Synthesis of Highway Practice 180

Performance Characteristics of Open-Graded Friction Courses

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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 the National Research Council 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 National Research Council 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 the responsibilities of the National Research Council and the 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

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, 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 useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on 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 these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to construction, maintenance, pavement design, and materials engineers, pavement contractors, and others interested in the use of open-graded friction courses (OGFC) as an asphalt concrete pavement wearing surface. Information is provided on performance benefits and limitations of OGFC, material and mixture properties, and current construction practices in use in the United States and Europe.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available 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 reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

Advances in mixture design and construction techniques have overcome several of the performance limitations identified in early applications of open-graded friction courses, and have enhanced the performance benefits associated with OGFC use. This report of the Transportation Research Board describes the current state of the practice
with respect to the use of OGFC. Experience with the design, construction, and performance of OGFC is summarized, based on a review of the literature, documentation of experience from applications in the U.S. and Europe, and site visits to several states.

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 researcher 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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Special appreciation is expressed to Harry A. Smith, who was responsible for collection of the data and preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of E. Ray Brown, Director of Research, National Center for Asphalt Technology, Auburn University; Alfred D. Donofrio, Century Engineering; Jim Gee, Engineer of Materials and Research, Arkansas State Highway and Transportation Department; Michael A. Heitzman, Pavements Division (HNG-42), Federal Highway Administration; Peter A. Kopac, Research Highway Engineer, Pavements Division (HNR-20), Federal Highway Administration; G.W. Maupin, Jr., Research Scientist, Virginia Transportation Research Council; and Harold R. Paul, Asphalt Technology Research Administrator, Louisiana Transportation Research Center.

Frank R. McCullagh, Engineer of Design, Transportation Research Board, and D.W. Dearsbaugh, Senior Program Officer, assisted the NCHRP Project 20-5 Staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.
PERFORMANCE CHARACTERISTICS OF OPEN-GRADED FRICTION COURSES

SUMMARY

Over the past 20 years, the reduction of wet-weather skidding accidents has been a major objective of highway agencies at all levels, individually, and working through such organizations as the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), the Transportation Research Board (TRB), and the American Society for Testing and Materials (ASTM). Although highway safety involves the interaction of driver, vehicle, and roadway, the primary responsibility of highway agencies with regard to minimizing wet-weather skidding accidents is to provide pavement surfaces suitable for the needs of motorists during rain storms. Substantial progress toward minimizing wet-weather skidding accidents has been made through an evolutionary process involving (a) establishing standards for measuring pavement surface friction characteristics, (b) determining reasonable friction values, (c) developing design, construction, and maintenance procedures for high friction pavement surfaces, (d) improving tire tread design, and (e) regulating minimum tread depths to reduce water build-up at the tire-pavement interface. State highway agencies experimented with various high friction surface types with descriptive terms such as plant-mix seal, popcorn mix, porous asphalt surface, open-graded asphalt friction course, and open-graded friction course. The practices of pavement grooving and the use of a coarse surface macrotexture, particularly on portland cement concrete pavements, also were used to reduce wet-weather skidding accidents. This synthesis is limited to and uses the terminology “open-graded friction courses” (OGFC) for asphalt-aggregate pavement surfaces with a larger percentage of voids than conventional asphalt concrete surfaces and a coarse macrotexture.

With this major emphasis on reducing wet-weather skidding accidents and the use of OGFC as a means for accomplishing this objective, it is understandable that by the mid 1970s a majority of state highway agencies had at least experimented with use of OGFC in some form. NCHRP Synthesis of Highway Practice 49, Open-Graded Friction Courses for Highways, published in 1978, reported that 15 states were using OGFC extensively and several additional states were considering such use. However, by the mid 1980s it was perceived that use of OGFC may be on the decline based on reports that some states had discontinued or placed moratoriums on their use. Because of this perception, the AASHTO Subcommittee on Construction conducted a survey in 1988 on current OGFC use and an NCHRP synthesis study was funded to update Synthesis 49. This document is the result of the follow-up study, and includes a summary of the AASHTO survey in Chapter Four.

Seven European countries report substantial use of OGFC. Extensive research and
experience indicates that properly designed, constructed, and maintained OGFC surfaces 
a) minimize hydroplaning potential, (b) provide high wet-weather friction, (c) reduce splash and spray, (d) reduce headlight glare during periods of rain, and (e) reduce traffic noise. Reported limitations and disadvantages of OGFC use are (a) snow and ice removal difficulties, (b) permeability deterioration, (c) increased cost, (d) early raveling, (e) deterioration of underlying layers, and (f) maintenance patching difficulties.

The increase in OGFC use in both the U.S. and Europe is evidence that this type of surface is a successful technology. In many states the benefits are considered to outweigh any limitations and problems. The reported limitations have been addressed by agencies that currently use OGFC surfaces extensively.

Based on the European OGFC research and experience plus information in the U.S., the areas of design (including percent air voids and thickness) and binder properties warrant further investigation. It seems apparent that a single OGFC mix design, specifically percent air voids and surface thickness, would not be the optimum for all traffic volumes, climatic conditions, and roadway types. Experiences in Europe and in Oregon to a more limited extent have indicated advantages in using a 2-inch thick OGFC surface with air void content over 20 percent. These surfaces appear to provide increased internal drainage with reduced probability of clogging and better traffic noise reduction, than the OGFC of less than 1-inch thickness and 15 percent air voids generally used in the United States. Further study to optimize the OGFC design process for specific conditions is suggested.

The number of state highway agencies that regularly use OGFC during new construction or pavement rehabilitation has increased from 15 in 1977 to 27 in 1988. The AASHTO survey reported that approximately 56,400 lane miles of OGFC had been placed by 1988; however, the survey report includes this comment: “It appears that the transfer of technology related to the design and construction of OGFC could be more successful. With 10 agencies each reporting over 10,000 lane miles in place at the beginning of 1988 and 27 reporting continuing use, why have 21 stopped using it?”

One of the more serious causes of premature OGFC failures is the oxidation of the asphalt binder films on the coarse aggregate particles. The combination of European research and experience with additives to increase binder film thickness, research currently being conducted in the Strategic Highway Research Program, Project A-003B, and the activities of TRB Committees A2D01: Characteristics of Bituminous Materials, and A2D03: Characteristics of Bituminous-Aggregate Combinations to Meet Surface Requirements, on use of additives to improve the performance of asphalt cement should be very helpful in overcoming this problem. An effort to combine information from these activities is a high priority need.
CHAPTER ONE

INTRODUCTION AND BACKGROUND

As the mileage of limited-access high speed highways and overall traffic volumes increased in the 1950s and 1960s, vehicular accidents, injuries, and fatalities also increased. Efforts to control and reduce traffic accidents included development of procedures for measuring pavement surface friction, research on friction needs, requirements for safe vehicular operation, and techniques for providing surface friction. The reduction of wet-weather skidding accidents became a primary cooperative effort of committees of the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), the Transportation Research Board (TRB), the American Society for Testing and Materials (ASTM), and many individual state highway agencies. These efforts led to the recognition of pavement surface texture, aggregate microtexture, and water film thickness as major factors in wet-weather accidents.

Early efforts to improve the surface texture of asphalt concrete (AC) pavements included surface treatments (seal coats, chip seals, etc.) consisting of an application of asphalt cement, the spreading of cover aggregate (generally 3/8-inch top size), followed by rolling to embed the aggregate. This treatment, when done properly, was very effective in initially providing improved friction (skid resistance), but it had certain limitations. It sometimes was necessary to close the newly treated traffic lane for a period of time to permit the aggregate to be properly rolled and cured. Primarily under high speed traffic, the aggregate would become loose and could cause broken windshields and headlamps, particularly shortly after placement. Aggregate loss would result in reduced friction characteristics and in some cases, polishing of the aggregate had the same result.

In an effort to retain the benefits of the surface treatment friction courses and reduce the limitations and disadvantages, several state highway agencies began to experiment with mixing the normal chip seal aggregate with relatively high percentages of paving-grade asphalt cement in a hot-mix plant, and placing the mixture with an AC paver at a thickness of about 3/8-inch. This treatment became known as a plant-mix seal coat. The aggregate was essentially one size. This treatment contained a larger percentage of voids than conventional AC pavement layers because of the one size aggregate. It soon became apparent that the plant-mix seal coats provided improved friction characteristics without the disadvantages of the conventional seal coats, as well as other benefits such as reduced splash and spray, noise, and headlight glare. However, there were construction difficulties, maintenance problems, and concerns about long-term performance.

During the developmental stage of high friction surfaces by a number of highway agencies, a variety of descriptive terms was employed, such as plant-mix seal, popcorn mix, porous asphalt surface, and open-graded friction course. Throughout this synthesis, the terminology "open-graded friction courses" (OGFC) is used for all asphalt-aggregate pavement surface courses containing substantially larger percentages of voids than conventional AC surfaces. The primary objectives of the OGFC are to improve pavement surface friction characteristics and thus to reduce wet weather accidents, but ancillary benefits include reductions in splash and spray, noise, and headlight glare during periods of rain.

