should be corrected by means other than the open-graded surface treatment. Considerations need to be given to adequate cross slope and minimal distances to require the water to move. It would be better, for instance, to attempt to drain only one-half of an interstate roadway by use of a crowned section than attempting to drain the full width by cross-sloping.

"Since the complete advantage of an open-graded friction course requires adequate drainage it is, therefore, imperative that consideration be given to optimizing all factors influencing drainage. Skid resistance, noise levels, etc., are also optimized by proper drainage."

Open friction courses have been successfully placed over existing asphaltic concrete and portland cement concrete pavements. However, several states (see Chapter Six) have had difficulty with some overlays directly over portland cement concrete and recommend either an intermediate course of dense-graded material or careful sealing of all joints prior to placement of the OFC. A heavy tack coat, well distributed over all parts of the pavement, also appears necessary for good adhesion when OFC is applied directly over portland cement concrete.

TACK COAT REQUIREMENTS

A tack coat should be used where OFC is to be placed over old bituminous surfaces (the most usual situation). Differences of opinion exist with respect to use of tack coat when the friction course is placed as a part of new construction. Some believe the tack coat unnecessary in this instance, but others recommend that a small amount be applied as a diluted emulsion.

The amounts used vary from about 0.03 gallons of diluted emulsion per square yard (0.14 L/m^2) to as high as 0.10 gal/yd^2 (0.45 L/m^2). As indicated in Chapter Six, numerous types and grades of asphalt materials are used for tack coats. The most prevalent materials are emulsions—SS-1, SS-1h, and CSS-1. The specific amount of tack coat to be used on a given job is usually left to the judgment of the engineer. An important consideration is that the material should be uniformly and completely spread over the old surface. In some cases the tack coat is rolled with rubber-tired rollers to assure complete distribution.

Gallaway and Epps reported the problem of rubber-tired construction equipment slipping when heavy tack coats were used but encountered no problems with crawler track equipment (21).

OPTIMUM THICKNESS OF OVERLAY

Most OFC is laid at a target thickness of either 5/8 or 3/4 in. (16 or 19 mm), as reported by 37 of the 47 departments responding to the questionnaire (see Chapter Six). Some states report successful use of mats as thin as 1/2 in. (13 mm), although other experimental projects laid at 1/2 in. did not perform properly (29). Thicknesses up to 1 in. (25 mm) generally perform satisfactorily but in most cases do not appear necessary for attaining the desired performance.

Gallaway and Epps discussed several factors affecting the decision regarding optimum mat thickness (21). They identified cost as the primary reason for making the mat as thin as is practical. However, there are constraints that may demand either a thicker or thinner mat. The field considerations they listed are:

1. Minor surface irregularities.
2. Condition of the surface overlaid.
3. Structure clearances.
4. Dead weight on bridges.

Flushed areas and minor surface irregularities dictate thicker mats. Applying too thin a mat may cause dragging of the screed, with subsequent failures by raveling. This problem is shown in Figure 5. Using thicker mats to smooth out minor irregularities should be done cautiously. As discussed above, the pavement design must provide for adequate water drainage so that collection basins are not formed.

Thin mats over flushed areas have greater potential for permitting the asphalt to bleed through to the new surface than do thicker mats over the same areas. In very heavy rains, thicker mats also provide for greater water drainage capacity before flooding.

Costs, critical clearances, and dead weight on bridges all generally dictate the use of thinner mats. However, as discussed by Gallaway and Epps, using thicker mats promotes easier placement and compaction, improved riding quality, and lower probability of bleed-through in flushed areas (21). These attributes would increase a contractor's confidence in successful placement of the material, which in turn would lead to lower unit bid prices.

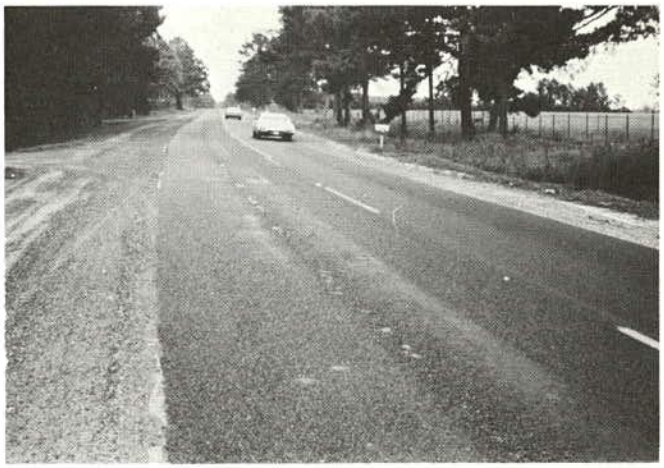
TEMPERATURE CONSIDERATIONS

Open friction courses should not be laid either in cold weather or at ambient temperatures above 100 F (38 C). As reported in Chapter Six, several failures have been attributed to loss of bond and subsequent flaking off because of cold-weather laydown. "Fat spots" and flushing are reported to occur when ambient temperatures are extremely high. Most states have established a minimum air temperature in the range of 60 to 70 F (16 to 21 C) for laydown. Some states, such as Pennsylvania (29), specify a minimum pavement surface temperature of 70 F. Others establish the time of year during which overlays are made. (Louisiana, for example, prohibits construction of OFC from November through March.) Arizona (28) has established time periods based on ground elevation (which is related to temperature); placement at low elevations during June, July, and August is prohibited in Arizona because of the likelihood of extremely high ambient and road surface temperatures (>100 F).

The temperature of the mixture must be controlled within a normal working range to prevent problems. Because of the rapid cooling of the thin layer after placement, temperatures must be high enough for adequate working time; but because of the nature of the mixture, temperatures cannot be so high that drain-down of the asphalt occurs, thus concentrating asphalt in the mixture at the bottom of the truck.

The FHWA Notice (6) suggests that target mixing temperatures normally run between 230 and 260 F (110 and 127 C), and replies from the states, as reported in Chapter Six, verify this as the most common range, although quite a few states report mixing temperatures outside this range. As discussed in Chapter Three, the target mixing temperature should be set initially by considering the viscosity of the asphalt. However, the relatively wide range of mixing temperatures used by the states indicates that the working range of temperatures for laydown and compaction is sufficiently broad to allow for normal variations during construction. Avoiding problems caused by either too low or too high a temperature is not difficult.

Under the older concept of using maximum asphalt to



A dragging screed causes aggregate crushing and raveling between wheel paths where overlay is too thin.

Close-up of damaged area.

Figure 5. Problems associated with too thin an overlay. (Photos courtesy of the Texas Transportation Institute, 21.)

provide for drain-down of the asphalt and for sealing of the old pavement after placing the new surface, many problems with drain-down in the truck were reported. The asphalt that drained down through the mixture caused material to stick in the truck bed, and the excess of asphalt in the mixture near the bottom of a load caused fat spots on the roadway after placement. However, when design considerations such as those recommended by the FHWA procedure are used, the problem of asphalt drain-down can be controlled. The report of FHWA Demonstration Project No. 10 indicates that such problems did not occur unless the mixture temperature rose more than 10 to 15 F (6 to 8 C) above the target mixture temperature (9). Pennsylvania reported that no drainage problems were encountered using the FHWA design. Virginia reported some drain-down in the trucks for long hauls at the normal mixture temperature (30).

Generally, the replies to the questionnaire discussed in Chapter Six indicate that most states now have this problem under control and that trouble occurs only when temperatures at the mixing plant go higher than specified or when hauling time is unusually long. Only one state recognized the addition of fines (material passing the No. 200—75-μm—sieve) as a means of counteracting drainage problems. This approach should not be overlooked, however, because it provides a means of creating a stiffer binder, which would tend to form thicker films and be less likely to drain from the aggregate. Advantage can also be taken of the fact that the presence of fines (and a stiffer binder) makes it possible to use placement temperatures 15 to 25 F (8 to 14 C) higher than those for comparable mixtures without such fines. Thus, the working time for placement and rolling can be increased.

Gulden and Powell, reporting on Georgia's experience with open-graded friction courses, stressed the importance of covering the haul trucks even in hot weather (31). When trucks are not covered, rapid cooling of the mixture on the top layer occurs. This causes crusting, in turn causing the development of small lumps, which do not feed well through the paver and result in pulled or rough areas in the overlay.

With lightweight aggregates, temperature control in cool weather can be a problem. Loss of mixture temperature is greater, and raveling of the surface can result. Raising the mixture temperature causes increased asphalt absorption of the aggregate unless the viscosity of the asphalt is increased.

LAYDOWN PROCEDURES

For best results, the paver should be kept moving. Production rates need to be adjusted to the rate at which the mixture can be placed. In the FHWA demonstration project, it was reported that in most states the laydown rate was underestimated and resulted in uneven production (9). Frequent starting and stopping of the paver results in a nonuniform surface, as shown in Figure 6.

Because the overlay thickness is usually 3/4 in. (19 mm), paver speeds can be considerably greater than speeds used for thicker, dense-graded mixtures. If the speed is too great, however, the paver may chatter, the mixture may tear, and other adverse effects may occur. Gallaway and Epps reported that paver speeds of about 50 ft/min (15 m/min) were common in Texas (21).

The addition of as little as two parts per million of silicone has been reported to improve handling and laydown. Typically, 1 ounce of silicone to 5,000 gallons of asphalt has been used. The addition of silicone has also been reported beneficial in reducing drainage tendencies in the truck.

Hand-raking should be kept at a minimum, because it results in nonuniform texture of the finished surface. Joints require special attention, however, and may require some hand-raking. Longitudinal paver joints should be butt joints, and no overlapping should be allowed. Overlapping results in a high ridge, which, because of the nonplastic nature of the mixture, can be removed only by crushing the aggregate. This problem occurs often at the start of new projects when crews are inexperienced in the use of OFC, but once the crews are informed of the proper procedure, the problem is quickly corrected (9).

Because of the use of predominantly one-size aggregate, it is difficult to feather open-graded mixtures or use tapered approach sections. Good results have been obtained in these transition areas when a shallow tapered trench (about 18 in.—460 mm—wide) has been cut in the old pavement and the OFC has been started at full depth.

ROLLING REQUIREMENTS

Minimal rolling is required. Rolling should be done immediately behind the paver. Normally, one or two passes with a medium-weight steel-wheel roller will compact the mixture as much as is possible. Continued rolling or rolling after the mixture has cooled often causes crushing of the aggregates and should be avoided.

In cool weather, special attention should be given to compaction of OFC made with lightweight aggregates. Pneumatic rolling, in addition to steel-wheel, may be helpful in preventing raveling.

CONSTRUCTION SPECIFICATIONS

Most states regularly using OFC have now incorporated this type of construction into their standard specifications or have adopted special provisions for OFC. Appendix D contains Delaware's specifications, which are included to provide information as to the format often employed.

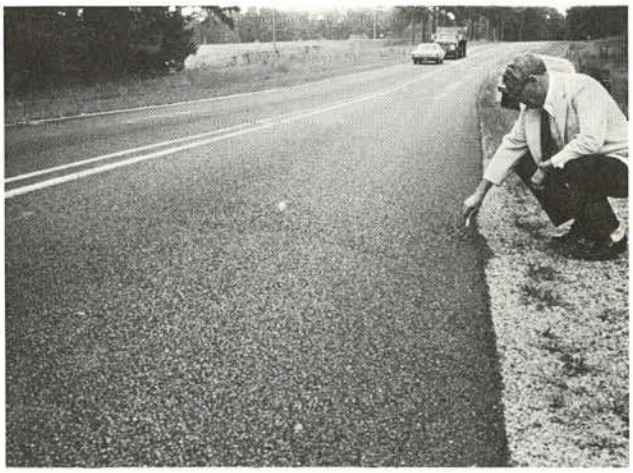


Figure 6. Surface irregularities caused by stopping the laydown machine. (Photo courtesy of the Texas Transportation Institute, 21.)

CHAPTER FIVE

MAINTENANCE

As cited earlier, the proper maintenance of open friction courses is of some concern to highway maintenance engineers. A review of the literature indicates that much of this concern is related to the overall effects of OFC on normal maintenance practice. In particular, many of the concerns expressed in the survey conducted by the AASHTO Sub-Committee on Maintenance and reported in the Maintenance Aid Digest (MAD-11) (18) are related to the effects of OFC on ice- and snow-removal practices. Also, much of the concern for lack of durability is based on conjecture and extrapolation. In a number of cases, poor performance of early open-graded plant-mix seals resulted from design or construction procedures now known not to be the best practices.

It must also be recognized that in a majority of the cases OFC is itself being placed as a maintenance procedure (or part of a maintenance procedure); thus, a major concern is the need to establish better design and placement techniques that will lead to longer life and better performance of the original overlay.

WINTER MAINTENANCE

Use of Salt

Considerable differences of opinion exist with respect to the use and effectiveness of salt in clearing OFC pavements as compared with dense-graded pavements. In the 1975 survey of maintenance practices mentioned above, several states reported a need for considerably more salt (18). For example, New Hampshire, Massachusetts, Maine, and Rhode Island reported using from 30 to 400 percent more salt. In the same survey, other states reported no significant differences. Some states also expressed differences of opinion with respect to ice formation and removal. Some states reported that ice does not form on the surface of OFC as quickly as it does on dense-graded surfaces under the same conditions, and others reported just the opposite. Similarly, some states reported easier ice removal and others reported that ice is held tighter.

Most of these reports are based on general observations and opinions. To obtain more specific data, Maine, Michigan, Utah, and Vermont conducted controlled experiments during the 1976-77 winter season. FHWA sponsored the study and coordinated the reports (32).

Although the objective of the study was to determine the relative amounts of salt needed on the two types of pavements when observed under the same storm conditions, the final report shows that in most cases the observations made were of the relative conditions of the two types of pavements when the same amount of salt was added. This distinction may help explain the differences in conclusions reached by each state.

Maine, Michigan, and Vermont reported that "about equal" or less salt was needed to maintain the same conditions on both types of surfaces. Utah reported that more salt was needed to clear open-graded pavements. The FHWA analysis of all the data led to the following conclusion:

"In summary, the data show that the clearing rates and appearance of open-graded and dense-graded pavements are not identical. While a dense-graded pavement will occasionally clear faster than an open-graded pavement, the opposite is also true. Regardless of the clearing rates, an open-graded pavement seems to provide a superior skid-resistant surface during most storms. More salt is not needed to maintain this superior surface."

Maine called attention to a difference between a clear pavement and one having adequate skid resistance, noting that under some circumstances the voids of the open-graded surface would become packed with snow so that an appearance of slipperiness existed. However, braking on such surfaces indicated that traction was adequate, because the tops of the coarse aggregate were clear and adequate tire contact was present.

It is apparent from this study and other observations that differences in behavior of both types of surfaces will occur under different atmospheric and highway conditions. More study is needed to establish the relation of temperature, amount of snowfall, wind, and so forth, to specific behavior. However, present indications are that earlier reports of the need for significantly greater amounts of salt to maintain safe conditions on OFC as compared with dense-graded pavements were in error. In general, the same plowing and salting efforts by winter maintenance crews will maintain about the same level of service on both types of pavement.

Use of Abrasives

To get the best performance from OFC, the use of sand or other abrasive materials should be avoided during snow- and ice-control operations. Such materials tend to fill the voids of the surface and prevent proper water drainage. However, for maximum safety and convenience to the traveling public, abrasives may be needed. It is also recognized that at the height of a snowstorm it is not practical for maintenance crews to differentiate between the treatment on OFC and dense-graded surfaces. The trade-off here needs to be determined by local conditions and experience.

WATER DRAINAGE

For best performance of OFC, the water drainage channels must be kept open. The shoulders must not form an impervious dam that would prevent water from flowing out through the side of the pavement. Proper drainage geometrics should, of course, be established prior to application of the OFC, but maintenance

personnel should be alerted to the necessity of maintaining free drainage. Such practices as the use of slurry seals to seal edge cracks or other longitudinal cracks should be avoided, because these seals might form a dam within the surface.

SERVICE LIFE

Little firm information exists on the service life of OFC. States have reported OFC service life expectancies ranging from a low of 7 years (Louisiana) to a high of 20 years (New Mexico) (18).