Experimentation with the design and construction of plant-mix seal coats led to FHWA research culminating in the 1974 publication, FHWA-RD-74-2, ”Design of Open-Graded Asphalt Friction Courses.” This was followed by FHWA Demonstration Project 10, "Improved Skid Resistant Pavements.” In 1976, AASHTO published Guidelines for Skid Resistant Pavement Design (1). In 1980, FHWA distributed “Skid Accident Reduction Program” (2), referencing a previous FHWA publication, “Open-Graded Asphalt Friction Courses,” 1980. The latest version (3), dated December 26, 1990, is included as Appendix A.

NCHRP Synthesis of Highway Practice 49, Open Graded Friction Courses for Highways, (4) published by the Transportation Research Board in 1978, contains a thorough review of OGFC research, development, and experience from the initial experimentation as a plant-mix seal coat through 1977. It describes mixture design procedures, construction techniques, maintenance concerns and activities, performance benefits, and limitations. Because a major objective of this study is to update the information in Synthesis 49 in the form of subsequent research and experience, a brief review of that Synthesis is found in Chapter Three.

STUDY APPROACH

The overall objective of this synthesis is to provide a comprehensive evaluation of the use of OGFC for wet-weather skid accident reduction on the nation's highways. This evaluation considers design and construction, performance benefits and limitations, maintenance and rehabilitation procedures and problems, and relationships with alternative procedures for providing highway pavement wet-weather friction characteristics. Accomplishment of the objective involved the collection and review of appropriate documents published since 1977; identification, collection and review of less formal sources of information such as unpublished reports of individual state experience; review of experience of other agencies outside the United States, particularly in European countries; and visits to and interviews with personnel of several state highway agencies in the northeastern and southeastern regions of the United States. The visits and interviews specifically included routine users of OGFC, as well as other states which have not used or have discontinued their use.
Because an extensive survey of state practices and experience with use of OGFC was conducted by the AASHTO Subcommittee on Construction in 1988 and the results distributed to the states, such a survey was not conducted during this project. A letter was sent to all states inviting submittal of copies of any reports and documents describing experience, practices, and policies concerning OGFC. Selected states were visited and personnel interviewed to obtain any available information that may not be documented. Northeastern states were selected as representative of a cold-wet climate and southeastern states as representative of a warm-wet climate. It is believed that cold-wet and warm-wet climate experience would be similar. OGFC are not generally used in dry climates.

Chapter Two of the synthesis contains a summary of the information collected and reviewed, followed by chapters describing in more detail the literature review, an AASHTO survey conducted by the Subcommittee on Construction in 1988, and state visits and interviews. Chapter Six contains an overall critical evaluation of the information collected and reviewed, plus the identification of current questions and concerns about the use of OGFC.
SUMMARY OF INFORMATION

Much information has been collected and reviewed pertaining to research and experience in the use of pavements surfaced with OGFC to improve the performance of roads in terms of service to the traveling public, particularly during wet weather conditions. The information was compiled from published and unpublished documents, twelve visits and interviews with state highway agency personnel, and the results of an extensive AASHTO questionnaire containing 51 responses. Of significant importance is Transportation Research Record (TRR) No. 1265, Porous Asphalt Pavements: An International Perspective 1990 (5), containing eleven papers describing the research and experience of seven European countries with the use of OGFC.

The OGFC information is summarized under the headings of (a) design and construction, (b) performance, and (c) maintenance and rehabilitation.

DESIGN AND CONSTRUCTION

The design of OGFC involves geometric considerations and requires an asphalt-aggregate mixture procedure that provides adequate voids and structural as well as environmental stability. The primary documents covering these considerations are "Pavement and Geometric Design Criteria for Minimizing Hydroplaning" (6), describing FHWA-sponsored research conducted by the Texas Transportation Institute and "Open Graded Friction Courses," FHWA Technical Advisory T5040.31 (3), included as Appendix A.

From a geometric standpoint, a pavement cross slope of at least two percent usually is necessary to ensure the effectiveness of OGFC under all but low intensity rainfall. The OGFC should be placed full width of the pavement and extend at least 3 ft onto the shoulder to drain surface water away from the traffic lanes and to maintain uniform surface texture (3). European experience (5) indicates that thickness of the OGFC should be a special consideration for multilane pavements and where abatement of traffic noise is a primary objective. When three or more lanes slope in the same direction, \( \frac{1}{4} \) in. thick OGFC can become flooded in all but low intensity rainfall, resulting in reduced effectiveness. According to European experience (5), OGFC up to 2 in. thick provide improved surface drainage and reduced traffic noise compared with the more conventional \( \frac{1}{2} \) in. thickness used in this country.

Detailed procedures for OGFC mixture design are included as an Attachment to FHWA Technical Advisory T5040.31, 1990 (3). It recommends use of high quality, polish resistant aggregate with at least 75 percent by weight of coarse aggregate having at least two fractured faces, and 90 percent with one or more fractured faces. The recommended gradation is as follows:

<table>
<thead>
<tr>
<th>U.S. Sieve Size</th>
<th>Percent Passing (by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>½ inch</td>
<td>100</td>
</tr>
<tr>
<td>¾ inch</td>
<td>95-100</td>
</tr>
<tr>
<td>No. 4</td>
<td>30-50</td>
</tr>
<tr>
<td>No. 8</td>
<td>5-15</td>
</tr>
<tr>
<td>No. 200</td>
<td>2-5</td>
</tr>
</tbody>
</table>

It has been noted that air void content of compacted OGFC ranges from 15 percent in the U.S. to 25 percent in European countries. Surface drainage capacity and efficiency are greater with increases in air voids and thickness. Use of 100 percent crushed aggregate enhances structural stability, particularly when thicker OGFC are used.

Durability is influenced primarily by asphalt cement film thickness and asphalt-aggregate resistance to stripping in the presence of moisture. A film thickness of 8 to 11 microns is recommended (3). Because the high voids content increases potential for stripping, the mixture should be tested for moisture susceptibility and, if necessary, anti-stripping additives used as appropriate.

OGFC should be placed only on structurally sound pavement with minimal cracks, ruts, depressions, or bleeding. The pavement surface must be sealed to force surface water to drain laterally through the OGFC rather than into the underlying base course. Other construction considerations include placing OGFC only when underlying surface and ambient temperatures are above 60°F, limiting handling and hauling to 40 miles or 1 hour to prevent drain down of asphalt, and controlling compaction to avoid aggregate crushing and reduction in voids content. The mixture temperature must also be considered (3), with care given to the effects of mixture constituent temperatures on the overall mixture temperature.

OGFC should not be placed directly over an existing portland cement concrete (PCC) pavement because it is difficult to establish an adequate bond between thin OGFC and the PCC surface. Lateral tire forces will result in bond failure and loss of the OGFC. When the rehabilitation of a deteriorated PCC pavement includes an asphalt concrete (AC) overlay, OGFC can be used as final wearing courses over the other AC layers.

PERFORMANCE BENEFITS

Substantial evidence indicates that properly designed, constructed, and maintained OGFC pavement surfaces provide the benefits described below.

Reduced Hydroplaning Potential

The void structure of OGFC permits internal drainage of water during rain storms, thus preventing the build-up of water
layers on the pavement surface that can produce hydroplaning and partial hydroplaning of vehicle tires at moderate to high speeds. The measure of internal drainage is the permeability of the mix and is influenced by the amount, size, and connection of air voids. The design air voids content of OGFC mixtures generally used in the U.S. is about 15 percent (4). The normal thickness of OGFC surfaces used in the United States is \( \frac{3}{4} \)-in. Most European countries use thicknesses of 1.5 to 2 in. and a void content of about 20 percent. Experience indicates that permeability and void content generally diminish under repeated traffic loadings for many OGFC surfaces.

High Wet-Weather Friction

Friction measurements with ribbed and smooth tires at 40 mph have shown that friction levels of OGFC surfaces are generally higher than those for dense-graded AC and PCC pavements and are less speed sensitive due to the combined effect of internal drainage and good macrotecture (4). At moderate to slow speeds, friction levels are influenced to a greater extent by the microtexture of the coarse aggregate in the mix. Some state highway agencies prefer to provide adequate pavement friction levels by the use of dense-graded AC surfaces with substantial macrotecture and careful selection of polish resistant aggregates. Some agencies have found that OGFC with a substantial reduction in air voids continue to have high levels of wet-weather friction due to macrotecture (7,8).

Reduced Wet-Weather Accidents

There is very little documented information on the influence of OGFC on wet-weather accidents and the relationship between accidents and friction numbers on OGFC and dense-graded AC pavement surfaces. Table 1 from a Connecticut study (9) and Table 2 from a Virginia study (10) provide evidence of high OGFC friction values. On two of four sections in Connecticut, accident rates were reduced after placement of OGFC, even though only police-reported accidents were recorded before the placement and both police-reported and operator-reported accidents were recorded on the sections after the OGFC were placed. On a section of U.S. 23 in Virginia with a high incidence of wet-weather accidents, an open-graded friction course was placed as a skid reduction measure. A survey of accidents one year before and one year after placement revealed that wet-weather accidents had been reduced from 39 percent (7 of 18) to 17 percent (2 of 12) of total accidents on the section (10). The personal observation of New York Thruway personnel is that an open-graded friction course placed on a detour eliminated a wet-weather accident problem area.

Reduced Splash and Spray

No other surface type provides the degree of reduced spray produced by vehicle tires during a rain storm (Figure 1). This spray is particularly annoying to motorists on heavily traveled high speed highways where trucks are a large percentage of traffic. The excessive spray reduces average traffic speed and increases congestion (5). Consequently, use of OGFC reduces traffic congestion during rain.

<table>
<thead>
<tr>
<th>TABLE 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE FRICTION NUMBERS ON VIRGINIA OGFC PAVEMENTS IN 1975 (10)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Route Number</th>
<th>Year of Construction</th>
<th>Vehicles per day per lane</th>
<th>Friction Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. 23</td>
<td>1972</td>
<td>900</td>
<td>66</td>
</tr>
<tr>
<td>U.S. 23</td>
<td>1973</td>
<td>900</td>
<td>66</td>
</tr>
<tr>
<td>U.S. 460</td>
<td>1973</td>
<td>2,650</td>
<td>64</td>
</tr>
<tr>
<td>U.S. 460</td>
<td>1973</td>
<td>2,200</td>
<td>60</td>
</tr>
<tr>
<td>U.S. 60</td>
<td>1972</td>
<td>450</td>
<td>57</td>
</tr>
<tr>
<td>U.S. 60</td>
<td>1972</td>
<td>450</td>
<td>72</td>
</tr>
<tr>
<td>U.S. 60</td>
<td>1973</td>
<td>2,000</td>
<td>54</td>
</tr>
<tr>
<td>U.S. 301</td>
<td>1974</td>
<td>3,700</td>
<td>54</td>
</tr>
<tr>
<td>U.S. 17</td>
<td>1973</td>
<td>2,950</td>
<td>58</td>
</tr>
<tr>
<td>U.S. 301</td>
<td>1973</td>
<td>1,050</td>
<td>60</td>
</tr>
<tr>
<td>U.S. 29</td>
<td>1973</td>
<td>4,300</td>
<td>60</td>
</tr>
<tr>
<td>1-81</td>
<td>1973</td>
<td>3,400</td>
<td>68</td>
</tr>
<tr>
<td>1-81</td>
<td>1974</td>
<td>3,250</td>
<td>60</td>
</tr>
<tr>
<td>VA-42</td>
<td>1973</td>
<td>1,800</td>
<td>66</td>
</tr>
<tr>
<td>U.S. 50</td>
<td>1973</td>
<td>1,300</td>
<td>51</td>
</tr>
</tbody>
</table>

The "Before" friction measurements were made just prior to the placement of the OGFC and the "After" measurements about 5 years after placement.
OGFC (Figure 3). Elements of noise suppression have been identified as reduction of noise developed by the tire-pavement interaction during vehicle travel, which is speed dependent, and absorption of noise by OGFC, which is not speed dependent. Sound absorption is influenced by void content and thickness of OGFC. European countries are using OGFC surfaces with about 20 percent voids and thicknesses of 1.5 to 2 in. with a primary objective of noise reduction in residential areas to minimize the need for noise barriers. There is a public perception that OGFC provide a smooth and quiet ride.

PERFORMANCE LIMITATIONS

The development and use of OGFC has not been a panacea for eliminating wet-weather skidding accidents. There are certain limitations and disadvantages that must be considered during the selection of an appropriate skid-resistant surface for a new construction or rehabilitation project.

Premature Raveling

Oxidation or hardening of the asphalt cement due to thin film thickness and air and water movement through the voids has caused early failure of the surface by raveling or removal by snow plows and traffic. FHWA Technical Advisory T5040.31 (3) recommends an asphalt film thickness of 8 to 11 microns to reduce oxidation. Experimentation with and use of various additives has reduced this problem. A recent development in Europe has been the addition of cellulose fibers to the mixture to substantially increase binder film thickness (5). Premature raveling can also be caused by stripping of the asphalt cement from the aggregate due to moisture susceptibility. All OGFC mixes should be subjected to a moisture susceptibility test during mixture design.

Snow and Ice Removal Problems

Although experience and opinions differ, there is consensus among maintenance personnel in northeastern states and European countries that the accumulation of snow, formation of ice, and action of de-icing chemicals are different on OGFC surfaces than on conventional dense-graded surfaces. It has been documented that the surface temperature of OGFC can be several degrees lower than other conventional pavements (5). During the early stages of a winter storm with dropping temperatures, this can result in differences in the timing of ice formation and the scheduling of de-icing procedures. The permeability of the OGFC can reduce retention of de-icing chemical solutions on the pavement surface and permit refreezing as precipitation continues. Several agencies have identified procedures for overcoming the difficulty described above, generally by increasing the frequency of de-icing chemical applications or mixing abrasives with chemicals, or both. The increased use of chemicals by two to three times normal usage is considered most effective on high traffic volume roadways and the abrasive/chemical mixtures appear to be effective on lower traffic volume roadways. The agencies, both U.S. and European, located in cold-wet climatic
regions that continue to use OGFC consider the benefits to outweigh the snow and ice removal difficulties.

**Increased Cost**

OGFC should be placed on a structurally sound AC paved surface. Existing PCC pavements must be overlayed with some type of AC course that has been sealed at the surface to provide for lateral drainage of water as it passes through the OGFC. Existing AC pavements should be resurfaced or milled to provide a structurally sound pavement free of ruts, potholes, and cracks, and sealed at the surface prior to the placement of an OGFC. These actions, plus the fact that most state highway agencies do not consider any structural contribution of the OGFC, can result in an increase in cost of about $1.25 /yd² in 1990 prices. This cost increase may not be justified on projects being designed for low traffic volumes and speeds, and where precipitation levels are relatively low. Some agencies find that surfaces with adequate skid resistance can be designed, constructed, and maintained by emphasizing surface macrotexture and careful selection of coarse aggregates.

**Permeability Deterioration**

Substantial experience indicates that the permeability of many OGFC surfaces decreases with time and traffic. Some agencies base the lack of OGFC use on this type of experience. Others have deviated from OGFC mixes by increasing the fines content and placing emphasis on surface macrotexture rather than permeability. Such surfaces are actually gap-graded AC rather than OGFC mixtures. The European approach is to place the OGFC initially with 20 to 22 percent air voids resulting in a very high permeability that will continue to provide adequate internal drainage, even though some deterioration may take place.

**Deterioration of Underlying Layers**

This has been a severe problem in areas where local aggregates generally used in base course layers are susceptible to water-induced stripping and has resulted in a moratorium on the use of OGFC in some states. Ideally, a sealant beneath the OGFC layer should prevent downward movement of water and thus protect the underlying layers. However, sealants are not 100 percent impervious. The problem is being alleviated in some
states by the addition of lime or other anti-stripping material to the mix of the underlying layers, and increasing the emphasis on placing a high quality sealant beneath the OGFC.

MAINTENANCE AND REHABILITATION

As indicated previously, OGFC pavement surfaces can be designed and built to perform satisfactorily and provide certain benefits. However, limitations and problems have been identified. With approximately 60,000 lane miles placed and 27 state highway agencies continuing their use at the time of the 1988 AASHTO survey, long-term maintenance and rehabilitation of OGFC must be addressed. Although little long-term maintenance and rehabilitation experience has been documented at this time, the following observations are made based on the information collected and reviewed during this study.

- Experience with the use of fog sealants to deter asphalt cement hardening has been mixed. Some agencies continue the practice but the Florida DOT (a major OGFC user) has not found fog sealants to be effective in extending OGFC service life.
- A primary concern of maintenance personnel is the need for patching OGFC because of petroleum spills, depressions resulting from snow plow activity and other equipment, and local areas of bleeding and shoving. Use of available dense-graded patch material is generally required, at least as a temporary patch. The desirable practice is to mill out these patched areas and place OGFC mixtures when such material is being produced in the area for a construction project.
- Maintenance personnel should be aware of the need to preserve the lateral drainage capability of OGFC. Consequently, the edges of patches should not be sealed and shoulders along OGFC should not be resurfaced or sealed in a manner that will disrupt the lateral drainage. Crack and joints should not be sealed in a manner that will deter the lateral movement of water through the OGFC. Only transverse cracks and joints should be sealed.
- Currently available information indicates that an open-graded friction course is likely to have a service life of 8 to 12 years. Replacement of the surface may be required even though the pavement is structurally adequate. Opinions collected during this study suggest that new OGFC or dense-graded AC surfaces should not be placed directly on deteriorating OGFC.

The practices currently preferred for rehabilitation of OGFC at the end of their service life are (a) mill off the OGFC with equipment that will produce a smooth surface, place a seal/tack coat, and place new OGFC; (b) mill to just below the existing OGFC, place a dense-graded AC course of about 1.5 in. thickness, place a seal/tack coat, and place new OGFC; (c) mill to 1.5 to 2 in. below the existing OGFC, place a dense-graded AC course of the desired thickness for structural adequacy, place a seal/tack coat, and place new OGFC. The material removed by milling can be used as recycled asphalt pavement (RAP) but should not be used in the new OGFC.
CHAPTER THREE

LITERATURE REVIEW

A search of the Transportation Research Information Service database was conducted for all items on OGFC dated after 1977. A total of 20 studies were identified as sponsored by the FHWA, state highway agencies, and foreign agencies. Comments in the abstracts were generally favorable concerning performance of OGFC. However, some inconsistencies were reported, particularly regarding friction values and life expectancy.