Traffic and other local conditions will, of course, affect the service life of all pavements. Thus, although some states would be satisfied with a projected service life of 8 to 10 years, others believe a 10-year service life is inadequate. Only time will establish the "normal" service life of OFC and the cost-effectiveness of such treatments. In general, however, most OFC pavements are performing as expected, and most early failures noted to date have been explained by poor design or construction practices that are now carefully avoided.

A number of asphalt technologists are concerned with the possibility of rapid hardening of the asphalt in OFC because the openness of the mixture provides access to oxygen and moisture. However, the asphalt film thickness provides a countercondition that slows hardening. Delaware reported the degree of asphalt hardening for several experimental sections. Tests indicated that viscosities at 140 F (60 C) had increased significantly in 15 months, but no conclusions as to the effect of such hardening can yet be drawn. In general, data are now insufficient to enable accurate assessment of the effect of asphalt hardening on the ultimate service life of the surface.

PREVENTIVE MAINTENANCE

Allen, Peters, and Longfellow recommended that a program of preventive maintenance be made a part of the total design strategy for OFC (28). They suggested a planned program for monitoring the pavement condition and, when the need is indicated, for applying flush applications to add more bitumen or rejuvenating materials. It is their belief that such a program adds substantially to the life of the surface by preventing raveling. The need for such treatment is expected to become evident in the third or fourth year of service.

Georgia reported the use of a blend of CRS-2 emulsion, Reclamite, and water applied at the rate of 0.10 gal/yd^2 (0.45 L/m^2) as a means to retard raveling. In this application, traffic was held off the road for 25 minutes and then controlled at low speeds for approximately two hours by use of a pilot truck. Later experiments using diluted emulsion without Reclamite appeared to provide similar improvement without as great a reduction in friction number immediately after treatment.

Virginia also reported some success with emulsion treatments to retard raveling. In one section constructed in 1973, some distress during the winter (1973-74) was noted. Consequently, one part of the project was treated with CSS-1h emulsion. The treatment was begun by the application of CSS-1h emulsion at 0.094 gal/yd^2 (0.43 L/m^2), but the asphalt did not appear to penetrate the pavement. For the remaining application, therefore, one part water was mixed with two parts emulsion. This was applied at a rate of 0.18 gal/yd^2 (0.81 L/m^2). The diluted emulsion penetrated the pavement well and appeared to set quickly. Relatively little sanding was required when the latter section was opened to traffic.

From 1974 through 1976, both the treated and the untreated sections performed about the same, with no noticeable deterioration. However, during the severe winter of 1976-77, the section that was treated did not ravel, but the untreated sections raveled badly. As a result of this experience, Virginia plans to treat additional sections (in the Staunton District) with diluted CSS-1h emulsion.

These results indicate that such treatments may offer a means of prolonging the service life of the pavement. However, as pointed out by FHWA (18), caution must be exercised to prevent clogging of the surface to the extent that water drainage is retarded, thus defeating the original purpose of the OFC. It appears that no controlled experiments have been conducted yet to determine the optimum amount or type of rejuvenating material that should be added to provide maximum additional life and still prevent clogging of the water drainage channels.

OVERLAYS AND RECONSTRUCTION OF OFC

The question of whether OFC can be overlaid with an additional OFC also arises. At the present time, the only state specifically reporting overlays is Arizona, where no serious problems were encountered. Normal construction procedures were used.

Arizona also reported successful removal of OFC from a pavement, along with salvaging and reuse of the material removed. This work was done with a CMI Roto-Mill. Although experiencing some difficulty because of variations in thickness of the old OFC, Arizona considered the experiment successful. The salvaged material had some degradation of the aggregate, but not as much as might have been expected. Results of extraction and gradation tests on the salvaged material are listed below, with the original specifications in parentheses.

Passing 3/8-in. (95-mm) sieve	100% (100%)
Passing No. 4 (4.75-mm) sieve	61% (35-70%)
Passing No. 8 (2.36-mm) sieve	29% (8-20%)
Passing No. 200 (75-μm) sieve	4% (0-4%)
Asphalt content	4.7% (5.5-6%)

Arizona plans to make further study of this procedure. The plan is to remove the existing OFC with a Roto-Mill, rejuvenate the underlying asphaltic concrete to a minimum depth of 3/4 in. (19 mm), and place a new 70-lb/yd^2 (38-kg/m^2) open-graded friction course with an average thickness of 5/8 in. (16 mm) and a minimum of 1/2 in. (13 mm). At the time of preparing this synthesis, work was under way and proceeding as planned.

Arizona also reported that the use of heater-planers to remove OFC did not give satisfactory results for the conditions in that state.

CHAPTER SIX

SUMMARY OF STATES' EXPERIENCE

Discussions with a number of representatives of state transportation departments often resulted in conflicting opinions concerning some aspects of the construction and performance of OFC. Also, it was difficult to judge to what extent various practices were being followed. Accordingly, a questionnaire was sent to all members of the AASHTO Sub-Committee on Materials; it requested information on the design, construction procedures, and performance relating to OFC in each state.

Replies were received from 50 member departments (48 states plus the District of Columbia and Puerto Rico), 49 of which reported some use of OFC. The replies indicated some diversity of practices and opinions, but those states making extensive use of OFC generally expressed satisfaction with the performance of properly designed and constructed projects. A few states expressed reservations on the basis of observations of experimental projects, but most states that had begun construction of OFC within the last four years indicated they would increase their use of this type of construction. In general, the replies support the recommendations made in previous chapters of this synthesis, which were based primarily on published research reports.

Following is a summary of each question (or group of questions) as it appeared in the questionnaire. Because the questionnaire was sent to the states in the fall of 1976, it should be understood that replies reflected what was applicable at that time. In some instances, policies and practices may have changed since then.

1. What is the present extent of your use of OFC?

Table 2 gives a tabulation of the replies to this question, arranged in order of the FHWA regions. Also given are the number of projects and the dates the states first placed OFC, along with pertinent comments by the state. Only the mileage was requested, so all states did not report the time of their first interest.

Twenty states are now making extensive use of OFC in their construction or maintenance programs. Each of these states has more than 100 mi (160 km) of such pavements in service, and several have more than 1,000 mi (1 600 km). Eight states with moderate amounts of OFC in service reported regular use for trouble spots—areas with high accident rates or with potential hydroplaning hazards. Ten states have only experimental projects to date but plan to make much more extensive use of OFC in the near future. Eleven states have installed experimental sections but have not yet made a decision on the extent of OFC's future use. Only one state has not constructed OFC.

The geographical distribution of the states making the most use of OFC is of interest. Figure 7 is a map of the United States showing the boundaries of the FHWA field regions. Except for Maine, the states in Region 1 have rather recent experimental construction (probably within the last three years), but most intend to make more use of OFC in the future. All have prepared specifications for use. For a number of years, Maine has used an open-graded mixture that differs from the gradation recommended by FHWA; that state is now reevaluating its situation to determine if such construction should continue. Also, Maine has recently constructed OFC, based on FHWA recommendations, in experimental projects.

The states in Region 3 have used only moderate amounts of OFC. Pennsylvania has conducted research studies and constructed experimental sections. Because of closing-up problems, that state feels further work is needed before a decision is made to use OFC as standard practice. Basically, Pennsylvania believes that its dense-graded overlays, for which careful aggregate selection is made, provide equal service and may be more economical than OFC. Similarly, Maryland feels that its dense-graded overlays provide friction numbers equal to those of OFC. On the other hand, Virginia, which uses an open gradation having a minimum of fine material, has been using OFC in accident-prone areas since 1972, with generally satisfactory results. The use varies with districts in the state but apparently is increasing.

All Region 4 states except Mississippi make considerable use of OFC, and Mississippi will begin more extensive use in the near future. In Region 5, limited use has been made of OFC to date. Most Region 5 states reported experimental use and use in specific areas where hydroplaning might occur. All Region 6 states use OFC extensively. In Region 7, Missouri does not use OFC, and the other states use it only in short, experimental projects. In Region 8, Colorado, South Dakota, Utah, and Wyoming use OFC extensively. It should be noted, however, that South Dakota uses a mixture that is dense by other standards and that the state is just beginning to try more open gradations. Montana has recently begun significant use of OFC. In Region 9, Arizona and California make extensive use of OFC. In these two states, the use began under the older concept of plant-mix seal. California reported the most mileage of any state (9,950 mi—16 000 km) and still considers the surface both a friction course and a seal. In Region 10, Oregon makes extensive use of OFC, but the other states only recently have constructed experimental projects using OFC.

2. Do you consider the open-graded mixture a seal coat as well as a friction course?

Sixteen states consider the OFC a seal coat as well as a friction course. However, some of these states that had expected some sealing by asphalt drain-down to the interface after laydown expressed reservations with respect to complete waterproofing. The other 33 states consider the surface a friction course only. Several

states have not obtained complete sealing against water penetration through the old pavement by using OFC. Almost all states commenting recognize the necessity to upgrade structurally unsound pavements prior to applying OFC.

It is likely that there are differences of opinion with respect to the definition of sealing. In areas where drying out, or oxidation, of the asphalt at the surface causes incipient raveling, the friction course does provide protection from further deterioration that would result from continued exposure. This action might be construed as a type of sealing. Several states still consider asphalt drain-down after installation to the lower portion of the surface course to provide sealing actions, although, as reported by Gallaway and Epps, 100 percent waterproofing rarely occurs (21). Most states now recognize that the primary purpose of the open-graded overlay is to provide a more skid-resistant surface, which minimizes hydroplaning dangers.

3. What course thickness do you normally use?

Twenty-eight states use a nominal thickness of 3/4 in. (19 mm), and nine use a nominal thickness of 5/8 in. (16 mm). Eight use a thickness of 1 or 1.5 in. (25 or 38 mm), and one uses a thickness of about 1/2 in. (13 mm). In the latter case, the requirements are cited in terms of pounds of mixture per square yard of pavement.

Of interest is the comment by one state that thicknesses above 3/4 in. (19 mm) are to be avoided because of the danger of "kicking out" of the top stone. Some states are also concerned about the danger of rutting with thicker courses. However, no problem was reported by those states using greater thicknesses. On the other hand, some states reported difficulty with a thickness of 1/2 in. (13 mm) because of dragging under the paver screed and inadequate coverage. Others regularly use an amount based on pounds per square yard, which calculates to an average thickness of 5/8 in. (16 mm).

4. What type of material do you use for tack coat? How much?

Almost all types of asphalt material are used for tack coat. The amount generally varies from 0.03 gal/yd^2 (0.14 L/m^2) of asphalt emulsion (often applied diluted 1:1 with water) to 0.10 gal/yd^2 (0.45 L/m^2). One state uses an amount as high as 0.15 gal/yd^2 (0.68 L/m^2). However, the state considers this a prime coat. In general, most specifications allow the engineer to choose the type and amount of tack coat. The emulsions most often used are SS-1, SS-1h, and CSS-1. RS-1 and RS-2 are also employed. About one-fourth of the states permit use of cutbacks (either RC or MC) but provided no information on the extent of their use. Similarly, hot asphalt AC-10 and AC-20 are permissible in some states, but the extent of their use was not reported.

5. What are your gradation requirements?

6. What would you estimate as being the typical amount of material passing each sieve size within the master range?

The 50 agencies reporting indicated 35 different master ranges for gradations. That is, the range for one or more sieves was expressed differently. However, typical amounts reported for each sieve size show that the material in use by most of the states falls within the master range now recommended by FHWA.

Most states employ a nominal top size of 3/8 in. (9.5 mm), but many permit a small amount of material to be retained on the 3/8-in. sieve. Five states require 100 percent material passing the 3/8-in. sieve; two states set the limit at 97 to 100 percent; six states require 95 to 100 percent; eight permit 90 to 100 percent; and the balance permit more large material, with 80 to 100 or 85 to 100 percent. However, of the 47 agencies reporting on typical amounts passing (for the nominal 3/8-in. aggregate), 37 reported amounts passing between 95 and 100 percent and 6 reported amounts in the range of 90 to 94 percent. Several states reported the use of larger stone—nominal 1/2 in. (12.5 mm), with 100 percent passing the 3/4-in. (19-mm) sieve as an alternate. Georgia, in particular, is experimenting with the larger stone, but as yet the use is limited. Kentucky and California have specifications for smaller aggregate as well as the 3/8 in. but most often use the larger size.

For those specifications that require at least 90 percent material passing the 3/8-in. (9.5-mm) sieve, 10 different ranges for material passing the No. 4 (4.75-mm) sieve are used. The minimum permitted is 20 percent, the maximum 64 percent. However, examination of the typical amounts passing the No. 4 sieve shows that all states use material that falls within the range of 30 to 50 percent. Limits on the No. 8 (2.36-mm) sieve range from 0 to 30 percent, with 14 different combinations of ranges. Here again there is much more uniformity in the typical percentages reported. Thirty-five of the 40 typical percentages fall within the range of 5 to 15. In addition, for those states using the No. 10 (2.00-mm) sieve in lieu of the No. 8, the percentages also fall within the range of 5 to 15.

Limits on material passing the No. 200 (75-μm) sieve range from 0 to 7 percent. Seventeen states use 0 as the lower limit, with the upper limit ranging from 1 to 6 percent. Twenty-three states use the limit of 2 to 5 percent recommended by FHWA. It is interesting that, of the forty-six states reporting typical amounts, these amounts are outside the range of 2 to 5 percent in only five states. In four states the amount is lower—1.0 percent in two states and 1.5 percent in two states. The high value is 7 percent; this gradation was used for a very limited installation on two rural highways.

7. For material passing the No. 200 (75-μm) sieve, do you add filler or permit only the natural fines?

In most cases, only the natural fines are used in the amount passing the No. 200 (75-μm) sieve. Where the lower limit is more than 0, most states permit the addition of filler but rarely add it. Two states add filler as a requirement. New Jersey requires a minimum of 2.0 percent of the material passing the No. 200 sieve to be ground limestone, and Oregon adds 0.5 to 1.5 percent portland cement or hydrated lime.

8. Do you determine the voids in the coarse aggregate as a part of your design procedure? If so, by what method?

Fifteen states do not determine the voids in the mineral aggregate. Thirteen states use the FHWA vibratory procedure. Five states use other procedures. The balance of the states did not reply to this question. Most states that used OFC prior to publication of the FHWA procedure still rely on their experience with their own sources of aggregate. The majority of those states that have initiated programs more recently employ the FHWA procedure.