SUMMARY OF MAJOR DOCUMENTS

Several research projects relative to OGFC performance have been completed since 1978. A synopsis of the essential findings of Synthesis 49 and other major studies since its publication are included in this section.

NCHRP Synthesis of Highway Practice 49: Open Graded Friction Courses for Highways (4)
This document, published in 1978, describes the early development of OGFC and the substantial experimentation and initial use from the 1940s to 1978. Early users generally agreed on the following advantages of OGFC:

- Hydroplaning potential during rainstorms is reduced.
- Skid resistance at high speeds during wet weather is improved.
- Splash and spray are reduced.
- Headlight glare during wet weather is reduced.
- Traffic noise levels are reduced.
- Traffic can be allowed earlier than with chip seals.

At the time of the synthesis preparation, 15 state highway agencies used OGFC as standard practice during both new construction and rehabilitation or reconstruction of existing AC pavements. Several additional states were considering such practice. A number of states had expressed concern about the durability of OGFC, but failures of such surfaces had not been widely reported at that time. A large portion of the mileage that had been constructed at that time was less than six years old. Most failures reported were attributed to poor mixture design and construction practices. The FHWA OGFC Design Procedures had recently been released and were included in the report appendix.

Several concerns and research needs were identified during collection of information for Synthesis 49; these are summarized as follows:

- Role of OGFC in Minimizing Hydroplaning Dangers During Heavy Rainfall: Calculations using conceptual models indicated that rainfall in the range of one inch per hour would inundate the OGFC, making it ineffective. However, it was noted that because of the surface macrotexture tire-pavement contact can continue. At the time of preparation of Synthesis 49, the FHWA was supporting studies at the Texas Transportation Institute to document the potential of OGFC for minimizing hydroplaning. (These studies are described in references 7, 8.)
- Optimum Gradation of OGFC for Skid Prevention: Most states were using a nominal aggregate top size of 3/16-inch. The most significant differences were in the amounts passing the No. 8 and No. 200 sieves. Some states required more of the finer material to provide stability of the mix while others required less, placing major emphasis on providing voids in the mix to encourage internal drainage. The synthesis suggested further research to determine an optimum gradation.
- Optimum Asphalt Content and Grade for Maximum Durability: Voids in OGFC permit entrance of water and air that accelerate asphalt hardening. It was determined that the asphalt film thickness on the aggregate particles is the predominant factor in the rate of asphalt hardening. Studies of additives to reinforce and encourage increased film thickness were suggested.
- Effect of OGFC on Winter Maintenance Techniques: Highway agencies surveyed expressed different opinions as to whether OGFC surfaces were more difficult to maintain in a safe condition during ice and snow storms than conventional dense-graded AC surfaces. This was the primary concern expressed by northern states. The rates of de-icing chemical applications and the possible effect of abrasives on the OGFC void structure and drainage capability were determined to merit study.
- Noise Levels for OGFC: Because of greater macrotexture, some concerns were expressed that noise levels for OGFC may be higher than for other surface types. Early studies included in Synthesis 49 indicated that noise levels for OGFC surfaces were lower than for dense-graded AC and PCC surfaces. However, further investigations were recommended.

FHWA Report No. RD-79-30 “Pavement and Geometric Design Criteria for Minimizing Hydroplaning” (6)
This report describes in detail research conducted over several years by the Texas Transportation Institute on tire-pavement interaction in the presence of water. Laboratory and full scale field tests were conducted for a variety of roadway conditions to evaluate the hydroplaning phenomenon. Conditions studied included pavement texture, cross slope, and internal drainage of OGFC. About 4,000 tire-pavement interaction tests on four laboratory-designed OGFC pavement sections with air void contents at 15 to 25 percent were conducted during the study. The performance of OGFC was also studied under natural rainfall conditions at five test sites in Texas. Several significant findings of these studies are:

- OGFC offers a means of providing pavement macrotexture levels generally higher than current dense-graded AC surfaces,
- Friction values of OGFC are less sensitive to speed than other surfaces,
- Sealing the shoulder area adjacent to an OGFC will disrupt lateral drainage from the OGFC and reduce its effectiveness,
- A pavement cross slope of two percent is necessary to provide effective performance of OGFC under all but low intensity rainfalls, and
- The data showed conclusively that a combination of two percent cross slope and a properly designed and constructed OGFC, coupled with appropriate geometric design, furnishes the driving public with the best known condition for high pavement friction during wet weather.

**FHWA Report No. RD-89-100 “Patching of Open-Graded Friction Courses” (11)**

This report lists the most common failure modes of OGFC and practices for repair and patching of failed areas as identified by review of literature and interviews in selected state highway agencies. Failure modes were reported as raveling, delamination or loss of bond, and distress in the underlying pavement. Raveling frequently results from improper mixture design, placement during cold or wet weather or both, and oxidation over time. Loss of bond may also result from placement during cold and/or wet weather and from improper application of the tack coat. OGFC placed over portland cement concrete (PCC) pavement frequently failed due to loss of bond. An intermediate AC layer over PCC pavement is recommended before placement of OGFC. Fog sealants are reported as used by some states as a preventive maintenance activity at the first sign of raveling. This may delay raveling, but can reduce lateral drainage efficiency.

Spot failures of the OGFC result in the need for patching to preserve the integrity and serviceability of the surface. However, it was found that maintenance forces generally did not have access to OGFC mixtures, equipment, and procedures for the placement of such patches in a timely manner. Consequently, patches are usually placed with readily available dense-graded hot-mix and cold-mix AC materials. Disadvantages of such patches include discontinuity of the pavement surface with partial loss of OGFC benefits and limited service life. The study recommended use of skid resistant mixtures for patches over 20 ft in length.


This document (included herein as Appendix A) replaces FHWA Technical Advisory T5040.13, “Open Graded Asphalt Friction Courses,” January 1980. It explains that, “Open graded friction courses constructed with high quality, polish resistant aggregates have an outstanding capacity for providing and maintaining good frictional characteristics over the operating range of speeds on high speed highways. Their macrotexture facilitates drainage of water from the tire-pavement interface, improves tire contact with the pavement, and reduces the potential for hydroplaning.” Advantages of OGFC surfaces are listed as:

- Improving wet weather night visibility of pavement markings, and
- Conserving high quality, polish resistant aggregates when placed as thin surface course.

Limitations are listed as:

- Increasing potential for stripping of underlying pavement,
- Requiring special snow and ice control methods,
- Requiring special patching and rehabilitation techniques,
- Providing no structural value to the pavement, and
- May not perform satisfactorily at locations with extensive turning movements.

Environmental conditions, alignment, accident rates, and desired frictional requirements should be considered in selecting OGFC for any location. To perform as intended, they must be properly designed, constructed, and maintained. OGFC should only be placed on structurally sound pavements with minimal cracks, ruts, bleeding, and depressions; the underlying pavement should be sealed with a 50 percent diluted asphalt emulsion; coarse aggregates should be polish resistant and at least 75 percent (by weight) of particles with at least two fractured faces and 90 percent with one or more fractured faces; mixes should be designed in accordance with updated procedures in FHWA T5040.31; one ounce of silicone should be added to each 5,000 gal. of asphalt cement; the course should be placed only when pavement and ambient temperatures are 60°F or above; it should be placed full width and extend at least 3 ft onto the shoulder; handwork should be minimized; and maintenance should avoid any activities which may obstruct the lateral flow of water.

**NCHRP Synthesis of Highway Practice 104, Criteria for Use of Asphalt Friction Courses (12)**

The primary purpose of OGFC is to provide pavement surface characteristics that will improve safe vehicle operation, particularly during wet weather conditions. This report identifies the four factors that influence wet-weather accidents as (a) vehicle, (b) driver, (c) road, and (d) weather. The road contributions to reducing wet-weather accidents are adequate pavement friction levels when wet and the ability to drain quickly during and after rainfall.

In 1980, the FHWA issued Technical Advisory T5040.17, “Skid Accident Reduction Program” (2), describing the factors that should be considered to minimize wet-weather skidding accidents. The Advisory is included as an appendix in Synthesis 104. The advisory recognizes OGFC as an excellent pavement surface for high levels of friction and drainability.

General criteria for selection of a friction course should include the use of (a) seal coats for secondary and low traffic volume roads; (b) OGFC for primary highways with high traffic volumes to provide excellent wet-weather friction characteristics, minimize hydroplaning, and reduce splash and spray; and (c) dense-graded AC surfaces for primary highways with high traffic volumes where adequate friction levels can be produced and maintained. The report points out that the national speed limit of 55 mph in effect at the time had reduced the danger of hydroplaning and that attention had been given to designing dense-graded surfaces with optimum macrotexture to provide good friction.
NCHRP Report 184, Influence of Combined Highway Grade and Horizontal Alignment on Skidding (13)

Although not directly related to OGFC, this report does contain significant information concerning the relationship between pavement surface drainage and wet-weather accident experience. Pavement width and cross slope are the primary factors affecting surface drainage. The thickness of water film on a multilane roadway curve with paved shoulders all sloping in the same direction can be twice that of a crowned tangent section with the same cross slope. Partial tire hydroplaning (reduction of tire-pavement friction as opposed to full hydroplaning with complete loss of tire-pavement interaction) is the resulting adverse effect of excessive water film thickness. Two high wet-weather accident rate sites that were investigated were found to be multilane roadways on one degree curves with all PC concrete paved lanes sloping in the same direction at a cross slope of 0.0156 ft/ft.