9. How do you establish the target asphalt content? If you use the modified oil equivalent test, what

TABLE 2
STATES' USE OF OPEN FRICTION COURSES (AS OF FALL 1976)

STATE	APPROX. NO. MILES	NO. PROJ-ECTS	DATE FIRST USED	REMARKS
Region 1				
Connecticut	6	—	1975	Experimental
Maine	100+	—	1967	Denser gradation than usual OFC; experimental use of FHWA gradation
Massachusetts	15	—	—	Experimental and at special problem areas
New Hampshire	—	—	—	(No reply)
New Jersey	39	—	1973	Experimental; specs. prepared for further use
New York	9	4	—	Experimental; specs. prepared for further use
Puerto Rico	30	—	—	Recent program; to evaluate in 1977
Rhode Island	38	—	—	Specifications prepared for continued use
Vermont	14	2	—	Specifications prepared for continued use
Region 3				
Delaware	20	—	1974	42 additional miles under construction
D.C.	0.4	2	—	Recent construction; special provisions used
Maryland	16	—	—	(None)
Pennsylvania	48	11	1974	Research study and experimental projects; test experimental specs.
Virginia	—	—	1972	Regular use in accident-prone areas; research conducted
West Virginia	2	1	1974	Experimental; will add to regular specs.
Region 4				
Alabama	341	—	1974	Recently begun use in state; specs. available
Florida	400	—	1973	Regular use in accident-prone areas; specs. available
Georgia	700	—	1970	Now used on all new construction of Interstates; also for other highways with 40 mph+ speed limit
Kentucky	175	—	1972(ca)	Regular use; specs. available
Mississippi	—	—	—	Experimental use; now preparing specs. for continued use
North Carolina	1500	—	—	Regular use; specs. available
South Carolina	180	—	—	Regular use on all high-speed, high-volume roads; specs. available
Tennessee	100	—	—	Regular use in paving and resurfacing Interstates; specs. available
Region 5				
Illinois	40	16	1974	Use at high-accident locations
Indiana	4.5	2	1974	Used hot-mix emulsion and combinations of aggregate and bituminous in 1 project
Michigan	—	7	—	Proceeding cautiously; using only where hydroplaning problem might occur
Minnesota	10	4	1973	Experimental projects; most placed summer 1976
Ohio	8	2	—	Recent construction; experimental projects
Wisconsin	4.3	2	1974	Experimental sections in rural areas
Region 6				
Arkansas	10	—	—	90 additional miles let to contract; specs. available
Louisiana	1000	—	1970(?)	Regular use on all high-volume roads; criteria for use established; specs. available
New Mexico	(High)	—	—	Used extensively on practically all new construction
Oklahoma	250	—	1973	Used on all reconstruction of Interstates or primary asphalt concrete roads, generally over dense-graded courses
Texas	884	—	—	Experimental in some districts but operational in others

TABLE 2 *(continued)*

STATE	APPROX. NO. MILES	NO. PROJ-ECTS	DATE FIRST USED	REMARKS
Region 7				
Iowa	4.3	—	—	Experimental sections
Kansas	3.5	7	1974	Experimental sections only
Missouri	—	—	—	Does not use OFC
Nebraska	5.7	2	1973	Experimental projects only; limited experience
Region 8				
Colorado	300	—	1966	Colorado developed design method; specs. revised since early projects
Montana	83	—	1975	(None)
North Dakota	5	—	—	Experimental project; recently constructed
South Dakota	350	—	—	Pavements are dense by other standards; open gradations now being tried
Utah	(High)	—	—	Used on all Interstates with 3000 ADT
Wyoming	1014	—	—	Used on Interstates and primary roads with ADT higher than 750
Region 9				
Arizona	(High)	—	—	Now used on approximately 90% of new projects
California	9950	—	—	Early use as seal coat as well as friction course
Hawaii	10	2	—	(None)
Nevada	—	—	—	(No reply)
Region 10				
Alaska	5.6	1	1976	Two additional experimental projects planned for 1977
Idaho	50	—	—	(None)
Oregon	1400	—	—	Regular use on all overlays on I-5 and I-80N plus primary system
Washington	2	2	—	Experimental projects in areas with high traffic volume; experimental use of rubber in binder

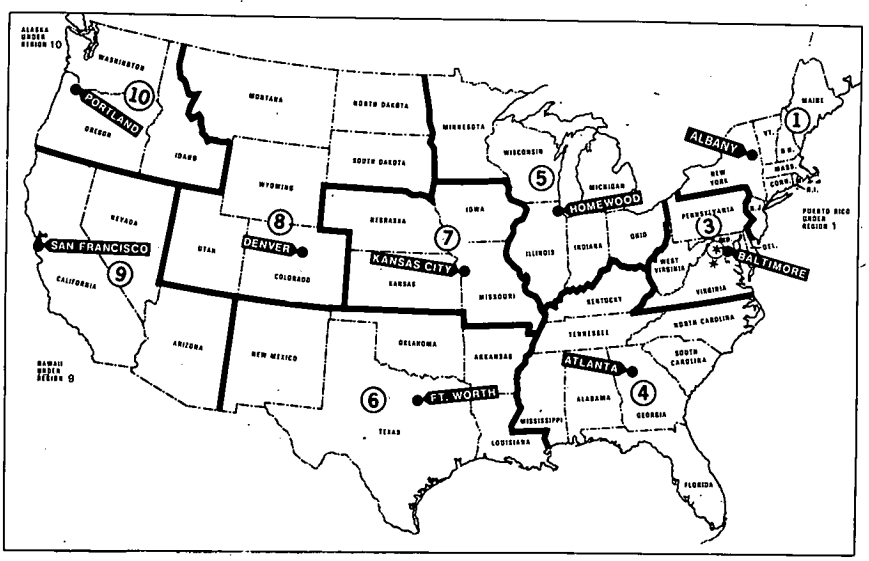


Figure 7. Field regions of the Federal Highway Administration.

formula do you use for calculating the percentage of asphalt? Is this amount accepted as final, or are adjustments made on the basis of further tests or observations?

Twenty-two states use the FHWA procedure for determining asphalt content. However, nine of them permit some adjustments based on field observations. Twelve states base asphalt content on experience and on visual examination of trial mixtures. Five use the K_c determined by the oil equivalent test but use a formula other than 2 K_c + 4.0, the one recommended by FHWA. Georgia uses the formula 2 K_c + 3.5 plus adjustment based on the laboratory drainage test. Kentucky uses 1.5 K_c + 4.5 plus adjustment on the basis of the drainage test. Colorado, Kansas, and Wyoming use 1.5 K_c + 4.0 as the starting point, plus adjustment based on observation of laboratory specimens. Several other states use their own procedures based on laboratory specimens and tests.

10. What is the grade of asphalt you use?

Twenty-five states use AC-20; fourteen use 85-100 penetration grade; seven use AC-10; two use AR 4000; two use AR-8000; and one each uses 60-70 penetration, 70-85 penetration, AR-2000, and AC-40. Two states add neoprene latex to the asphalt to increase the binder adhesion and stiffness. It is interesting that Louisiana has used the AC-40 grade with excellent results. That state believes that stiffness of the asphalt gives greater film thickness and holding power for the aggregate, which prevents raveling. The thicker film also counteracts the asphalt's tendency to harden during service. It should be noted, however, that Louisiana asphalt specifications require a material having a low viscosity-temperature susceptibility.

11. Do you use a single-size aggregate, or do you add fine aggregate (material passing the No. 8--2.36-mm--sieve) to the mixture? If the fine aggregate is used, how do you determine the amount to use?

Most states allow blending to meet the requirements of the gradation. Ten states use only a single aggregate at the mixing plant, but several of them recognize that this must be a special blend by the producer to meet the required specification. Only seven states use the FHWA procedure to determine the amount of fine aggregate.

12. How do you establish mixing temperature? What is the normal range of mixing temperatures used?

Optimum mixing temperature varies, of course, with the grade of the asphalt being used. Accordingly, there is considerable spread in the ranges of mixing temperatures reported. In general, most states reported a usual range based on experience. Eighteen states consider the viscosity of the asphalt, most of them using the FHWA-recommended range of 700 to 900 centistokes (7 to 9 cm^2/sec). Seven others use the asphalt drainage test as recommended by FHWA. The midpoints of the reported mixing temperature ranges vary from 215 to 280 F (102 to 138 C). Of the 34 ranges reported, 27 of the midpoints fall between 220 and 260 F (104 and 127 C). In general, those states reporting lower mixing temperatures had fewer problems from drainage in the trucks during construction.

13. What is the extent of asphalt drainage problems in trucks? How do you correct them?

14. Have you added silicones or mineral fillers to the mixture to cure problems from asphalt drain-down?

Fifteen states reported having no problem with drain-down of asphalt in the trucks, and the others reported that they had problems only when mixing temperatures were higher than specified. Only two states reported modifying the asphalt content to cure asphalt drain-down. Two other problems reported by several states were residue buildup in the trucks because of asphalt drain-down and too rapid a cooling of the mixture because of the uninsulated bottoms of trucks. One state reported increasing the fines (material passing the No. 200—75-µm—sieve) as a means of curing asphalt drain-down in trucks. Several states use antistrip additives, and others use silicones as measures for correcting this problem. In the majority of cases, however, a reduction in mixing temperature eliminated the asphalt drain-down. An extended length of time in the truck (haul distance) was also recognized as a potential cause of the problem and is limited by a number of states.

Eighteen states use silicones. In most cases, however, these are added to assist in laydown rather than specifically to cure problems from asphalt drain-down. Silicones are sometimes added because they are required by the specification and at other times are added at the option of the contractor.

15. What is the extent of problems relating to closing up of the mixture? Do you have specific data on changes in permeability or changes in friction-number gradient that can be attributed to the closing of the mixture?

Twenty-one states reported having no problems or only minor problems with closing up of the mixture. Nineteen reported some problems. In general, permeability dropped off considerably in one to one and a half years, but usually the drop in the measured friction number or in the friction-number gradient was not as great as might have been expected on a proportionate basis. Several states reported that their installations were too recent to enable them to determine if closing up would eventually occur. Several states indicated that the closing up resulted more from trapped debris, sand and cinders from deicing operations, or material from untreated shoulders than from consolidation changes within the mixture.

16. Can you cite case histories of failures or problems? Can these be associated with deviations from intended design or use of design practices that are no longer considered best in light of recently developed information?

The case histories cited and remedial measures taken are summarized below.

a) Bleeding occurred, believed to be caused by postdensification and use of fuel oil in trucks. (Use of fuel oil was eliminated.)

b) There was early closing of the mixture because of too high a percentage of material passing the No. 8 (2.36-mm) sieve (28 percent). (This was reduced to a maximum of 18 percent.)

c) Loss of bond over portland cement concrete caused lateral creep and shear failures. (State no longer uses OFC directly over portland cement concrete.)

d) Attempts to pave at 40 F (4 C) resulted in lumps going through paver and irregularities after compaction. (State now requires a 60 F + (16 C +) air temperature for placement.)

e) OFC failed when placed over structurally

inadequate pavement. (Poor pavement now upgraded structurally prior to placement of OFC.)

f) Poor coating of aggregate and friable aggregate caused raveling and loss of surface. (State now selects aggregate more carefully and makes general use of antistripping agents.)

g) Too high a mixture temperature during laydown plus too high an asphalt content caused flushing. (Design was modified and mixture temperature reduced.)

h) There was bleeding in spots either because of too much tack coat or because OFC was placed over rich spots in base pavement. (Tack coat was reduced, or excess asphalt was scraped from base.)

i) Flushing occurred because the percentage of fines was too high (17 percent material passing the No. 10—2.00-mm—sieve), because the mixing temperature was too high (320 F—160 C), and because the mixture was laid at a thickness of 1 in. (25 mm). (The amount of material passing the No. 10 sieve is now 10 percent; the mixing temperature is now 245 to 255 F—117 to 124 C; and the mixture is now laid at a thickness of 5/8 in.—16 mm.)

j) There was early closing and loss of friction number. (Permissible abrasion loss was reduced from 65 to 50 percent, and amount of material passing the No. 8—2.36-mm—sieve was reduced to 15 to 19 percent.)

k) Raveling occurred in six-year pavement, especially in areas subjected to turning movements, because pavement did not have antistrip additive. (Specifications now require an antistrip agent for all projects.)

l) OFC was placed directly over pumping pavement, and pavement continued to pump and deteriorate. (Surface is now sealed and upgraded with dense mixture prior to placement of OFC.)

m) Potholing and raveling occurred because of too low a temperature during placement, a poor tack coat, and possibly over-rolling. (Placement temperature and rolling are now controlled.)

n) Potholing occurred, and OFC broke up when placed directly over open-graded leveling course. (Base pavement is now upgraded and leveled with dense-graded course.)

o) Problems occurred in early projects because of asphalt drainage in trucks from too high a mixing temperature. (Mixing temperature is now controlled at a lower range.)

p) Raveling occurred at turning locations, attributed to low temperature at laydown. (State now requires a temperature of 70 F—21 C—two days prior to laydown and at laydown.)

q) Raveling of feathered joints occurred. (OFC is no longer feathered.)

r) There was loss of bond over portland cement concrete. (OFC is no longer placed directly on portland cement concrete, and a dense-graded intermediate layer is used.)

s) Rapid raveling occurred at reflection cracks. (Cracks are now presealed.)

t) Breakage and loss of bond over joints in rigid pavements were reported by two states. (States no longer place OFC directly over portland cement concrete.)

u) All failures, though limited in number, were caused by lack of initial bond when paving was done in cool weather. (State no longer places OFC between November and March.)

v) Closing and flushing were attributed to the tack coat and an excess of asphalt in the underlying pavement; also, there were excess fines in OFC. (State eliminated use of tack coat and now scrapes excess asphalt from flushed areas prior to laying OFC.)

w) One project with lightweight aggregate failed during construction because of grossly inadequate asphalt content, which resulted from failure to recognize the difference in density of lightweight aggregate. (OFC was replaced immediately.)

x) Pavement flushed because (1) it was placed at an extremely high ambient temperature (105 F +—40 C +), (2) it was placed over a newly constructed base, (3) it had a high volume of traffic immediately after laydown, and (4) the asphalt content was too high. (Failed sections had not been constructed in accordance with the usual state practice; more careful control is now exercised.)

y) Spot flushing occurred from too high a mixture temperature at laydown. (Mixture temperature is now controlled at a lower range.)

z) Loss of aggregate occurred during first year of first project. (The addition of fog seal corrected the problem.)

17. What has been your state's overall experience with winter maintenance of OFC?

Twelve states had no data regarding this question because of either warm climates or too little experience. Twenty-two others experienced no differences in removing ice and snow from OFC and dense-graded or other pavements. However, four states use more salt on OFC. Three states believe that removal of ice and snow from OFC is more difficult. According to three other states, the degree of difficulty depends on the conditions during the snowstorm: when temperatures are low, snow might blow off the dense-graded areas but be trapped and compacted over OFC; at other times the snow over OFC remains slushy much longer than it does over dense-graded areas. It was also reported that under some conditions frost or ice formed over OFC but did not form over dense-graded mixtures. Kansas indicated that this condition occurred specifically with sections containing lightweight aggregates.

18. What are the estimated cost ratios between open-graded friction courses and dense-graded bituminous surfaces?

19. What would be your best estimate of the cost per square yard per year of useful life for (a) chip seals, (b) open-graded asphalt friction courses, (c) dense-graded overlays?

A number of states reported that they had little or no information on relative costs. Of the 25 states providing estimates, 5 indicated no significant differences between OFC and dense-graded bituminous surfaces in terms of costs per square yard. The replies are not always specific, but they are interpreted to mean that about 3/4-in. (19-mm) OFC was equal in cost to 1 in. (25 mm) of dense-graded surface. Twenty states reported cost ratios per ton that ranged from being essentially equal (1.03:1) to being as high as 2.5:1 (OFC: dense-graded surfaces). The median ratio is 1.5:1.

The information given in reply to question 19 could not be analyzed to provide good estimates of cost per square yard per year of life, because in many cases it could not be determined if the expected difference in life for different types of surfaces was included in the cost figures given. Most states indicated that the life of the OFC could not now be estimated.

20. Is OFC more difficult or less difficult to paint than dense-graded surfaces? What is the comparative life of the stripe with respect to daytime visibility? With respect to wet night visibility?

A number of states had not made observations concerning this question. Eleven states had not noted any difference in painting procedures or in painting difficulty. Fifteen expressed the opinion that OFC was more difficult to paint, most saying it was because more paint was used. Several indicated that the first painting was more difficult and had shorter life but subsequent paintings were equal in difficulty to the painting of dense-graded surfaces.

Most of the states commenting on wet night visibility indicated that OFC gave better visibility than did dense-graded surfaces. Several expressed the opposite opinion, however. Differences of opinion were also expressed with respect to daytime visibility. In almost all cases the opinions expressed were general impressions and not the result of specific examinations.

Georgia provided the interesting observation that visibility was poorer when the stripe was viewed in the direction opposite to that of painting but equal or slightly better when viewed from the same direction as that of painting.

21. Have you devised special maintenance procedures not previously reported in MAD-11 (Maintenance Aid Digest *of the AASHTO Sub-Committee on Maintenance)? If so, can you describe briefly?*

No state reported successful special maintenance procedures for OFC. A number indicated that only the usual maintenance procedures for dense-graded surfaces had been used. Wisconsin and Louisiana indicated that special maintenance procedures had been considered. Wisconsin reported that badly raveled longitudinal cracks were filled with pea gravel and sprayed with RC asphalt. However, this technique did not provide the open-textured repair that was hoped for. Water drainage was impeded at these maintenance locations. Louisiana reported the planned use of identically textured emulsion mixtures as a replacement for raveled spots in the OFC. Arizona later reported successful maintenance techniques as discussed in Chapter Five.

CHAPTER SEVEN

FUNDAMENTAL CONSIDERATIONS AND RESEARCH NEEDS (Hot Mixtures)

A number of states and FHWA have conducted both laboratory and field studies of OFC. Most of the studies have begun with certain reasonable assumptions based on past experience, and experimental installations have necessarily been limited to combinations that were believed to provide the needed performance. In the majority of cases, such installations have been successful, and, quite correctly, specifications have been developed around such successful applications. There remains a need, however, to understand more completely the role of OFC with respect to the total objective of providing the safest and most economical highway transportation possible. This chapter describes some of the fundamental considerations and the research needed to establish the optimum characteristics of OFC.