NCHRP Synthesis of Highway Practice 158, Wet Pavement Safety Programs (14)

Published in 1990, this synthesis contains the results of a very comprehensive survey of 50 state highway agencies on accident reporting, friction testing, procedures for correction of low friction, and design of AC pavements with adequate friction. All agencies reported having accident record systems, and most have operational pavement friction testing programs. However, the criteria used to evaluate friction test results have little uniformity. Policies do exist in 60 percent of the agencies for some type of evaluation but only 10 agencies have designated time periods for corrective actions. Most of the agencies indicated that requirements exist for obtaining adequate friction for new pavement construction. Eleven states specifically noted the use of OGFC on new AC pavements and 10 others indicated use of special mix design procedures to reduce wet-weather accidents. Procedures for corrective actions were generally rated as signing, grinding, grooving, and resurfacing. The questionnaire was not intended to identify types of resurfacing during rehabilitation.

INDIVIDUAL STATE HIGHWAY AGENCY REPORTS

Because an AASHTO survey on use of OGFC was conducted in 1988, no detailed questionnaire was circulated to state highway agencies during preparation of this synthesis. However, each state was requested to submit documentation of field experience and current policy concerning use of OGFC. The responses summarized below reflect state experience as it was described in the reports submitted.

Arizona

OGFC have been used extensively by Arizona DOT (15). The reasons for their use are listed as good skid resistance, rideability, and appearance. At the time of the response, 95 percent of Interstate pavements were surfaced with OGFC and for non-Interstate, the amount was 26 percent. A seal coat surface is preferred for good skid resistance on lower traffic volume rural pavements. A dense-graded AC surface is preferred in urban areas with traffic signals and a speed limit of 45 mph or less.

INTERSTATE - ACFC*

NON - INTERSTATE

Urban with Traffic Signals and Speed Limit 45 MPH or less

DENSE AC PREFERRED

Steep Grades 4% or More

TRAFFIC**

5,000 ADT

2,000 - 5,000 ADT

ACFC

ACFC OR SEAL COAT

2,000 ADT

SEAL COAT

* Above 6,000 foot elevation consider asphalt rubber or polymer as the binder.

**For those Non-Interstate Highways above 6,000 foot elevation an ACFC is generally discouraged.

FIGURE 4 Arizona DOT Surface Treatment Selection Policy.

The surface treatment selection guidelines are shown in Figure 4. The terminology for OGFC in the Arizona guidelines is Asphalt Concrete Friction Course (ACFC).

Arkansas

The Arkansas State Highway and Transportation Department's internal report dated May 1990, "A Performance Evaluation Summary of Open Graded Friction Course in Arkansas" (16), describes the performance and maintenance experience obtained from 65 projects. The report indicates that, except for a brief period after construction, the OGFC did not provide significant enhancement of skid resistance, reduction of hydroplaning potential, or reduction of vehicle spray. The most serious problem was raveling, which caused a major increase in windshield and headlight breakage. One of several specific examples is that on the westbound lanes of a section of I-40, there were 87 claims for broken windshields in a single year, resulting in payments by the state of more than $43,000. It is likely that the actual number of damaged windshields was higher.

Connecticut

The Connecticut Department of Transportation provided copies of two reports, "Performance of an Open-Graded Bituminous
Concrete Overlay,” October 1978 (7) and “Performance Observations on Open-Graded Bituminous Concrete Overlays in Connecticut,” May 1981 (9).

The first document includes initial observations of OGFC test sections placed in 1975 on I-91 PCC pavements. It was noted that the OGFC sections were susceptible to gouging by snow plows, and absorption of rainwater was diminishing, yet friction characteristics remained high. For the one-year period prior to placement of the OGFC, four wet-weather accidents were recorded, and for the one-year period after placement, two wet-weather accidents were recorded, one of these being caused by a heavily intoxicated driver.

Performance data over a six-year period are presented in the second document for OGFC overlays of PCC pavements on Interstate highways with traffic volumes in excess of 20,000 vehicles per day. Most sections involved the placement of a 2-inch dense-graded AC layer over the PCC with the OGFC placed on the dense-graded layer. However, several OGFC sections were placed on the PCC pavement with only a sand-asphalt scratch coat between. These sections failed rather early by loss of bond. Friction numbers at 40mph (FN40) stabilized at values of 40 to 50, irrespective of lane or traffic volume. Air permeability tests indicated a choking of the void structure with time. Wheel path rutting was minimal after six years of heavy traffic for both 2-in. and 1.5-in. OGFC. “Before” and “after” accident records for two sections were analyzed to evaluate the effect of OGFC on accident rates. As indicated in Table 1 in Chapter Two, accidents per million vehicles decreased after placement of the OGFC on the I-91 sections but increased on the I-95 sections. However, prior to placement of OGFC, only police-reported accidents are included in the records. The records after OGFC placement include all police and operator-reported accidents. The general indication is that accident rates are lower after OGFC placement. There is no actual indication in the report of the number of accidents that occurred during wet weather.

Florida

Technical Report 90-4, “Open Graded Friction Courses—Florida's Experience,” (17) was prepared by the Florida Department of Transportation. It reports that, beginning in 1973, it has been the policy of the department to require OGFC on all multilane highways with a posted speed greater than 45 mph. The combination of substantial volumes of tourist traffic, the frequent occurrence of high intensity rainfall, together with the need for efficient vehicular travel and safety are primary considerations for this policy. Motorists driving on OGFC surfaces seem less likely to slow down or pull off highways during rain storms, a frequent cause of wet-weather accidents.

Although accident statistics are not available, friction characteristics of OGFC at high speeds during wet weather have been verified by measurements with a locked wheel friction tester at both 40 mph and 60 mph. Friction characteristics of PCC and dense-graded AC pavements decrease with increasing speed but remain stable on OGFC. Also, the general public perception is that OGFC provide a smooth riding pavement with reduced noise levels. Some problems have been experienced but they have been overcome. Controls are required for the mixture design and construction procedures to prevent isolated spots with excess asphalt. Storage of the mixture in surge bins is limited to one hour. The OGFC are placed at a maximum thickness of 2-in. Florida has not experienced moisture damage in underlying layers reported in other areas of the country. Service life of OGFC is 10 to 12 years while the pavement structure has a service life of more than 15 years. Rehabilitation involves milling and replacement of the OGFC. The Florida DOT average bid price in 1990 for OGFC was $1.25/yr² for the specified 2-in. thickness. Improvements in properties of the asphalt binder by use of additives appear to hold promise for increased performance. An excerpt from the Florida DOT Flexible Pavement Design Manual for New Construction and Pavement Rehabilitation is included as Appendix B.

Kansas

The Kansas Department of Transportation provided a report titled, “Open Graded Asphalt Friction Courses, Final Report,” December 1986 (18). The report describes the construction and performance of seven test sections using various aggregates and mixture designs. The test sections were built in 1974 and data were collected through 1982, at which time all sections had been overlayed. All sections performed satisfactorily during their service lives, maintained excellent surface friction properties, and resulted in reduced spray and hydroplaning potential during rainstorms. However, by use of selected aggregates, friction characteristics of adjacent dense-graded AC surfaces were also good. Economic justification for reduced wet-weather accidents is only applicable in the northeastern part of Kansas (the most heavily traveled part of the state) based on annual rainfall and evaporation rates. Problems were encountered with the development of frost on some OGFC when the adjacent sections remained clear, and the open texture tended to trap snow and ice, requiring additional salt applications. These problems were confirmed by laboratory investigations. The report suggests consideration of using appropriate percentages of polish resistant aggregates in dense-graded AC mixtures to provide the desired surface friction.

Louisiana

A report entitled “Asphaltic Concrete Friction Course Survey” (8) was sent from the Louisiana State Department of Transportation. Beginning with experimental OGFC in 1970, and regular use after 1973, approximately 4,000 lane miles of OGFC have been placed in Louisiana. These surfaces performed well until the relatively severe winters of 1982–1983 which resulted in reports of extensive wheel path raveling. A field study of 40 OGFC projects in three districts was conducted to document the extent of the problem. The sections contained expanded clay, gravel, and slag aggregates, and were divided into 2- to 4-year and 6- to 8-year age groups for the evaluation. Regardless of aggregate type, the 2- to 4-year sections were observed to have little or no raveling and continued to have mostly open to slightly closed texture. The texture of the 6- to 8-year sections was mostly closed and raveling in the wheel path was observed to be 1 to 10 percent by area. After a second severe winter in 1983–1984, and continued field complaints and pavement section failures, a moratorium was placed on use of OGFC in new construction.
Maryland

The Pavement Design Criteria of the Maryland State Highway Administration (19) for use of OGFC (Plant Mix Seal) dated December 7, 1989, is included as Appendix C. According to this document, "the primary function of a Plant Mix Seal (OGFC) is to minimize hydroplaning potential during rainstorms. Additional benefits include reduced noise levels and spray back. A relatively uniform particle distribution is used with the maximum size aggregate of 1/2-in. Plant Mix Seals will be placed on roadways where truck volumes are equal to or greater than 500 per day in the fifteenth year and where the posted speed limit is 50 mph or greater. Plant Mix Seals will be assigned a structural value of 1/2-in. of AC and will be placed on an AC surface course only."

As a result of the general practice of using OGFC on new construction, there have been approximately 140 OGFC projects in the state since 1972. However, in the winters of 1989-1990 and 1990-1991, there was rapid deterioration of many OGFC projects in the form of raveling and the complete loss of the OGFC over large areas of the pavement surfaces as shown in Figure 5. Revised OGFC mixture design and specifications were adopted in 1988. Early in 1991, a decision was made to discontinue the use of OGFC until a thorough investigation can be completed, and it can be determined whether the 1988 mixture designs have corrected any deficiencies. The state is evaluating the 1988 mixture design with a polymer additive, and placed an OGFC surface as part of the reconstruction of a section of I-495 during the summer of 1991.

Michigan

A report, "Michigan's Experience with Open-Graded Asphalt Friction Courses," (20) was prepared in 1987 by the Michigan Department of Transportation. The report provides design and performance information for 18 OGFC resurfacing projects throughout Michigan, including five on airport runways. Most of the surfaces have performed quite well, but there have been enough failures to contribute to the learning experience. Because of their ability to drain surface water rapidly, OGFC surfaces are particularly appropriate for high speed highways and for airport runways. In areas where traffic moves more slowly, there appears to be little reason for their use. The report states that OGFC (a) should never be placed directly on a PCC pavement; (b) should not be placed directly on an AC layer with a high void content, and (c) should not be placed in layers less than 100 lb/yd² (1 1/4 in. thickness). To avoid premature raveling, latex-rubber admixture in the proportion of three percent rubber solids of the total placement weight has proven beneficial. During a study on the use of de-icing chemicals on OGFC, Michigan experienced little difference between OGFC and dense-graded AC. In the most northern Michigan district, where sand is mixed with de-icing chemicals for winter maintenance, the OGFC are reported to be in excellent condition and still providing good drainage. The report also indicates that airport officials are particularly pleased with the performance of OGFC.

New York

"Open-Graded Asphalt Surface Course Mix Types 10F and 10FX," is included in the New York State Department of Trans-
for presentation at the 1991 meeting of the Association of Asphalt Paving Technologists. The preferred surface course for new AC pavement construction and structural overlays during rehabilitation is designated the Class F mix. The nominal maximum aggregate size is 1 inch. It is placed as a 1.5- to 2.0-in. surface course and is considered an OGFC. Oregon DOT also has a Class E mixture, with a maximum aggregate size of \(\frac{3}{4}\) in. in a 1-in. nonstructural overlay, used to improve friction and hydroplaning resistance. A performance evaluation was completed involving ten projects constructed with the Class F mix and seven projects constructed with dense-graded AC surfaces. All sections were built in the 1984–86 period, have been subjected to 155,000 to 2.0 million equivalent single axle loads (ESALs), and are located in the same geographic areas. The OGFC sections provided improved friction characteristics and resistance to cracking and rutting over the dense-graded AC sections. Typical void levels in the OGFC after five to six years service ranged between 10 and 13 percent. Substantial reductions in splash and spray during rain were observed on the OGFC sections. Attempts to measure noise levels did not differentiate between the two surface types. The evaluation supports continued use of the OGFC.

EUROPEAN EXPERIENCE

Transportation Research Record No. 1265, Porous Asphalt Pavements: An International Perspective, 1990 (5) contains 11 papers describing the research and experience of seven European countries with OGFC. These papers were presented at the 69th Annual Meeting of TRB in January 1990. The sessions were conducted jointly by TRB and the Permanent International Association of Road Congresses (PIARC). Extensive research work is described in the 100 page document, some of which is summarized here.

OGFC surfaces have been used in many European countries for more than ten years and, based on research and experience, the use continues to expand. They are normally placed in thicknesses of 40 mm to 50 mm (1.5 to 2 in.) or about double the average thickness of OGFC surfaces in the United States.

Belgium

OGFC are used on roads, airfields, and in tunnels. In rainy weather, this results in the absence of hydroplaning, increased skid resistance, and reduced splash and spray. Additional advantages are reduced noise, light reflection, and rolling resistance. The Belgium Road Research Centre has conducted extensive research on OGFC performance, design, and construction, and limitations. Current practice is to design OGFC with about 22 percent voids and place the mixture at a compacted thickness of about 40 mm (1.5 in.). Particular benefits are noted on wide pavements, changes in super-elevation, sags in longitudinal profile, and hilly regions. These surfaces are also used in urban areas and tunnels to reduce traffic noise by as much as 6 to 10 dBA.

The paper notes that OGFC should not be used on low traffic volume or slow speed roads, or farming areas where dirt and mud are often tracked onto the pavement, because of the lack of sufficient self-cleaning by traffic, or in locations subjected to very high tangential loads. Differences have been noted in the formation of icy conditions on OGFC and conventional surfaces. However, the differences are not considered to be an underlying cause of accidents. A unique practice in Belgium is the placement of a surface dressing (sealant coat) on the surface of an OGFC paved shoulder to prevent clogging and maintain permeability. A joint Dutch and Belgian effort has developed a cold-laid porous asphalt mixture for patching and maintenance repairs. The paper in TRR No. 1265 (5) contains no details of the mixture design.

To maintain reasonably high binder contents and film thicknesses without the binder draining from the mixture during hauling and placing of OGFC, a small amount of asbestos fibers has been successfully added to the mixture in Belgium. Because the use of these mineral fibers is now prohibited by Belgian law, research is being conducted using cellulose fibers. Laboratory tests appear promising. Higher binder contents with as little as 0.3 percent cellulose fibers result in less loss of binder by drainage than mixtures with lower conventional asphalt binder contents. The voids content of the OGFC mixture with 5.5 percent fiber modified binder is equivalent to the mixture with 4.5 percent binder without the fiber. The higher binder content is expected to improve durability. Full scale road test sections were placed in 1988 and are under observation.

France

After ten years of research and experimental use, OGFC are being applied to solve hydroplaning, splash and spray, traffic noise, and night driving glare problems. Of particular interest is the theoretical and experimental research on noise reduction characteristics of OGFC surfaces. Models were developed to describe the acoustical properties of OGFC pavements in terms of a noise absorption coefficient. Experiments have been conducted in the laboratory and on a circular test track to verify the models. It has been determined that traffic noise levels on OGFC of 40 mm to 50 mm (1.5- to 2-in.) thickness are 3 to 6 decibels (dBA) lower than on dense-graded asphalt concrete depending on reflection paths and surface thickness, reducing the need for noise barriers and increasing uses in urban areas.

Another research effort conducted in France involved the performance comparison of four OGFC mixtures on a circular test track to demonstrate the influence of mixture design on stability. A total of 1,100,000 wheel passes were applied to the sections. All OGFC mixtures were produced with high voids and porosity and used the same aggregate source. The binder for one mixture was pure asphalt cement, two contained an elastomer modifier, and the fourth was a pure asphalt cement with mineral fibers. (No specific description was provided for the mineral fibers.) Three mixtures contained 4.5 percent asphalt binder, compared to the mixture with mineral fibers which contained 6.0 percent. This mixture performed better than the others in terms of retention of voids and permeability and minimization of rutting (Figure 6). Research and experience in France has also shown that rubber-modified OGFC mixtures permit increased binder content and produce improved long-term performance (years of service prior to being replaced) while maintaining the other OGFC advantages.

Italy

OGFC have been used extensively on Italian motorways to reduce traffic noise, improve skid resistance, reduce hydroplan-
Binders:
(1) Asphalt cement
(2) Elastomer-modified asphalt cement
(3) Elastomer-modified asphalt gradation and modified aggregate gradation
(4) Asphalt cement with 1% fibers

FIGURE 6 French test track performance of OGFC mixtures (from 5).

...ing, and eliminate splash and spray. Very comprehensive research (laboratory tests and field experience) has been conducted on the theory of sound-absorbing properties of OGFC. Some of the important implications of this research are:

- The sound-absorbing effect is not linked to vehicle speed, confirming beneficial use in urban areas.
- Use of OGFC could influence the design and height of noise barriers.
- Additional research could improve the sound-absorbing characteristics of OGFC.

It has also been observed in Italy that, on several motorways paved with OGFC, snow adheres more easily and lasts longer. Studies were conducted to determine the physical process that results in the formation of ice on OGFC and to analyze the phenomenon by means of laboratory tests. An important finding was the documentation that OGFC pavements cooled more rapidly because of high porosity and surface area. Consequently, ice and snow removal may require up to three times the amount of salt used on dense-graded pavements. Research is continuing to devise improved ice removal treatments, including the consideration of using liquid chloride applications.

Netherlands

Research has been conducted since 1972 to assess the advantages and limitations of OGFC (known as porous asphalt wearing courses). The primary advantages to road users have been found to be improved safety, reduced congestion, and reduced noise. Reduced congestion on heavily traveled motorways in urban areas is based on the ability to maintain close to normal traffic speeds during rainfall due to reduced splash and spray. Additional costs are incurred with the use of OGFC because of shorter service life (10 years compared to 12 years for dense-graded AC) and increased maintenance costs, particularly for snow and ice removal. On the basis of a cost-benefit analysis, the Dutch Department of Public Works has decided that OGFC shall be applied on busy motorways with an average of more than 35,000 vehicles per day, on limited-access highways prohibited to slow moving traffic, and on highways with a recognized noise problem, resulting in use of OGFC on about 100km (62 mi.) of motorways per year. The layer thickness is normally about 50mm (2 in.) to provide adequate drainage within the OGFC.