ROLE OF OFC IN MINIMIZING HYDROPLANING DANGERS DURING HEAVY RAINFALL

The water drainage characteristics of OFC are significant with respect to OFC's ability to reduce the dangers of hydroplaning. Much of the water can drain from the highway below the top of the asperities in the pavement. At some point, however, the intensity of rainfall will be too great for all drainage to occur in such a manner and water films will be present on OFC surfaces. When this occurs, the danger of dynamic hydroplaning—the loss of tire contact—is present. Smith's calculations, based on conceptual models, indicate that rainfalls in the range of 1 in. (25 mm) per hour would be necessary to inundate the outer edge of the pavement (22). Calculations were for a pavement 24 ft (7.3 m) wide, 1 in. thick, with 15-percent void content, with a cross slope of 1/4 in./ft (2 percent), on a 0 percent longitudinal grade. Gallaway et al. indicated that a zero water depth could be maintained during a rainfall of 1 in./h on a cross slope of 1/4 in./ft (2 percent) with a drainage path of 36 ft (11 m) and a texture depth of 0.06 in. (1.5 mm) (33). (Texture depth was determined by the silicone putty test.) OFC generally shows, by the silicone putty test, texture depths ranging from 0.04 to 0.12 in. (1.0 to 3.0 mm) (33); these computations indicate general agreement between Smith and Gallaway.

However, because of uncertainties and because it is recognized that the ideal conditions assumed for calculations do not actually exist in the pavement, FHWA has continued to support work being conducted at the Texas Transportation Institute (TTI), where observations have been made of conditions during actual measured rainfall and where skid and other tests have also been con-

ducted. Although final data are not yet available, indications are that significantly less rainfall than was shown by Smith's and Gallaway's calculations will cause flooding of the surfaces but that such flooding does not result in immediate loss of friction on OFC. Apparently, tire pressure is sufficient to force downward most of the water that would normally be trapped between the tire and an impervious pavement.

Inasmuch as no specific reports of hydroplaning as the cause of accidents on properly built OFC could be found in the search of the literature and discussions leading to the preparation of this synthesis, it might be concluded that the question of maximum rainfall intensity is academic. It is quite likely that rainfall sufficient to create a flooding condition on the pavement would cause the prudent driver to slow down to a safe speed. All drivers are not prudent, however, and unexpected flooding conditions because of such things as blocked drainage could create hazards. Such a possibility should be accounted for in the overall highway design. It is hoped that the research under way at TTI will provide a better understanding of the effect of extremely heavy rainfall and that the information will be used to establish optimum characteristics for maximum safety.

OPTIMUM GRADATION OF OFC FOR SKID PREVENTION

The skid resistance of OFC depends greatly on the characteristics of the coarse aggregate, but the gradation of the aggregate and the overall characteristics of the surface mixture play important roles in the development of the surface's macrotexture. The macrotexture has been shown to have a major effect on the friction-number gradient—that is, the loss of friction number with increased speed.

As previously discussed, most states now use a nominal top-size aggregate of 3/8 in. (9.5 mm) for the coarse aggregate. Other sizes have been tried, however. Smith reported that installations using smaller aggregate (nominal top size 1/4 in.—6 mm) do not provide a surface with adequate macrotexture (22). Experiments with larger aggregates (nominal top size 1/2 in.—13 mm) in Georgia and other states appear to be providing satisfactory results. Interest in the larger stone is generated primarily because its use is economical and may reduce energy consumption. On an equal volume (or weight) basis, the larger stone requires less energy for crushing, and its use requires less asphalt because of the reduced surface area. However, a greater thickness and increased pounds per square yard are required for the larger stone. A report summarizing Georgia's experience with the larger aggregate is now available (34).

Not only is the nominal maximum size important, the gradation of the total aggregate is also of major importance in providing mat stability under traffic and in developing the final voids in the mixture. It is very likely that equally satisfactory service can be obtained with a number of different combinations of aggregate sizes, but at present no clear-cut information is available as to the optimum gradations that would combine maximum retention of texture (resistance to void-closing caused by traffic and resistance to clogging caused by debris), longest life (minimal deterioration of asphalt), and lowest cost in terms of energy use as well as dollars. Further research is needed before such information can be developed.

In particular, it must be determined how much fine aggregate (material passing the No. 8—2.36-mm—sieve) is required to provide the needed stability, or the chocking action that is referred to by FHWA (8). This question is also related to the optimum content of designed voids and to the degree to which designed voids reflect the condition in the road. The effect of loss of permeability and closing of the mixture needs to be better understood. In most cases where data have been reported, the loss of permeability as measured by outflow meters is not immediately reflected by loss of friction number as measured by ASTM E 274. Perhaps the conditions of the two tests are basically different, so that specific correlation does not exist. More data are needed to establish the true meaning of the various tests in relation to the potential for skidding or hydroplaning at normal highway speeds. The effect that closing of the mixture has on splash and spray must also be determined.

The role of the material passing the No. 200 (75-μm) sieve should be better defined. Some states attempt to reduce the amount passing the No. 200 sieve to a minimum, but others and FHWA advocate a small amount (limits of 2 to 5 percent) because it is dispersed within the asphalt to provide a stiffer binder. This can form greater film thicknesses that subsequently reduce the rate of asphalt hardening. Others feel that presence of material passing the No. 200 sieve tends to fill the voids and should therefore be kept to a minimum. As reported in the replies to question 7 (see Chapter Six), two states require the addition of 1 to 1.5 percent lime or portland cement filler. Research is needed not only to assess more accurately the optimum quantitative amount of material passing the No. 200 sieve but also to determine the effect of the material's mineralogical composition.

OPTIMUM ASPHALT CONTENT AND GRADE FOR MAXIMUM DURABILITY

The openness of the OFC mixture permits access of water and air into the mixture, which accelerates hardening. However, Smith's report on the Blair County experiments in Pennsylvania shows that, although rapid hardening did occur for mixtures having high permeability or air-void content, there was no relation between air voids and asphalt hardening above a certain value of air voids (22). This is interpreted to mean that for mixtures such as OFC the film thickness of the asphalt coating is the predominant factor in asphalt hardening. It is known that thicker asphalt films tend to decrease the rate of hardening, but no precise information is yet available as to whether increased film thickness could be built into the mixture design to prolong the life of the OFC without danger of other negative effects, such as local flushing from excessive asphalt.

Studies on the effects of reinforcing agents such as rubber or neoprene (tried by several states) indicate that they might increase service life. Other possible reinforcing agents for the binder are fillers, such as carbon black. A report by Rostler, White, and Dannenberg showed that pelletized carbon black could be dispersed in the asphalt binder when the carbon black was added at the pugmill mixer (35). Laboratory tests and limited field tests indicated a reinforcing action that might well be used to advantage in OFC.

In general, it does not appear that using a softer grade of asphalt, simply to start at a higher point on the time-aging curve, would be a fruitful course of action, because such material tends to result in thinner films, which would normally accelerate hardening (all other conditions being equal).

EFFECT OF OFC ON WINTER MAINTENANCE TECHNIQUES

Although relatively few states expressed serious concern over the differences between winter maintenance techniques required for OFC and those required for other types of surfaces, there continue to be differences of opinion as to whether OFC is more difficult or less difficult to maintain in a safe condition during ice storms and snowstorms. The observations discussed in Chapter Five on the relative behavior of OFC and dense-graded pavements under the same storm conditions dispel the notion that considerably more salt is needed or that significantly greater efforts are required to maintain a safe condition on OFC as compared with dense-graded pavements during the same storm. A number of questions remain unanswered, however.

The Cold Regions Research and Engineering Laboratory has a research project under way to determine the optimum salt requirements on OFC as well as other pavement surfaces. Information from this study should be very helpful.

Where sand or other abrasives are used as traction aids during snowstorms, the long-term effects of this use on the year-round performance of OFC need to be evaluated. One of the concerns expressed by Pennsylvania is that the regular use of sand or other material for aiding traction during snowstorms and ice storms contributes significantly to the clogging or closing up of the OFC. However, as pointed out in Chapter Five, during a winter storm it is not practical to treat small sections of OFC differently from other pavements, and the discontinuance of all abrasive minerals might permit hazardous conditions that are now adequately controlled.

NOISE LEVELS FOR OFC

Because of its greater macrotexture, some concern was originally expressed that noise levels for OFC might be higher than noise levels for other types of surfaces. In several states, however, tests sponsored by FHWA have shown that, in general, open friction courses generate less noise than other types of surfaces for the same tires and equipment (36, 37). In some cases there appeared to be no significant difference in the noise level. In general, motorists report that the lower-pitch sound they hear when driving over OFC is much less noticeable than the higher-pitch noise they hear when driving over dense-graded asphaltic concrete or portland cement concrete. It should be kept in mind that these reports apply to surfaces with the nominal 3/8-in. (9.5-mm) aggregate. The recent report by Georgia indicates that the 1/2-in. (13-mm) aggregate does not create objectionable noise (34). However, further verification on more installations is needed.

CHAPTER EIGHT

COLD-LAID OPEN FRICTION COURSES

Renewed interest in the use of emulsions was sparked by concern over energy shortages. However, present technology leaves unsolved problems with respect to weather limitations and slow curing of the mat because of the solvent added to promote mixing and adhesion. This is why state highway departments have shown little interest in using emulsions as an alternate to hot mixtures in areas where heavy traffic is normal or where hot-mix plants are readily available. However, in rural areas where hot-mix plants are not available and where high transportation costs for fuel and other materials would be expected, cold-mixed, cold-laid surfaces do offer potential advantages and are being investigated.

Many miles of road have been overlaid successfully with open-graded emulsion mixtures in past years, but this has been done mostly for maintenance in rural areas. Such pavements are usually choked with fine aggregate to prevent "pickup" under traffic. Accordingly, the final surface may be relatively impervious even though the material initially laid was open-graded. There is very little documentation of work that conforms to the requirements for OFC. Recent work in the Pacific Northwest and test sections in Arizona, California, and New York are under study. Arizona reports the successful installation of an OFC test section containing 5 percent CSS-1 emulsion in the mixture followed by a flush application of emulsion to increase the asphalt content. This section was performing well after three years in service. The aggregate used was the same as that used with Arizona's usual OFC section. Traffic was withheld from this section for about 16 hours to permit adequate curing.

In the New York experiments, the emulsion was CMS-2 containing naphtha for coating and workability. An attempt was made to withhold the choke stone, but pickup by traffic forced its use for most sections. Efforts to eliminate the stickiness and pickups with fine material such as portland cement and sand or stone screenings were unsuccessful. On one lane of one test section, cool weather, cloudy skies, and rain during the night permitted sufficient curing so that traffic pickup did not occur and no choke stone was used. This section retains the characteristics of an OFC, but all the choked sections have the characteristics of a dense overlay. The performance of all sections is being monitored, but conclusions as to overall quality are not yet available. The New York experience prompted FHWA to delay a demonstration project for cold-laid emulsion OFC until further experimental work could be conducted on how to avoid traffic pickup without the use of large amounts of choke stone that clog the water drainage channels in the final pavement. FHWA is encouraging continued experimental work along these lines.

Because the handling of emulsion mixtures requires special techniques, more success with emulsion mixtures is generally reported by the more experienced operators. Information is still being collected, and the Asphalt Emulsion Manufacturers Association is working toward establishing guidelines for using cold-laid emulsions that would apply to OFC as well as other types of emulsion mixtures.

In general, the major advantages offered by all types of cold emulsion mixtures are:

1. Capital investment is low, because there is no need for aggregate driers, baghouses, or sophisticated mixing plants.
2. Fuel is saved, because there is no need to dry and heat aggregates.
3. There is less air pollution from dust and fuel-burning.
4. Portable pugmills and travel plants can be used.

The disadvantages are:

1. The present practice of using solvent in CMS grades of emulsion for open mixtures accentuates pickup and tenderness in the curing period and reduces advantages 2 and 3 above.
2. There are weather limitations.
3. Dry choke stone is needed to prevent pickup.

MATERIAL SPECIFICATION

Emulsion Specification

Studies of newer types of emulsion are being conducted. At present, either CMS-2 or CMS-2h, as set forth in AASHTO M 208 (ASTM D 2397), is generally specified in all regions of the United States for emulsion mixtures with open-graded aggregates. As reported by Coyne and Ripple, medium-setting (MS and CMS) emulsions are designed to break chemically shortly after mixing (38). This provides quick rain resistance. Further curing is controlled by dehydration and loss of oil distillate. The oil distillate varies between 3 and 10 percent and is characterized as a naphtha, and it has a boiling point between 200 and 350 F (93 and 177 C). This solvent aids coating and workability. When travel plants are used, the percentage of solvent can be reduced to a minimum. High-solid-content, high-viscosity emulsion is desirable to produce a thick coating on the aggregate and to reduce drain-down.

Aggregate Specification

The aggregate gradation and characteristics should be the same as those for hot-mixed OFC, except that the material passing the No. 200 (75-μm) sieve should be limited to 0 to 3 percent, as determined by wet-sieve analysis, and should be nonplastic.

Also, it should be emphasized that sharp, crushed material passing the No. 8 (2.36-mm) sieve performs a vital function in stabilizing the mat, thereby reducing tenderness and the tendency to ravel (the so-called chocking effect).

MIXTURE DESIGN

The usual design procedures for hot asphalt mixtures do not directly apply for emulsion mixtures. Several procedures for emulsion have been recommended, but

Mr. John Trumbull of the Asphalt Emulsion Manufacturers Association assisted in the preparation of this chapter; his contribution is gratefully acknowledged.

none have been universally accepted. Previous experience with emulsions still plays a significant role in the obtaining of a successful design. The various factors are discussed in depth in *NCHRP Synthesis 30*, and reference should be made to that document for complete information (39).

The most common procedure for determining the optimum emulsion content for OFC is the use of drainage tests to find the maximum emulsion that the project aggregate can take without appreciable drainage. Mixtures of various percentages of emulsion are made up using dampened aggregate that is weighed into mixing bowls and stirred at ambient temperatures. An experienced engineer can, by inspection, determine the optimum percent emulsion for the start-up mixture. As work progresses, it is usually necessary to adjust or vary the percent emulsion required for adequate coating without drain-down and to adjust and vary the percent solvent for adequate workability and minimum curing time. Variations in the percentage of surface moisture on the aggregate and in the percentage of material passing the No. 200 (75-μm) sieve may require adjustment in design during the course of the job.

It has been suggested that Section 3 of the FHWA design procedure (for hot-mixed OFC) be used to determine the percentage of residual asphalt in cold-laid OFC. The amount of emulsion added would be the amount that would give a residual asphalt percent (base asphalt cement exclusive of water and naphtha) equal to the design asphalt content. Further studies of this technique should be conducted.

CONSTRUCTION

The Preconstruction Conference

On sizable jobs or critical test sections, a preconstruction conference is recommended. This meeting of key personnel is particularly useful in establishing a spirit of team effort between agency, contractor, and material suppliers. The engineer in charge can define areas of responsibility, resolve questions, and set up the working relationships for inspection, expediting, and so on. The mixture design should have been determined prior to this meeting. The emulsion supplier plays an important part in determining the desired mixture design and providing technical service and training in the use of the emulsion.

Preparation of Surface

The emulsion mixture is designed so as not to allow excess asphalt to drain down to the interface with the old surface. Consequently, any needed treatment of the old surface is a separate engineering judgment. Dried-out pavement may require an application of CRS-2. Less-dried-out pavement may be given a light tack coat of diluted CSS-1h. Fat spots may require removal. No solvents should be used in emulsions for seal or tack coats.

Mixing and Laydown

Central Plant

A continuous, portable pugmill has the advantage of providing convenient and accurate control of mixture proportions. All components of the mixture are at hand and can be varied accurately to allow maintenance of quality control and compensation for changes in weather, road conditions, and so forth. The mixing plant can be started up economically for small jobs, such as intersections or test sections, and the mixture can be fed to lightweight pavers that take up only one lane and permit some traffic during laydown and rolling. The plant investment is relatively low, and the production rate is very high—about 2,000 to 3,000 tons (1 800 to 2 700 Mg) per day.

Travel Plant

The self-propelled travel plant can produce and lay the mixture in one operation. The elapsed time from initial mixing to final placement is between 30 seconds and 5 minutes. This allows the solvent content to be reduced to about half of what is needed in the emulsion used at a central plant and therefore permits faster cure of the mat. Production rate is about 700 to 1,000 tons (600 to 900 Mg) per day. Figure 8 illustrates a type of equipment now being used with good success.

Compaction

As soon as the mixture exits from the screed of the paving apparatus, it should be rolled over once with a wet steel roller having a 1/2-roller-width overlap. Under present practice, for most emulsion mixtures this is followed by the application of dry choke stone (usually 1/4 in.—6 mm—top size uniformly applied at a rate of 4 to 6 lb/yd^2—2.2 to 3.3 kg/m^2). This can be worked over with a low-pressure pneumatic roller, followed by a steel-wheel finish.

The dry choke stone prevents early traffic pickup problems. However, as discussed previously, the choke stone will normally clog water drainage channels, causing the loss of many of the usual characteristics of OFC.

Lime dust has been used successfully to overcome tackiness and eliminate pickup. However, the application creates dust problems and causes complaints in populated areas.

Traffic Control

Normally, the work can be opened to traffic as soon as rolling and choking are completed. However, the engineer in charge should restrict or control traffic if curing conditions warrant.

Weather Limitations

The conservative rule is that work shall not proceed unless the air temperature is 50 F (10 C) and rising and it is predicted that no rain will fall during the construction day. A minimum temperature of 60 F (15 C) should be specified when lightweight aggregates are used.

MAINTENANCE

The maintenance procedures for OFC made with emulsions should be no different from those for hot-mixed OFC. These procedures are discussed in Chapter Five.

SUMMARY AND RESEARCH NEEDS

Reports of successful full-depth, open-graded emulsion pavements in the Pacific Northwest (40) and the success of the Arizona test section of OFC indicate

that experienced designers and operators can produce pavements with the desired benefits and OFC characteristics. Test sections of emulsion OFC in other parts of the country are still under observation or in the planning stage; experience with these sections is limited at this point, and recommendations are still being evaluated.

The most obvious need is the development of a solvent-free mixing emulsion that would cure rapidly so that the choke stone could be eliminated. Research is also needed to determine the best consistency grade for the base asphalt in given climate conditions. Should solvents be necessary, it must be determined which type is best suited to provide the desired properties of the coating with a minimum amount of solvent.

A laboratory procedure that would simulate the curing of the mixture on the road under normal conditions is also greatly needed.

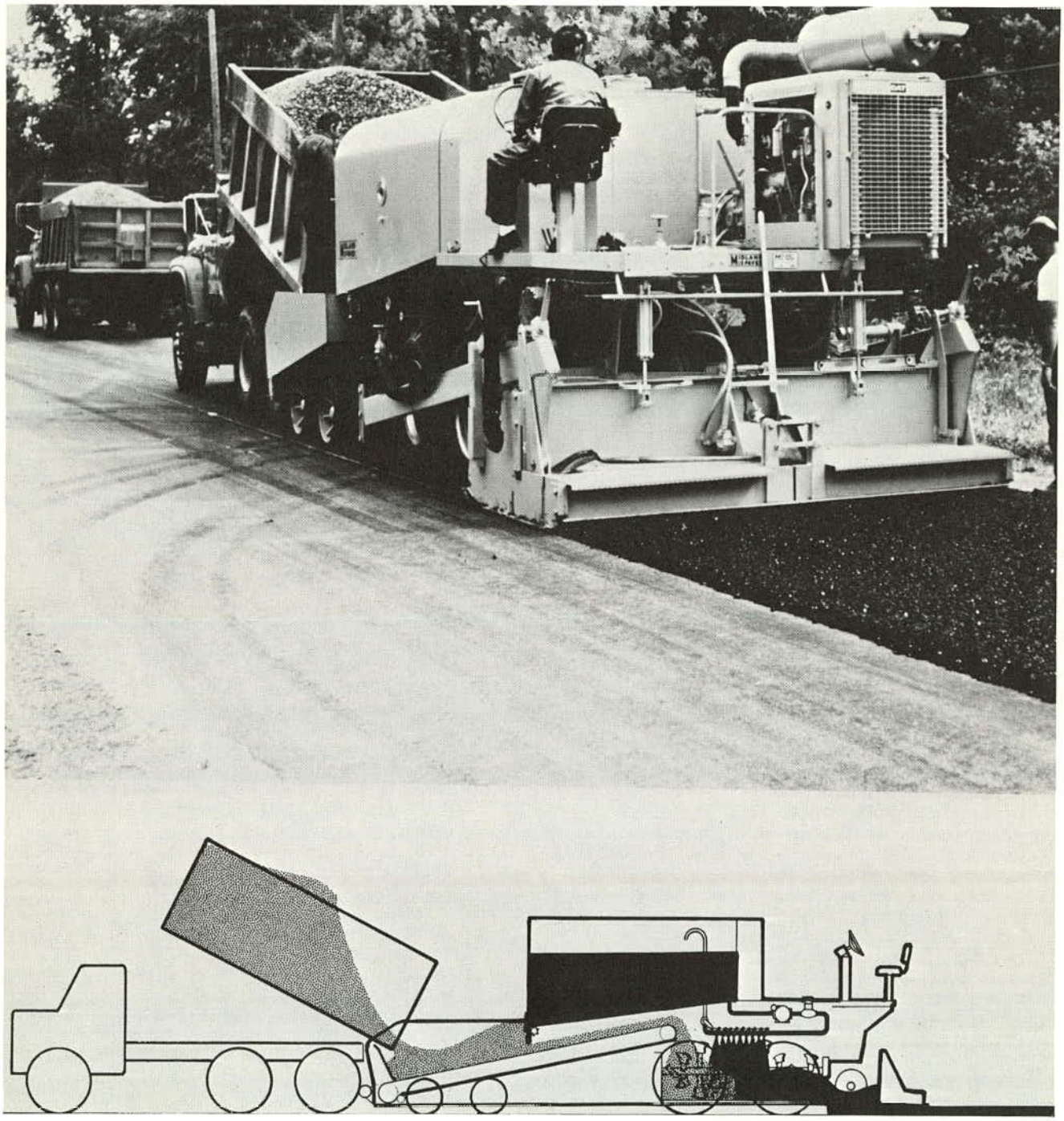


Figure 8. Paving train for on-site mixing of cold-laid emulsion mixtures.

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APPENDIX A

FHWA DESIGN PROCEDURE (Updated)

Material Requirements

1.1 It is recommended that relatively pure carbonate aggregates or any aggregates known to polish be excluded from the coarse-aggregate fraction (material retained on the No. 8 sieve). In addition, the coarse-aggregate fraction should have at least 75 percent (by weight) of particles with at least two fractured faces and 90 percent with one or more fractured faces. The abrasion loss (AASHTO T 96) should not exceed 40 percent.

1.2 Recommended Gradation for Open-Graded Asphalt Friction Course.

Sieve Size[a]	Percent Passing[b]
1/2 in.	100
3/8 in.	95-100
No. 4	30-50
No. 8	5-15
No. 200	2-5

[a] U. S. Sieve Series.

[b] By volume. (This is the same as by weight unless specific gravities of aggregates being combined are different.)

1.3 The recommended grade of asphalt cement is AC-10, AC-20, or AR-40, AASHTO M 226. For AC-10 and AC-20, the M 226 Table 2 requirements should apply where such asphalt is available. AR-40 requirements are given in Table 3 of M 226.

Preliminary Data

2.1 Test coarse and fine aggregates as received for the project for gradation unless otherwise provided. If mineral filler is submitted as a separate item, it should also be tested for specification compliance. Analyze gradation results to determine if proportions of aggregates and batching operations proposed by the contractor will meet the job-mix formula and the specification limits of step 1.2.

2.2 Determine bulk and apparent specific gravity for the coarse- and fine-aggregate fractions (retained and passing the No. 8 sieve) for each type of material submitted. Additional specific gravity tests are not warranted when the only distinction between aggregates is size of grading. Using the information verified in step 2.1, mathematically compute the bulk and apparent specific gravity for the coarse- and fine-aggregate fractions (retained and passing the No. 8 sieve) for the proposed job-mix gradation.

2.3 Test the asphalt cement to be used for specification compliance (AASHTO M 226), viscosity-temperature data, and specific gravity at 77.0 F.

Asphalt Content

3.1 Determine the surface capacity of the aggregate fraction that is retained on a No. 4 sieve in accordance with the following procedure (25).

Note: For highly absorptive aggregates, use the procedure described in step 3.3.

K_c is determined from the percent of SAE No. 10 oil retained, which represents the total effect of superficial area, the aggregate's absorptive properties, and surface roughness.

3.1.1 Quarter out 105 g representative of the material passing the 3/8-in. sieve and retained on the No. 4 sieve.

3.1.2 Dry sample on hot plate or in 230 ± 9 F oven to constant weight and allow to cool.

3.1.3 Weigh out 100.0 g and place in a metal funnel (top diam 3-1/2 in., height 4-1/2 in., orifice 1/2 in., with a piece of No. 10 sieve soldered to the bottom of the opening).

3.1.4 Completely immerse specimen in SAE No. 10 lubricating oil for 5 min.

3.1.5 Drain for 2 min.

3.1.6 Place funnel containing sample in 140 F oven for 15 min of additional draining.

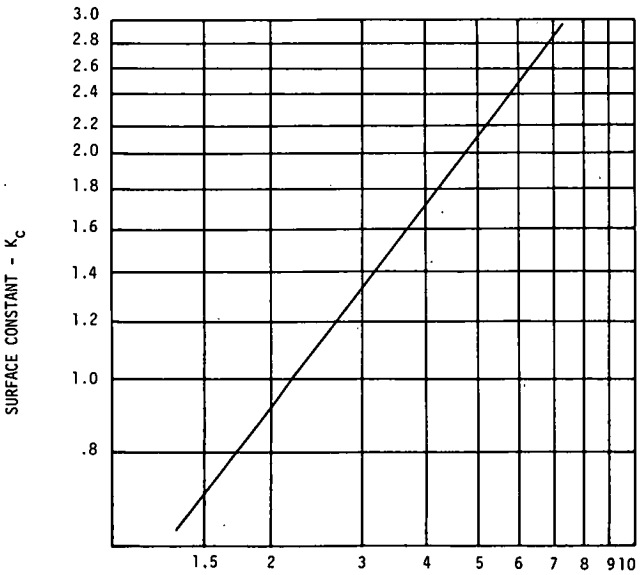
3.1.7 Pour sample from funnel into tared pan; cool, and reweigh sample to nearest 0.1 g. Subtract original weight and record difference as percent oil retained (based on 100 g of dry aggregate).

3.1.8 Use chart shown in Figure A-1 for determination of K_c.

(a) If specific gravity for the fraction is greater than 2.70 or less than 2.60, apply correction to oil retained, using formula at bottom of chart in Figure A-1.

(b) Start at the bottom of chart in Figure A-1 with the corrected percent of oil retained; follow straightedge vertically upward to intersection with the diagonal line; hold point, and follow the straightedge horizontally to the left. The value obtained is the surface constant for the retained fraction and is known as K_c.

3.2 Determine the required asphalt content, which is based on weight of aggregate, from the following relationship (2):



Material used: Aggregate--passing 3/8-in. sieve, retained on No. 4 sieve
Oil--SAE No. 10

Oil Retained Corrected (%) = Oil Retained (%) X $\frac{\text{apparent specific gravity of coarse aggregate}}{2.65}$

Figure A-1. Chart for determining surface constant (K_c) of coarse aggregate.

$$\text{Percent asphalt} = (2.0\ K_c + 4.0) \times \frac{2.65}{(SG)ca}$$

Where K_c = surface constant

(SG)ca = apparent specific gravity of coarse aggregate (3/8 in. to No. 4)

3.3 For highly absorptive aggregates, use the following procedure for determining K_c and asphalt content.

3.3.1 Follow the recommended design procedure from step 3.1 through step 3.1.3.

3.3.2 Follow the instructions in step 3.1.4, except immerse the specimen for 30 min.

3.3.3 Follow the recommended procedure from step 3.1.5 through step 3.1.7.

3.3.4 Pour the sample onto a clean, dry, absorptive cloth; obtain a saturated surface dry condition; pour sample from cloth into a tared pan; reweigh sample to nearest 0.1 g. Subtract original weight of aggregate and record difference as percent oil absorbed (based on 100 g of aggregate).

3.3.5 Subtract the percent oil absorbed value (see 3.3.4 above) from the percent oil retained value (see 3.3.3 above), and obtain the percent (free) oil retained value. This value represents the percent oil retained value that would have been obtained had the aggregate been a nonabsorptive type. The above technique allows one to evaluate the aggregate's surface and shape characteristics without the overwhelming influence of a large quantity of absorbed oil.

3.3.6 Follow the procedure recommended in steps 3.1.8 and 3.2. The only exception is that the percent (free) oil retained value is used (from step 3.3.5) to obtain K_c. Thus, the asphalt quantity determined is the "effective" asphalt content.

3.3.7 Follow the recommended procedure indicated through sections 4 and 5. Because asphalt absorption is not presently included in the formula for the determination of fine aggregate content, it is particularly desirable that the effects of oil absorption in the K_c test be excluded in the case of the highly absorptive aggregate.

3.3.8 Prepare a trial mixture using an asphalt content equal to or somewhat greater than (try to estimate amount that will be absorbed) the effective asphalt content determined in step 3.3.6 and also using the aggregate gradation as determined in step 3.3.7. Using a suitable technique, such as the test for maximum specific gravity of asphalt mixtures (AASHTO T 209), determine the actual quantity of asphalt absorbed (in percent, based on total weight of aggregate).

3.3.9 Determine the total asphalt content of the subject mixture by adding the effective asphalt content (from step 3.3.6) to the absorbed asphalt content (from step 3.3.8).

3.3.10 Follow the recommended procedure indicated in sections 6 and 7, using the total asphalt content for all subsequent computations and trials (from step 3.3.9).

Void Capacity of Coarse Aggregate

4.1 Use the following procedure to determine the vibrated unit weight and void capacity of the coarse-aggregate fraction (material retained on a No. 8 sieve) of the proposed job-mix gradation (26).

4.1.1 Apparatus

Rammer—A portable electromagnetic vibrating rammer as shown in Figure A-2, having a frequency of 3,600 cycles per min, suitable for use with 115-V ac. The rammer shall have a tamper foot and extension as shown in Figure A-3.

Mold—A solid-wall metal cylinder with a detachable metal base plate and a detachable metal guide-reference bar as shown in Figure A-4.

Wooden Base—A plywood disc 15 in. in diam, 2 in. thick, with a cushion of rubber hose attached to the bottom. The disc shall be constructed so it can be firmly attached to the base plate of the compaction mold.

Timer—A stopwatch or other timing device graduated in divisions of 1.0 sec and accurate to 1.0 sec and capable of timing the unit for up to 2 min. An electric timing device or electrical circuits to start and stop the vibratory rammer may be used.

Dial Indicator—A dial indicator graduated in

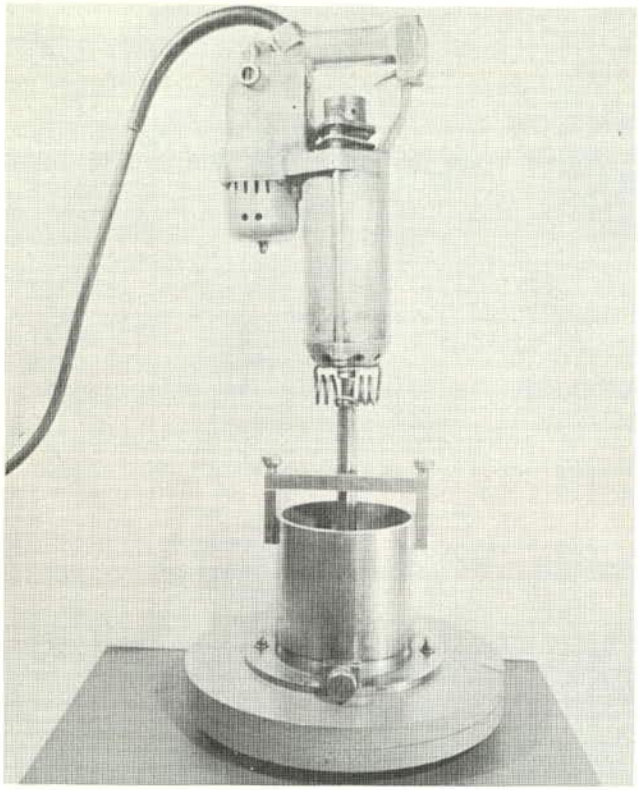


Figure A-2. FHWA vibratory compaction apparatus.