Spain

The first applications of OGFC in Spain were in 1980 to improve traffic safety in areas of frequent rainfall. Beginning in 1986, OGFC were used more extensively, and now the use has expanded to provide a smooth, safe, and quiet ride in any type of weather for all types of traffic conditions and roads. OGFC are used as the top layer of new pavements and as the primary repair surface for aged or slippery surfaces without structural problems. Care is exercised before selection of OGFC in areas of frequent snowfall, urban and industrial areas where extensive abrasion or oil spillage occurs, bridge decks, and areas having moderate to severe reflective cracking. Earlier applications used mixtures with 15 to 18 percent voids. Current practice is to use mixtures with voids content over 20 percent, and there is a trend toward use of modified asphalt binders to increase binder film thickness. The concern for durability was addressed by the study of polymer-modified asphalt binders in comparison with conventional binders to increase film thicknesses. Both laboratory and field investigations were conducted. The laboratory studies provided evidence that the polymer-modified binder was more effective than conventional binder in resisting deformation and disintegration, increasing adhesion, and reducing drain down during construction handling. Field investigations of sections in place about two years are verifying the laboratory study findings. Use of the polymer asphalt binder permits the attainment of thicker binder film and larger percent voids with prospects for increased durability and retention of permeability.
Switzerland

The first open-graded friction course placed in Switzerland was on an airport runway in 1972. The use on roads began in the late 1970s. A research study was begun in 1982 to determine long-term behavior under normal traffic conditions. A total of 17 OGFC pavement sections with thicknesses of 1.0 to 2.0 in. are being studied. A polymer-modified asphalt is generally used as the binder. Primary considerations of the study are skid properties, permeability, traffic noise, and behavior under winter conditions. The essential findings of the initial four years of this ongoing study are described. Experience on rural motorways is considered good so far. The excellent quality of surface drainage reduces risk of hydroplaning and sight-disturbing spray. Permeability is maintained by the suction action of high speed traffic, noise is significantly reduced, and winter maintenance can be controlled. In urban areas, the experience has not been as good. Drainage at the edge of the OGFC layer is often obstructed, permeability is reduced by clogging, friction properties are not always adequate, and the reduced permeability results in a loss of noise benefits.

The noise measurement portion of the study is very comprehensive and has produced one significant finding: Besides generally reducing noise levels, use of OGFC can result in significant reduction of the particularly disturbing higher sound frequencies. For this reason, it has been possible to obtain positive reactions from road neighbors even with rather limited reductions in measured noise levels. Friction measurements were made on OGFC and dense-graded surfaces during several winters in an attempt to quantify any differences. Although winter road conditions are generally quite variable, it was found that variations in friction values for OGFC were within the variations observed for conventional pavements. It was observed that the good drainage and macrotexture of OGFC surfaces was advantageous during periods of snow and slush. However, there is a tendency for snow to stick sooner on OGFC because of more rapid cooling. Also, more extensive use of de-icing salts is required and concerns are expressed regarding the use of abrasives such as sand.

United Kingdom

The Transportation and Road Research Laboratory (TRRL) of the United Kingdom first adopted OGFC more than 20 years ago to reduce splash and spray, but use has not been extensive because (a) the spray-reducing properties were found to deteriorate with time and (b) aging of the asphalt resulted in early disintegration of the surface. Because the OGFC has considerable potential for reducing traffic noise, efforts are underway to evaluate the effectiveness of polymer modified asphalt binders to improve durability and performance. Test sections were constructed on a heavily trafficked dual carriageway in 1984. Results of acoustical measurements during the first four years of the study are reviewed. Noise levels adjacent to the new OGFC were reduced by 4.0 to 5.5 dBA compared with conventional nonporous surfaces. After four years of exposure to heavy traffic, the noise reductions continued to average 4 dBA.

Report on the 1990 European Asphalt Study Tour(23)

A report presented during TRB's 70th Annual Meeting in January 1991 described the observations of a team of 21 participants during a two-week tour of six European countries (Denmark, France, Germany, Italy, Sweden, and the United Kingdom) to review and evaluate asphalt pavement technology and experience. The report has now been published by AASHTO as “Report on the 1990 European Asphalt Study Tour” (23). Of the major differences between the United States and European approaches, it was noted that a greater emphasis is placed on asphalt pavement skid resistance and noise reduction in Europe. OGFC, under various designations, are advocated in several countries largely because of favorable noise and friction properties. Some of the concerns raised about the durability of earlier versions of these mixtures appear to have been overcome by the use of modified binders. However, long-term durability and performance information is not available at this time.
CHAPTER FOUR

AASHTO SURVEY OF CURRENT OGFC USE

The AASHTO Subcommittee on Construction conducted a very extensive survey in 1988 concerning the use of OGFC covering general use, maintenance, failure case histories, costs, and service life. Consequently, a questionnaire survey was not conducted during preparation of this synthesis. State highway agency experiences are included in the synthesis by a summary of the AASHTO survey and the review of documents received as the result of a letter inquiry and follow-up contacts with state highway personnel.

Results of the AASHTO survey have been distributed to the AASHTO membership but there has been no general publication of the information. The information compiled from the 51 completed questionnaires (47 states, one territory and three Canadian provinces) is summarized as follows:

General Use

In the 1988 survey, 27 agencies reported current use of OGFC. Others had used OGFC only experimentally or had discontinued use. Approximately 56,400 lane miles were reported to have been placed since 1947 with 10 agencies reporting placement of more than 1,000 lane miles each. Criteria most often reported for specifying OGFC were traffic speed, traffic volume, friction requirements, and high accident locations.

Maintenance

In areas subjected to snow and ice conditions, 12 agencies indicated no difference in the effectiveness of de-icing chemicals on OGFC and other surfaces, eight agencies indicated less effectiveness on OGFC, and two indicated a greater effectiveness on OGFC, though there was little actual documentation of the relative effectiveness. Two agencies reported that abrasives were not used to control slipperiness on OGFC.

Repairs to damaged OGFC are generally made by removing the OGFC and patching with conventional dense-graded material. Eleven agencies indicated the use of an asphalt emulsion with 50 percent water applied at a rate of about 0.1 gal/yd² as a fog sealant. Most agencies that use OGFC reported normal maintenance practices such as crack sealing. Some agencies have placed dense-graded pavement layers over deteriorating OGFC, but the more general practice is to remove the OGFC by milling before the overlay is placed. The milled material has been used in recycling operations but there were no reports of an OGFC being recycled to new OGFC.

Case Histories of Failures

Reasons given for lack of or discontinued use of OGFC included early failure, stripping of underlying courses, construction difficulty, and reduction in friction and internal drainage characteristics with time. Of the 51 responses, 12 agencies reported early raveling and stripping of the asphalt from the surface, eight reported severe stripping of underlying courses, and nine reported closing up of the OGFC resulting in a reduction in desired performance.

Costs and Service Life

The average costs reported for OGFC during the 1988 survey were $1.22/yd² and $35.52/ton; for dense-graded AC, $2.25/yd² and $29.45/ton; and $0.73/yd² for chip seal. The higher per square yard cost for dense-graded AC reflects the greater thicknesses normally placed. The responses indicated a life expectancy for OGFC of 8 to 11.5 years, depending on exposure to traffic. The average of the estimated costs per square yard per year of service was $0.18 for OGFC, $0.18 for chip seal, and $0.22 for dense-graded AC. However, a direct comparison is not realistic because the dense-graded AC is usually placed in thicker layers than OGFC and provides structural benefits not generally credited to OGFC or chip seal.

Comments and Conclusions

The most frequently listed advantages attributed to OGFC were good friction, reduced hydroplaning, less fine spray, and quieter ride. Disadvantages were listed as difficulties during snow and ice removal and raveling.

Properly designed and constructed OGFC surfaces have performed satisfactorily longer than 12 years, 40 agencies attested to good friction retention; other benefits, such as reduced hydroplaning, splash and spray, noise, and improved wet weather night visibility, are generally accepted. Although it is acknowledged that snow and ice removal procedures can be difficult under certain conditions, some agencies have been able to overcome this problem. Georgia reports alleviating the problems of early raveling and stripping of underlying courses by the use of anti-stripping additives and sealing the surface of the underlying layer.

The following comment is included in the survey report: "It appears that the transfer of technology related to the design and construction of OGFC could be more successful. With 10 agencies each reporting over 1,000 lane miles in place at the beginning of 1988 and 27 who report continuing use, why have 21 stopped using it?"
STATE VISITS AND INTERVIEWS

By review of the AASHTO survey information discussed in the previous chapter and responses from a letter inquiry to state highway personnel, obvious inconsistencies exist in the reported experience and use of OGFC. Cases were noted of the inconsistencies between adjacent state highway agencies with similar climatic and traffic conditions. To obtain more detailed information about actual experience with OGFC than possible from survey questionnaires and reports, field visits and interviews were conducted in the cold-wet climatic area of several northeastern states and the warm-wet area of several southeastern states.