0.001-in. increments and having a travel range of 3.0 in.

4.1.2 Sample: Select a 5-lb sample of the coarse-aggregate fraction from the proposed job-mix formula as verified in step 2.1.

4.1.3 Procedure

(a) Pour the selected sample into the compaction mold and place the tamper foot on the sample.

(b) Place the guide-reference bar over the shaft of the tamper foot and secure the bar to the mold with the thumb screws.

(c) Place the vibratory rammer on the shaft of the tamper foot and vibrate for 15 sec. During the vibration period, the operator must exert just enough pressure on the hammer to maintain contact between the sample and the tamper foot.

(d) Remove the vibratory rammer from the shaft of the tamper foot and brush any fines from the top of the tamper foot. Measure the thickness (t) of the compacted material to the nearest 0.001 in.

> Note: The thickness (t) of the compacted sample is determined by adding the dial reading, minus the thickness of the tamper foot, to the measured distance from the inside bottom of the mold and the end of the dial gauge when it is seated on the guide-reference bar with stem fully extended.

4.1.4 Calculations

Calculate the vibrated unit weight (X) as follows:

$$X = 6912(w)/\pi(d)^2 t \ (\text{lb/ft}^3)$$

Where w = wt of coarse-aggregate fraction (lb)

d = diam of compaction mold (in.)

If w = 5 lb and d = 6 in.:

$$X = 305.58/t \ (\text{lb/ft}^3)$$

where t is in inches

Determine the void capacity (VMA) as follows:

$$VMA = 100(1 - X/U_c) \ \text{(in percent)}$$

where U_c = bulk solid unit weight (lb/ft^3) of the coarse-aggregate fraction. U_c is calculated from bulk specific gravity, as determined in step 2.2, multiplied by 62.4 lb/ft^3.

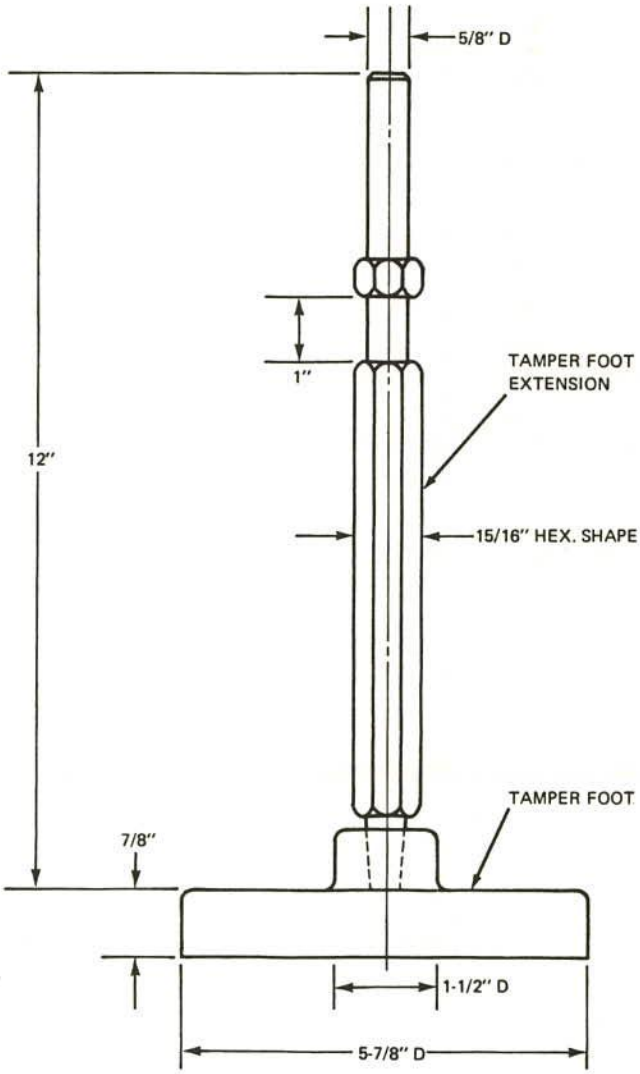


Figure A-3. Tamper foot and extension.

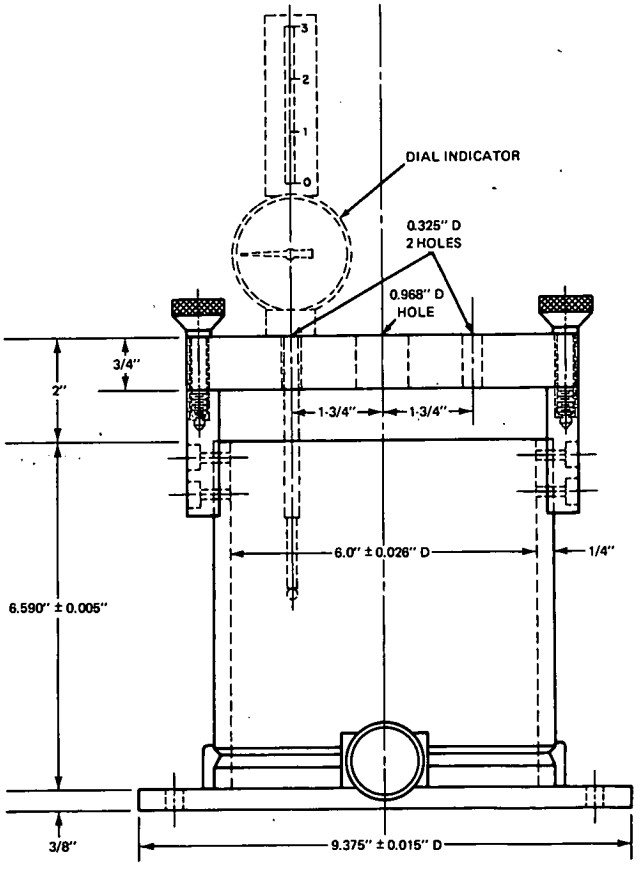


Figure A-4. Cylindrical mold for testing granular materials.

Optimum Content of Fine Aggregate

5.1 Determine the optimum content of fine-aggregate fraction using the following relationship:

$$Y = \frac{[\%\ VMA - V] - [(\%\ AC)(X)/U_a]}{[(\%\ VMA - V)/100] + [(X)/U_f]}$$

Where:

Y = Percent passing the No. 8 sieve (by weight)

X = Actual vibrated unit weight of coarse aggregate (retained on the No. 8 sieve)

U_f = Theoretical bulk dry solid unit weight of fine aggregate (passing the No. 8 sieve)

U_a = Unit weight of asphalt cement

% AC = Percent asphalt by total weight of aggregate $(2.0\ K_c + 4.0)\frac{2.65}{(SG)ca}$

V = Design percent air voids (15.0 percent)

% VMA = Percent voids mineral aggregate of the coarse aggregate (retained on the No. 8 sieve), which is $100 - (100)(X)/U_c$

U_c = Theoretical bulk dry solid unit weight of coarse aggregate (retained on the No. 8 sieve)

Note: X, U_a, U_c, and U_f are in pounds per cubic foot.

In the above relationship, asphalt absorption by aggregate has been assumed to be negligible. Because asphalt absorption requirements are considered in the test for K_c (see step 3.1), the estimated air voids of 15 percent in the mixture will actually be greater by an amount equivalent to the volume of asphalt absorbed, in percent. This condition provides, if anything, an additional safety factor.

As an alternative to the use of the mathematical relationship, one may use the design chart shown in Figure A-5, provided that the assumptions used in designing the chart are satisfied; that is, the specific gravity values (bulk dry) for the coarse- and fine-aggregate fractions do not deviate beyond the limits of 2.600 to 2.700.

If the value thus obtained for fine-aggregate content is greater than 15 percent, a value of 15.0 percent shall be used.

5.2 Compare the optimum fine-aggregate content (Y) determined in step 5.1 to the amount passing the No. 8 sieve of the contractor's proposed job-mix

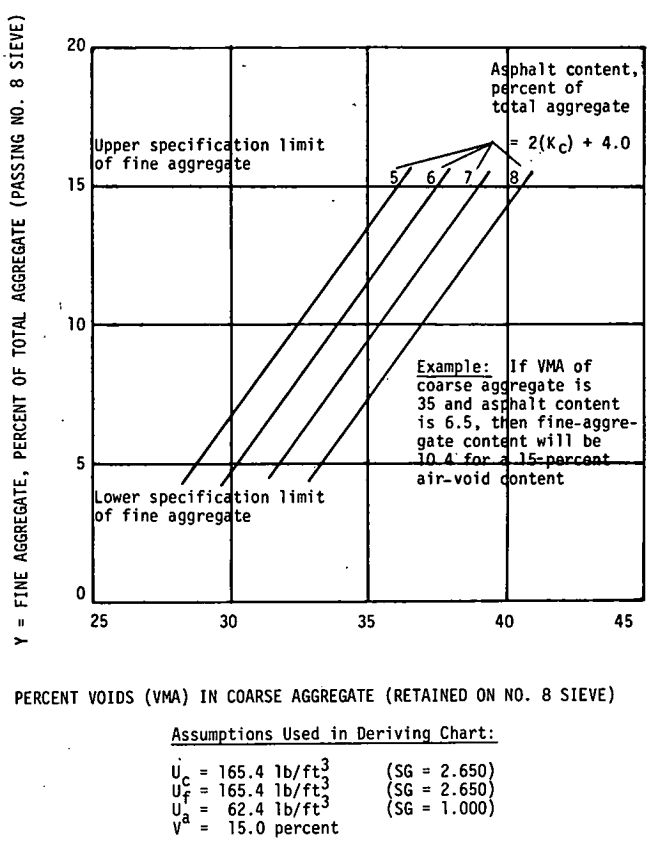


Figure A-5. Determination of optimum fine-aggregate content.

formula. If these values differ by more than plus or minus 1 percentage point, reconstruct a revised or adjusted job-mix formula using the value determined for optimum fine-aggregate content. Recompute the proportions of coarse and fine aggregates (as received) to meet the revised job-mix formula for submission to the contractor.

Note: If the proposed and revised job-mix gradations are significantly different, it may be necessary to rerun portions of this procedure.

Optimum Mixing Temperature

6.1 Prepare a 1,000-g sample of aggregate in the proportions determined in section 5. Mix this sample at the asphalt content determined in step 3.2 at a temperature corresponding to an asphalt viscosity of 800 centistokes determined in step 2.3. When the mixture is completely coated, transfer it to a pyrex glass plate (diam 8 to 9 in.) and spread the mixture with a minimum of manipulation. Return it to the oven at the mixing temperature. Observe the bottom of the plate after 15 and 60 min (Fig. A-6). A slight puddle at points of contact between aggregate and glass plate is suitable and desirable. Otherwise, repeat the test at a lower mixing temperature, or higher if necessary.

Note: If asphalt drainage occurs at a mixing temperature that is too low to provide for adequate drying of the aggregate, an asphalt of a higher grade should be used.

Resistance to Effects of Water

7.1 Conduct the Immersion-Compression Test (AASHTO T 165 and T 167) on the designed mixture. Prepare samples at the optimum mixing temperature determined in step 6.1. Use a molding pressure of 1,000 psi rather than the specified value of 3,000 psi.

After a four-day immersion at 120 F, the index of retained strength shall not be less than 50 percent unless otherwise permitted.

Note: Additives to promote adhesion that will provide adequate retained strength may be used when necessary.

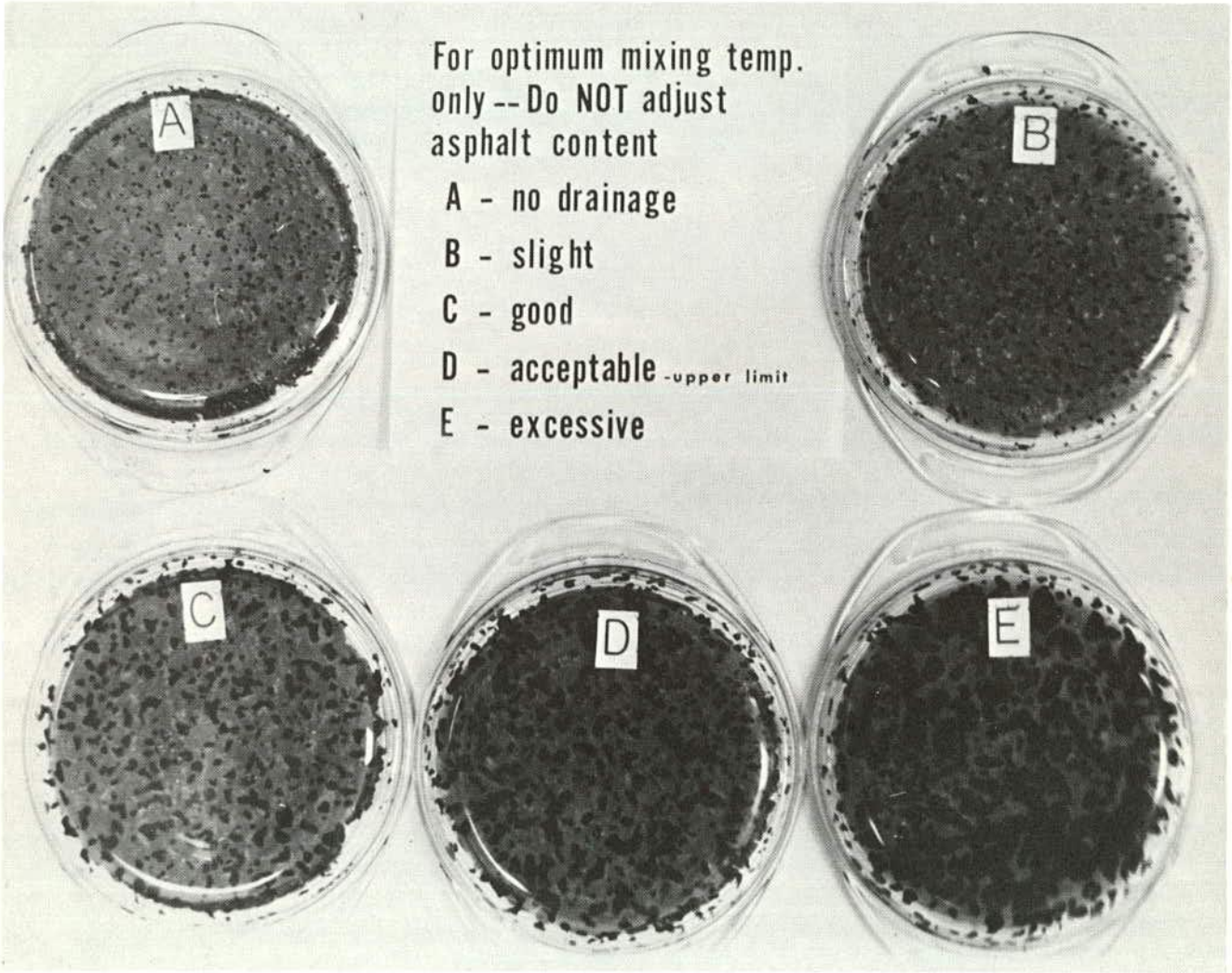


Figure A-6. Drainage test results.

REPORT ON OPEN-GRADED ASPHALT FRICTION COURSE DESIGN

1. AGGREGATES

A. Proposed Proportions (by weight)

B. Proposed Job-Mix Gradation

Sieve size	Specification limits	Percent passing			Job-mix blend
		_____	_____	_____	
1/2 in.		_____	_____	_____	_____
3/8 in.	95-100	_____	_____	_____	_____
No. 4	30-50	_____	_____	_____	_____
No. 8	5-15	_____	_____	_____	_____
No. 16		_____	_____	_____	_____
No. 200	2-5	_____	_____	_____	_____

C. Specific Gravity--Unit Weight

	Apparent SG	Bulk SG (dry basis)	Bulk solid unit weight (lb/ft^3)
Coarse aggregate (retained on No. 8 sieve)		_____	_____ (U_c)
Fine aggregate (passing No. 8 sieve)		_____	_____ (U_f)
3/8 in. - No. 4 Sieve fraction	_____		

D. Void Capacity of Coarse Aggregate

Unit weight (vibrated, lb/ft^3) = _____ (X)

Voids mineral aggregate (%) = _____ (VMA)

E. K_c Determination

Oil retention (g oil per 100 g aggregate) = _____

Oil retention (corrected, 2.65 SG) = _____

K_c (from chart) = _____

2. ASPHALT

A. Specific Gravity--Unit Weight

Specific gravity at 77 F (25 C) = _____

Unit weight (lb/ft^3) = _____ (U_a)

B. Viscosity--Temperature

Asphalt grade = _____

Temperature (°F)	Viscosity (centistokes)
290	_____
275	_____
260	_____
245	_____
230	_____
215	_____
Target: (-)	(700 - 900)

C. Asphalt Content (AC, %)

Percent aspnalt (aggregate basis) =

$$(2.0\ K_c + 4.0) \times \frac{2.65}{\text{apparent SG of coarse aggregate (3/8-in. to No. 4 sieve)}}$$

3. MIXTURE DESIGN

A. Optimum Fine-Aggregate Content (Y)

Using: Formula _____ Chart _____

Where: X = _____ lb/ft^3 VMA = _____ %

U_f = _____ lb/ft^3 AC = _____ %

U_c = _____ lb/ft^3 V = _____ %

U_a = _____ lb/ft^3

Find: Y = _____ % (specs limit: 5 < Y < 15)

Remarks:

B. Optimum Mixing Temperature

Temperature (°F)	Viscosity (centistokes)	Drainage	Use
_____	_____	_____	___
_____	_____	_____	___
_____	_____	_____	___

C. Maximum Specific Gravity of Mixture (AASHTO T 209)

Specific gravity (vacuum saturation) = _____

Unit weight (vacuum saturation) = _____ lb/ft^3

D. Resistance to Effects of Water (AASHTO T 165 and T 167, 2000 psi)

Air dry strength (psi) = _____

Wet strength (psi) = _____ 4 days at 120 F

Retained strength (%) = _____ 50% minimum

Air voids (%) = _____ Bulk volume by dimensional measurement

Remarks:

4. DESIGN SUMMARY

A. Aggregate Proportions (by weight)

B. Job-Mix Gradation

Sieve size	Percent passing: Job-mix blend
1/2 in.	_____
3/8 in.	_____
No. 4	_____
No. 8	_____
No. 16	_____
No. 200	_____

C. Asphalt Content

Aggregate basis (%) = _____

Mixture basis (%) = _____

D. Mixing Temperature

Target value (°F) = _____

Range = _____

E. Additives

F. Recommendations Accepted ____ Rejected ____

APPENDIX B

TEXAS HIGHWAY DEPARTMENT MATERIALS AND TESTS DIVISION ACCELERATED POLISH TEST FOR COARSE AGGREGATE

Scope

This test method describes a procedure for determining a relative measure of the extent to which aggregate in the wearing surface of the roadway will polish under traffic.

The aggregate samples under test are mounted on a specimen wheel to form a test strip 16 inches in diameter and subjected to the rolling action of a rubber tire. Size 150 silicon carbide grit and water are used to increase the rate of wear.

Part I of this method covers testing of single component aggregate samples and determining the Polish Value by using the Wessex Accelerated Polishing Machine and the British Portable Tester.

Part II of this method differs from Part I only in the use of two-component blends of aggregate particles rather than a single type of aggregate. Method A of Part II covers the determination of Polish Value of blends by actual testing. Method B of Part II covers the theoretical determination of Polish Value or blend percentage by use of a formula.

Part III describes a procedure for determining the amount of differential wear on individual particles of aggregate subjected to similar abrasive action by measuring quantitatively the loss of particle surface.

PART I
SINGLE COMPONENT AGGREGATE

The Polish Value is determined in accordance with ASTM Designation: E 303, Measuring Pavement Surface Frictional Properties Using the British Portable Tester.

Definitions

Initial Friction Value: The average of a set of initial readings on the test specimens before they are polished in the accelerated polishing machine.

Polish Value: The average of a set of readings on the test specimens after nine hours of polishing in the accelerated polishing machine.

Sampling

A 30-pound sample representing production designated for highway use shall be submitted by a representative of the State Department of Highways and Public Transportation. The sample shall be properly identified on Form 202 and the name of the pit or quarry and its exact location shall be explicit.

Apparatus

1. A Wessex Accelerated Polishing Machine based on a 1958 design by the Transport and Road Research Laboratory of Great Britain.

2. Metal Molds to form a test specimen 3.50 inches long by 1.75 inches wide by 0.63 inches deep.

3. A British Portable Tester to measure the Initial Friction Value and the Polish Value of the test specimens.

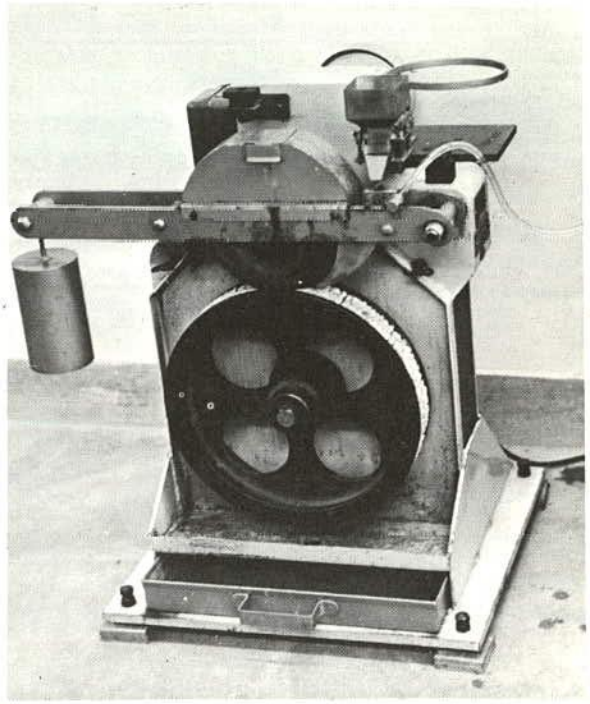


Figure 1

Wessex Accelerated Polishing Machine Showing Test Specimens Mounted on Specimen Wheel

Materials

1. Tap water.

2. Ottawa sand, Grade 20-30 meeting ASTM Designation: C 190. This material is optional.

3. Polyester resin and catalyst for bonding agent with a pot life of about 10 minutes and a curing time of 3-6 hours.

4. Mold release agent for use with polyester bonding agent. This material is optional.

5. Silicon carbide grit (150 size).

6. A supply of disposable cups and spatula or stirring rods for use in mixing the bonding agent.

Preparation of Test Specimens

Seven specimens are required for each material and are to be prepared as follows:

1. The aggregate to be tested shall pass the 1/2-inch sieve and be retained on the #4 sieve.

2. The screened aggregate shall be thoroughly washed clean and dried.

3. The molds shall be coated with the mold release agent (optional).

Note: A mold release agent may be used to facilitate release of the coupon. Generally a polyester compound does not require this agent.

4. The aggregate particles shall be placed in a single layer as closely as possible in the bottom of the mold. Aggregate particle orientation should allow adequate surface area for polishing as well as bonding.

Note: When possible, use of flat, elongated and odd-shaped particles should be avoided. Generally they will cause difficulty in placement and will result in erratic or biased Polish Values.

5. The interstices between the aggregate particles may be filled with the Ottawa sand to a depth between 1/4 to 1/2 the particle height. This step is optional.

Note: The Ottawa sand is needed as a barrier if the bonding agent has high fluidity. Generally a putty-like consistency of bonding agent eliminates the need for sand.

6. Prepare the polyester resin and catalyst for bonding agent according to manufacturer's instructions. The consistency of the polyester shall be such as to allow it to spread onto and between the particles, but not so thin that it flows into the Ottawa sand (if sand is used) and onto the curved mold surface.

7. Fill prepared mold to capacity with the polyester bonding agent.

8. Strike off the bonding agent level with the curved sides of the mold.

9. Leave specimen in the mold for a sufficient length of time (3-6 hours) to allow the bonding agent to cure properly.

10. Remove specimen from the mold and brush any excess sand from the specimen face (if sand was used).

11. Dress the bottom side of the test specimens with a grinding wheel or belt sander if warping prevents proper placement on the polishing wheel or BPT base plate.

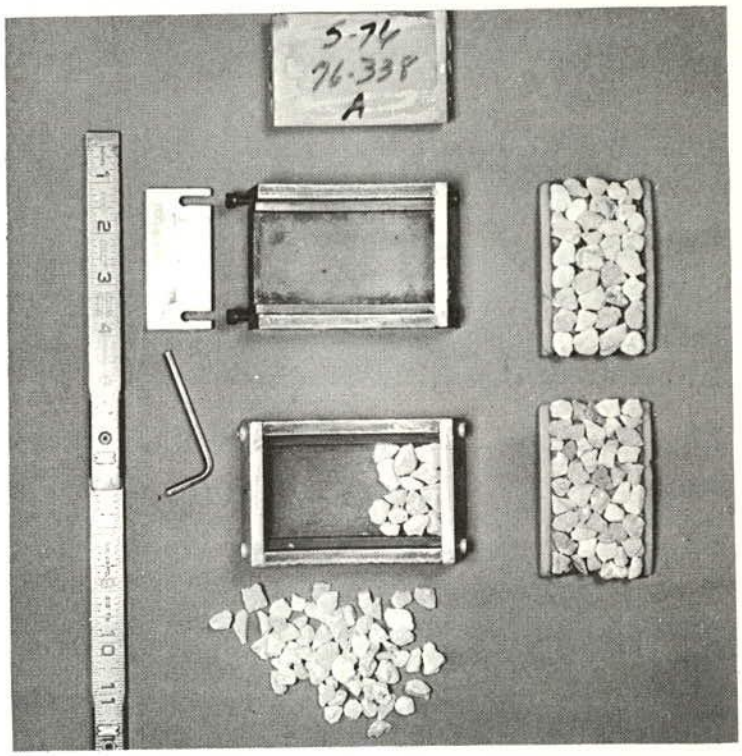


Figure 2

Metal Molds With Test Specimens

Procedure

1. Calibrate the British Portable Tester.

2. Determine the Initial Friction Value of the prepared test specimens. The Initial Friction Value is used for reference purposes.

3. A total of 14 specimens shall be clamped around the periphery of the specimen wheel of the Wessex Accelerated Polishing Machine. A rubber O-ring is placed on both edges of the test specimens to hold them against the specimen wheel. The wheel flanges are then bolted into place pressing down upon the O-rings and edges of the specimens firmly holding them in place.

A minimum of seven specimens of each material shall be tested to increase statistical accuracy. Dummy specimens may be used to completely fill the wheel if only one material is to be tested. The outer surfaces of the specimens shall then form a continuous strip of particles upon which the rubber tire shall ride freely without bumping or slipping.

4. The specimen wheel shall be brought to a speed of 320 ± 5 rpm. The rubber tire wearing wheel, inflated to 45 ± 2 psi, shall be brought to bear against the specimen wheel and loaded to 88 ± 1 pounds.

5. Silicon carbide grit (size 150) shall be continuously fed to the specimen wheel near the tire contact point at a constant rate of approximately 6 ± 2 grams per minute along with water fed at the rate of about 50 to 75 milliliters per minute.

6. The polishing action shall be continued for a total period of nine hours. Downtime does not affect test results.

7. The samples shall be removed from the specimen wheel and washed thoroughly to remove grit.

8. After cleaning, the samples shall be tested for Polish Value with the British Portable Tester.

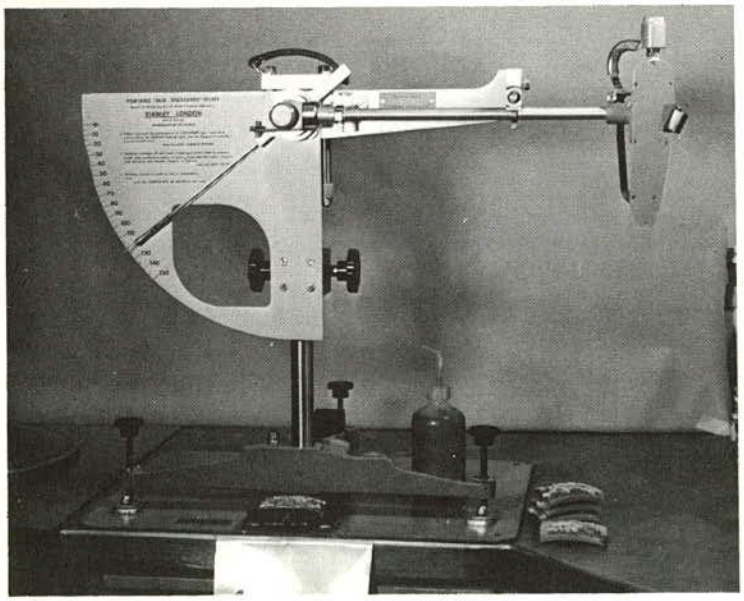


Figure 3
British Portable Tester

Report

The final report shall consist of the average final Polish Values.

PART II
BLENDED AGGREGATES

This part describes the additional steps to be taken when aggregate blends are tested as differentiated from single-component aggregates.

Definitions

Blend – A definite percentage mixture of two materials of different physical characteristics from different locations.

Note: Unless specific exceptions are noted, all apparatus, materials and procedures are identical with those outlined in Part I.

Method A – Determination of Polish Value for Random Blends

Sampling

The aggregate particles are selected on a percentage basis (i.e., 1 particle to 9 for a 10% blend, or 1 particle to 4 for a 20% blend, etc.). Although selection of particles is random, some care should be exercised in avoiding a preponderance of odd-shaped particles (such as flakes or blades) for either component.

Preparation of Test Specimens

Aggregate particles in the correct percentages are placed at random on the bottom of the mold. Preparation of the test specimen is then completed as outlined in Part I. Seven coupons are made for each blend to be tested. For aggregate percentages to be properly representative, the two aggregates which are to be blended must be similar in size.

Report

Information in the report for aggregate blends shall include the following:

1. Information from Form 202.

2. Initial Friction Values and the average for each aggregate and each blend tested.

3. Final Polish Values and the average for each aggregate and each blend tested.

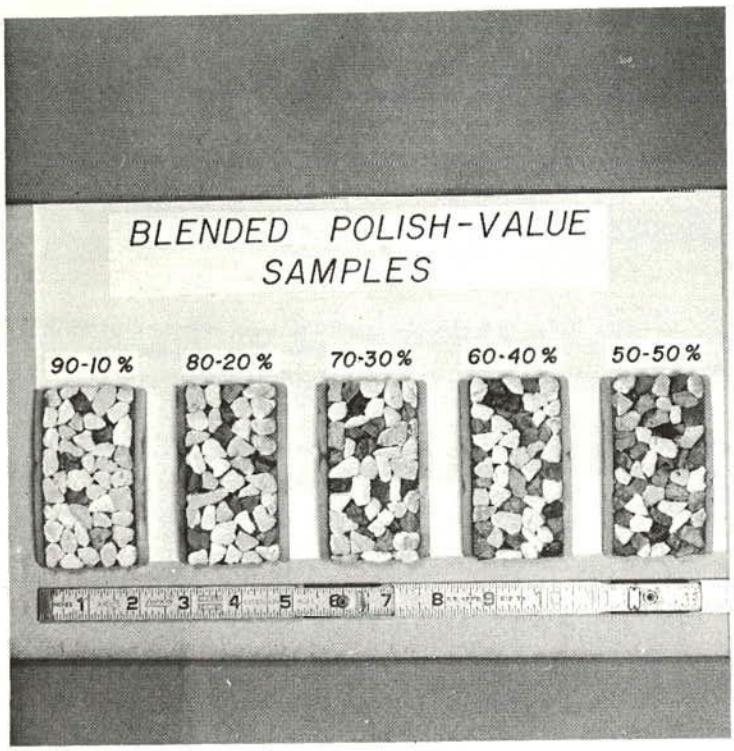


Figure 4

Specimens of Various Percentage Blends

Method B – Theoretical Determination of Polish Value and Blend Percentage

Definitions

Non-polishing aggregate – An aggregate used to improve the polish value of the aggregate mix.

Polishing Aggregate – An aggregate exhibiting a relatively low polish value which needs to be improved.

The percentage by volume of non-polishing aggregate to use in a blend to meet a specified Polish Value is determined by the following formula:

$$\%P_R = \frac{100\ [(PV_S+2)-PV]}{PV_R - PV}$$

$\%P_R$ = Percent (by volume) of the Non-polishing coarse aggregate

PV_S = Polish Value required by specification

PV_R = Polish Value of Non-polishing aggregate (P_R)

PV = Polish Value of polishing aggregate to be improved

The Polish Values of the components above are determined as in Part I using single component aggregate coupons.

PART III
DETERMINATION OF DIFFERENTIAL WEAR

Part III Describes a procedure for determining the amount of wear on individual particles of coarse aggregate by measuring the actual loss of the particle surface as it is abraded on the Accelerated Polishing Machine.

Apparatus

1. Specimen molds and supplies as in Part I.

2. Wessex Accelerated Polishing Machine as in Part I.

3. Height measuring dial gage affixed to the frame of the Polishing Machine as shown in Figure 5. The gage should be accurate to 0.001 inch.

Preparation of Test Specimens

A sufficient number of specimens should be made to obtain a valid average figure for each type of aggregate or blend or composite of aggregates to be tested. Preparation of test specimens is identical to that of Part I. The aggregate particles of the different types are selected at random and placed at random on the bottom of the mold.

An alternate method to measure wear on aggregate particles retained in separate type groups, uses a divider such as the one shown in Figure 6 to keep particles in quadrants. The divider is removed before application of the polyester bonding agent.

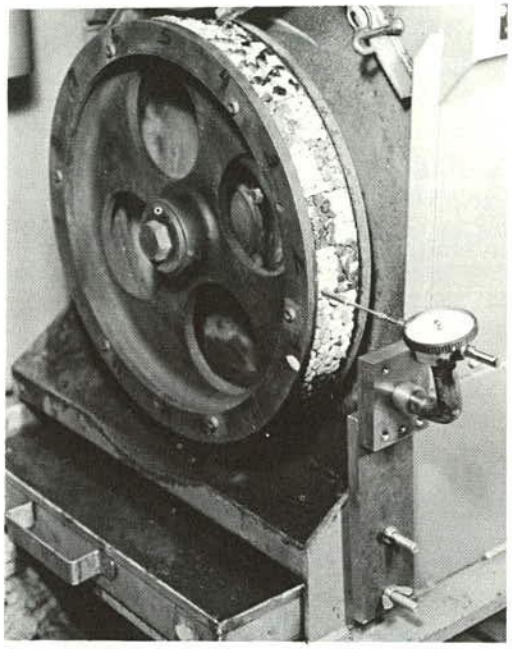


Figure 5

Polishing Machine with height gage

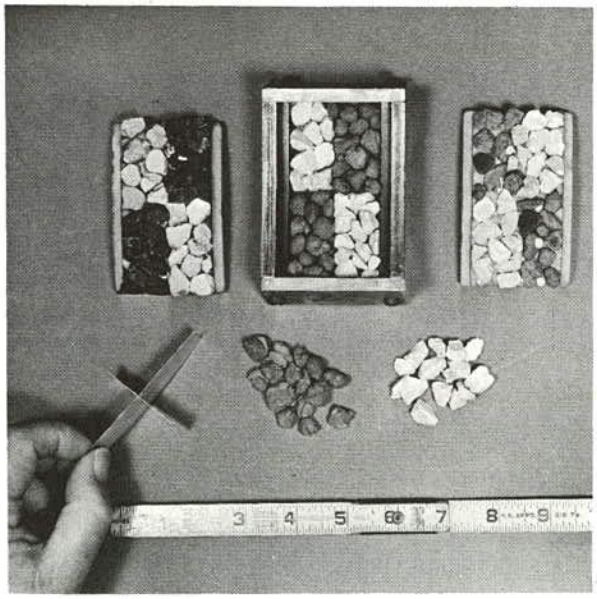


Figure 6

Divider used for separating aggregate in quadrants

Procedure

1. Mount the test coupons on the Accelerated Polishing Machine wheel as in Part I.

2. Zero the height measuring gage on a cleaned and marked spot on the wheel flange.

3. Mark with a fast-drying contrasting color paint the individual particles to be measured. A minimum of eight particles per coupon should be marked on the side. In this location the paint will not wear.

4. Measure and record the surface elevation of each marked particle of aggregate.

5. The wheel is run nine hours for the full test, but it may be stopped at set periods for measurement of wear in order that a set of values may be taken for rate-of-wear graphs.

6. Final height measurements are taken on the marked aggregate particles at the end of the nine-hour run. The loss of height is then averaged for each type of aggregate tested. These averages represent an index of differential wear or comparison between the particular aggregates tested in the given composition coupon.

APPENDIX C

LOUISIANA METHOD OF TEST FOR ABRASION OF LIGHTWEIGHT COARSE AGGREGATE

LDH TR 111-71
REV. 7/71

Scope

1. This method covers the procedure for testing lightweight coarse aggregate for resistance to abrasion in the Los Angeles testing machine with an abrasive charge.

Apparatus

2. The apparatus for this test shall be as described in AASHO T-96, Standard Method of Test for Abrasion of Coarse Aggregate by Use of the Los Angeles Machine.

Abrasive Charge

3. The abrasive charge shall be as required in AASHO T-96, Standard Method of Test for Abrasion of Coarse Aggregate by Use of the Los Angeles Abrasion Machine.

Test Sample

4. The test sample shall consist of clean aggregate which has been dried in an oven at a temperature not exceeding 235°'F. to constant weight and shall conform to one of the gradings shown in Table 1. The grading or gradings used shall be those most nearly representing the aggregate furnished for the work.

Procedure

5. The test sample and the abrasive charge shall be placed in the Los Angeles abrasion testing machine and the machine rotated at a speed of from 30 to 33 rpm. The machine shall be rotated for 100 revolutions for all gradings. At the completion of the test, the material shall be discharged from the machine and sieved on a No. 4 sieve in a manner conforming to Section 5 (a) of the Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregate, LDH Designation TR 113. The material coarser than the No. 4 sieve shall be washed, dried in an oven at a temperature not exceeding 235° F. to constant weight and accurately weighed to the nearest gram.

Calculation

6. The difference between the original weight and the final weight of the test sample shall be expressed as a percentage of the original weight of the test sample. This value shall be reported as the percentage of wear.

TABLE 1 - GRADINGS OF TEST SAMPLES

Sieve Size (Square Openings)		Percent of Weight and Grading of Test Sample, grams *		
Passing	Retained On	A	B	C
1½ in.	1 in.	25%	———	———
1 in.	¾ in.	25%	———	———
¾ in.	½ in.	25%	50%	———
½ in.	3/8 in.	25%	50%	———
3/8 in.	No. 3	———	———	50%
No. 3	No. 4	———	———	50%

* The weight of the test sample shall be determined as follows:

(1) Determine the loose unit weight of the lightweight coarse aggregate sample as received in accordance with the procedure described in AASHO T-19.

(2) The weight of the test sample is then computed from the following:

Weight of test sample in grams = Unit Wt. of Aggregate, lbs/cu. ft. X 51.55

Example: Unit weight of coarse aggregate = 35 lbs/cu. ft.

Weight of test sample, grams = 35 X 51.55 = 1804 grams

If this was Grade B aggregate then the 1804 grams would be divided into 50% passing the ¾ inch sieve and retained on the ½ inch sieve, and 50% passing the ½ inch sieve and retained on the 3/8 inch sieve.

APPENDIX D

DELAWARE DEPARTMENT OF TRANSPORTATION SPECIFICATION FOR PLANT MIX OPEN-GRADED WEARING SURFACE

Description:

This work shall consist of furnishing all materials and constructing open-graded wearing surface in accordance with the width and thickness shown on the Plans.

The pavement shall be constructed in conformity with the requirements of these Special Provisions and all applicable sections of Section 401 of the Standard Specifications.

Tapered sections (beginning and end of project) to or from the existing pavement to the full depth of the open-graded Wearing Surface shall be constructed by tapering with regular Type "C" Wearing Course.

Job Mix Formula: The open-graded wearing surface shall be composed of a mixture of approved aggregate and asphalt cement. Limestone or Serpentine aggregate will not be approved. The use of washed concrete sand in this mix will not be permitted.

At least one month prior to production, the contractor shall submit in writing a job mix formula to the Engineer for approval. At this time, the contractor shall list all sources of materials and provide adequate samples of all aggregates and asphalt in order to verify suitability of the proposed job mix.

Job mix suitability will be determined on the basis of laboratory tests.

GRADATION AND MIX REQUIREMENTS

Sieve	Master Range (% passing)	Tolerance from Job Mix
1/2"	100	-----
3/8"	92-98	±3%
#4	25-45	±5%
#8	5-15	±3%
#200	2-5	±1.5%

Asphalt Cement 6.0 to 8.0% (to be determined by Laboratory Tests.)

An approved heat stable anti-stripping additive shall be added to all cement used for open-graded surface course. The amount of additive used shall be 0.25 to 1.0% by weight of the asphalt cement as recommended by the additive manufacturer and approved by the Bureau of Materials and Research.

The additive shall be thoroughly and uniformly blended with the asphalt cement at the hot-mix production plant or at the asphalt cement source of supply by one of the following methods:

1. An approved in-line metering and blending system.

2. An approved propeller type blade blender in the asphalt storage tank in conjunction with an approved metering device for adding the required anti-stripping additive.

Heat stable anti-stripping additive shall conform to the following requirements:

1. The material shall contain no ingredient harmful to asphalt cement and shall not appreciably alter the characteristics thereof when added in the recommended proportions.

2. It shall be capable of thorough dispersion in the asphalt cement at the temperature of use and shall be capable of remaining in asphalt cement in storage at the normal storage temperatures without detrimentably affecting the asphalt cement. The additive shall remain effective as an anti-stripping compound when stored in the asphalt cement.

No separate payment will be made for the anti-strip agent. Payment will be included in the unit price bid for "Plant Mix Open-Graded Wearing Surface"

The target temperature ($\pm$ 10°F) of the mix leaving the mixer shall be established by the Bureau of Materials & Research on the basis of laboratory tests.

Should a change in source of material be proposed or should an approved job mix formula prove unsatisfactory a new job mix formula shall be submitted by the contractor.

Asphalt Cement shall conform to the requirements of Section 810 of the Standard Specifications. However, the temperature of the asphalt cement shall not be greater than

275°F. at time of introduction into the mixer.

On areas where irregularities or unavoidable obstacles make the use of mechanical spreading and finishing equipment impracticable, the mixture may be spread, raked and luted by hand tools.

No open-graded wearing surface shall be placed when the ambient temperature is below 60°F.

Compaction: After the bituminous mixture has been spread, struck off, and surface irregularities adjusted, it shall be thoroughly and uniformly compacted by rolling. The bituminous mixture shall be rolled in a longitudinal direction, commencing at the outside edge and progressing towards the center. Rolling shall be accomplished with a steel-wheel roller or rollers and shall be conducted in such a manner that shoving, distortion, or stripping will not develop beneath the roller. On superelevated curves, the rolling shall commence on the low side and progress to the high side. The amount of rolling shall be confined to only that necessary for consolidating the bituminous mixture and bonding it to the underlying surface. Excessive rolling shall be avoided.

The completed bituminous mixture shall be protected from all traffic until it has cooled sufficiently to resist distortion, abrasion, or pickup.

The contractor is advised that early breakdown is essential due to rapid temperature loss of the open-graded mix. It is anticipated that two complete passes of the roller will provide adequate compaction. Density tests on the open-graded wearing surface will not be conducted. The contractor will be directed to cease rolling when, in the opinion of the Engineer, maximum density has been achieved. Determination will be by visual means. Over rolling will result in aggregate fracture which shall be avoided.

Joints, Trimming Edges, and Cleanup: Placing of the bituminous mixture shall be as continuous as possible. Rollers shall not pass over the unprotected end of a freshly laid mixture unless authorized by the Engineer. Transverse joints shall be formed by cutting back on the previous run to expose the full depth of the course. A brush coat of bituminous material shall be used on contact surfaces of transverse joints just before additional mixture is placed against the previously rolled material.

The exposed edges of the completed mat shall be cut off true to the required lines. Material trimmed from the edges and any other discarded bituminous mixture shall be removed from the roadway and disposed of by the contractor.

Finished Work Samples: The Engineer may cut samples from the pavement for testing. Samples will be neatly cut by a saw or core drill. The contractor shall supply and finish new material to backfill voids left by sampling.

Aggregate shall conform to the requirements of Section 805 of the Standard Specifications, except slag will not be permitted. The use of limestone aggregate or natural sand, washed or unwashed, is prohibited.

Bituminous Mixing Plant: The requirements of Section 401.10 and 401.11 of the Standard Specifications shall apply.

Hauling Equipment: Requirements of Section 401.18 of the Standard Specifications shall apply.

Pavers: Requirements of Section 401.19 of the Standard Specifications shall apply.

Rollers: Rollers shall be in good condition, capable of reversing without backlash. The use of equipment which results in crushing of the aggregate will not be permitted. Rollers shall be steel-wheel capable of exerting a force of not less than 250 pounds per inch of width of compression roll or rolls. Rubber tired rollers will not be permitted on the open-graded wearing surface.

Preparation of Aggregates: The aggregates for the mixture shall be dried and heated to the required temperature. Flames used for drying and heating shall be properly adjusted to avoid damage to the aggregate and to avoid soot on the aggregate.

The temperature of the aggregates as introduced into the mixer shall not exceed a temperature which causes segregation of the asphalt and aggregate during transportation. The temperature shall not be lower than is required to obtain complete coating and uniform distribution on the aggregate particles and to provide a mixture of satisfactory workability.

Mixing: The dried aggregates and the bituminous material shall be measured or gauged and introduced into the mixer in the proportions specified by the job mix formula.

After the required amounts of aggregate and bituminous material have been introduced into the mixer, the materials shall be mixed until a complete and uniform coating of the particles and a thorough distribution of the bituminous material throughout the aggregate is secured.

Transporting, Spreading, and Finishing: The mixture shall be transported from the mixing plant to the point of use in vehicles conforming to the requirements outlined herein.

The mix shall be spread and struck off to the grade and elevation established. Bituminous pavers shall be used to distribute the mixture either over the entire width or over such partial width as may be practicable.

Method of Measurement: The number of tons of bituminous plant mix open-graded wearing surface to be paid for under this Section shall be the actual weight of bituminous plant mix open-graded wearing surface placed and accepted. The tonnage shall be based as follows:

> The weight of each load shall be determined by weighing each load truck or other approved hauling equipment and then deducting the tare weight of the truck or hauling equipment. The tare weight shall be checked twice daily, or as often as directed by the Engineer and appropriate adjustments made thereafter, in the use of the tare weight.
>
> The scale platform shall be of such length and width that it will conveniently accomodate all trucks or other approved hauling equipment, hauling materials. The entire vehicle load must rest on the scale platform and be weighed as one draft. All scales shall be checked and approved before use.
>
> Weight tickets showing a net weight of each load of material delivered to the project shall be signed by the State Highway inspector.

Basis of Payment:

The tonnage measured as provided above shall be paid for at the contract unit price per ton bid for "Plant Mix Open-Graded Wearing Surface", which price and payment shall be full compensation for furnishing all materials, preparing, hauling, and placing all materials and for all labor, equipment, tools, and incidentals necessary to complete the work. If "Actual Cost Payment Provisions" are applied to this item the asphalt cement shall be paid for separately as a bid item of the contract.

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To share in the tasks of furthering science and engineering and of advising the federal government, the National Academy of Engineering was established on December 5, 1964, under the authority of the act of incorporation of the National Academy of Sciences. Its advisory activities are closely coordinated with those of the National Academy of Sciences, but it is independent and autonomous in its organization and election of members.

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