COLD-WET CLIMATE

Connecticut

Trial sections of OGFC were placed in 1975 on heavily traveled portions of I-91 and an evaluation report prepared in 1978 (7). Details from the report are included in Chapter Two. A major finding of these initial trials was a loss of permeability with time for the particular mixture used, even though measured friction properties remained good. This resulted in the redesign of the mixture by increasing the fines and adjusting coarse aggregate to produce a high level of macrotexture resulting in little or no internal drainage. By selection of polish resistant coarse aggregate, this mixture provides a high level of wet-weather traffic safety. It is used extensively throughout the state on new and resurfacing projects.

Maine

The only experience with OGFC has been two experimental projects in 1976. There has been no further use because of reported snow and ice removal problems, the increase in cost because no structural value was assigned to the OGFC, and the conventional dense-graded mixture provides adequate friction levels.

Massachusetts

Rehabilitation and resurfacing projects on I-495 around Boston have received OGFC as a $\frac{1}{2}$-in. wearing surface since 1986. These projects have performed exceptionally well under high traffic volumes and heavy truck loading without wheel path rutting (Figure 7). These are multilane freeways with surface drainage of primary importance during rain storms. The OGFC extends over the shoulder even in areas of curb and gutter design. The high speed traffic provides suction forces that prevent clogging of the voids in the traveled lanes. The shoulders appear to have dirt collecting in the surface voids but the internal drainage appears to be effective as evidenced by water continuing to drain into the drop inlets for a period of time following a rainfall.

The snow and ice control engineer for this area has observed differences in conditions and treatments on OGFC. Because of the moderate climate and proximity to the coast, the area at times experiences a glazing of the pavement surface as temperatures drop to and below freezing during periods of fog and light rain. A single salt application on a dense-graded AC surface usually results in a wet surface under these conditions. It has been observed that OGFC surfaces may refreeze and require subsequent salt applications. The local explanation is that the salt solution that forms initially drains through the OGFC and any continued light rain will refreeze on the OGFC. At the present time, the benefits of OGFC during rain storms are considered to outweigh the need for special treatments during periods of freezing rain. Concern was expressed about the need for an OGFC patching material. Oil spills result in raveling and the area must be patched with dense-graded material.

New Hampshire

One OGFC demonstration project was placed in 1973 and, although no particular problems were noted, there has been

FIGURE 7  $\frac{1}{2}$-inch OGFC wearing surface on I-495 north of Boston performing exceptionally well after 4 years of heavy truck traffic. (Massachusetts I-495 by Smith)
little interest in further use. It was reported that the abundant availability of polish resistant coarse aggregate for use in dense-graded AC surface courses provides adequate friction during rainfall.

New York State DOT

In the early 1970s, several experimental OGFC projects were built using the FHWA mixture design procedures. Because projects were approved on an individual basis, use was quite limited until the early 1980s when a school bus accident on a new dense-graded surface resulted in increased interest and the design of a New York OGFC mixture. Criteria have now been developed for selecting OGFC projects. Snow and ice removal problems have been noted, particularly during the early and late portions of the winter season. Consequently, district maintenance engineers are to be notified of road sections that have received new OGFC. The general observation is that OGFC may require more frequent applications and larger quantities of salt for snow and ice removal.

OGFC have not been used extensively on the New York Thruway but a course was placed as a special surface on a detour around a bridge construction project, and the previous high wet-weather accident experience at this location was overcome. As a result, an OGFC will be used at any high wet-weather accident location on the thruway.

Vermont

OGFC placed more than 13 years ago continues to perform well. During the early years, concerns were reported by maintenance personnel about snow and ice removal. With the importance of the ski business, roads must be maintained in a safe driving condition regardless of weather conditions. With traffic volumes generally lower than in metropolitan areas like Boston, Vermont maintenance crews have determined that a mixture of salt and abrasives performs quite well on their OGFC surfaces. So far, they have not found that the sand remains after the winter season to clog the void structure of OGFC. As the Interstate system reaches the point of rehabilitation, it is expected that OGFC will be added to all sections as a part of the rehabilitation program (Figure 8). Photographs of the difference in splash and spray behind vehicles during a rain storm were obtained on adjacent sections of I-89 with the original dense-graded AC surface and with an OGFC (Figures 9 and 10).

The visits and interviews in northeastern states did not identify any technical basis for the decisions to use or not to use OGFC. The surface type selection appears to be based on previous experiences, available materials, and personal preferences.

WARM-WET CLIMATE

Alabama

Use of OGFC has been limited so far. No serious problems were identified but some concerns have been expressed about closing of the voids over time and reduced permeability. With emphasis on rehabilitation of Interstate and other major roads, use of OGFC is expected to increase.

Florida

OGFC surfaces have been used for more than 20 years in this state to provide maximum wet-weather vehicular safety. Over 10,000 lane miles of OGFC have been placed, and this surface type is currently required for all multilane highways with a design speed higher than 45 mph. A paper describing the Florida program will be presented at this conference.

FIGURE 9 Differential splash and spray from truck on dense-graded surface and OGFC during rain storm. (Vermont I-89 by Smith)
FIGURE 8  Vermont locations of OGFC on I-89 and I-91, February 1990.
experience was reviewed in Chapter Three (17). Some maintenance problems are acknowledged, but the benefits are considered to be more important than the limitations. Production and placing operations required to obtain high quality OGFC are more sensitive than for other surface types, but contractor experience can overcome this limitation. Only one pass of a steel wheel roller is required for compaction.

Service life of an OGFC in Florida is 10 to 12 years, after which it can be removed by milling and new OGFC placed. Fog sealants have not been found to be effective in extending the service life. The present mixture design contains a 1/2-in. top size aggregate and is placed at a 3/4-in. maximum thickness. Because premature raveling has occurred when an OGFC was not opened to traffic for several months after placement, construction is scheduled to permit traffic on the new OGFC as soon as possible.

**Georgia**

OGFC had been used during the 1970s but a moratorium on their use was placed in 1982 because of moisture-induced stripping in the underlying AC layers. Further studies have identified certain Georgia aggregates which are very susceptible to stripping in the presence of water. Lime is currently being used to minimize the stripping problem. The use of lime as an anti-stripping additive and prevention of water from penetrating into the layers beneath the OGFC have alleviated the stripping in the underlying AC layers. The latest policy requires the use of OGFC on all new and reconstruction projects on Interstates.

**Maryland**

Since 1972, this state has used OGFC on all new AC construction and resurfacing projects with a posted speed limit of 50 mph or greater and truck volumes equal to or greater than 500 per day. However, as reported in Chapter Three, problems with severe raveling during the winters of 1989–90 and 1990–91 have resulted in the discontinuation of this policy until a thorough study can be made of the raveling problems. Revised OGFC mixture design procedures were adopted and field experience using the revised procedures is being investigated.

**North Carolina**

OGFC have not been used for about 10 years because of stripping of underlying layers and closing of the void structure under traffic. Adequate wet-weather friction is provided by careful selection of aggregates used in dense-graded AC surfaces.
CHAPTER SIX

CONCLUSIONS

This chapter contains an evaluation of the research and experience reviewed in this synthesis, and identifies gaps in the information that should be addressed to optimize the use of OGFC to reduce hydroplaning and wet-weather accidents, splash and spray, night driving glare, and noise.

At the time of publication of *NCHRP Synthesis 49, Open Graded Friction Courses for Highways (4)* in 1978, 15 state highway agencies were using OGFC regularly and others were using these surfaces on an experimental or trial basis. Regular use had increased to 27 states by 1988. This growth in OGFC use is evidence that this surface type can be designed, constructed, and maintained successfully, and that the recognized benefits often outweigh the limitations. Many of the reasons and explanations for not using OGFC listed in Synthesis 49 have been overcome in subsequent years by several states. Of the people interviewed for this synthesis, several indicated that present policies limiting or prohibiting the use of OGFC should be reviewed in light of more recent information and experience.

The results of extensive European research and experience with OGFC should be an incentive to U.S. state highway agencies to review current practices and consider increased use of OGFC surfaces where appropriate. Of particular interest are the design of OGFC mixtures with void contents of up to 25 percent, layer thicknesses of 1.5 to 2 in., and the use of additives, including polymers and cellulose fibers, to produce increased binder film thicknesses. Also, European highway agencies place special emphasis on the noise-reducing capabilities of OGFC pavement surfaces. For example, OGFC is used as the pavement surface in tunnels in Belgium to reduce traffic noise. These European countries have also conducted research on the ice and snow removal problems associated with OGFC.

The use of OGFC is not a panacea to cure all highway pavement surface problems. It is generally recognized, however, that properly designed, constructed, and maintained OGFC surfaces improve vehicle control during wet weather and provide a smooth, quiet riding surface. Specific conclusions, based on the information and experience reviewed, are as follows:

- OGFC mixture design procedures as described in FHWA Technical Advisory T5040.31 (6) are generally used by state highway agencies.
- An OGFC should only be placed on a structurally sound AC surface.
- In relation to other surfaces that can produce high wet-weather friction, such as surface treatments (e.g., chip seals) and dense-graded AC pavements with a high level of macrotexture and polish resistant coarse aggregate, OGFC surfaces generally provide equal or better performance for minimizing hydroplaning potential, providing high wet-weather friction, reducing splash and spray, reducing headlight glare during wet weather driving, and reducing traffic noise both for vehicle passengers and highway neighbors.
- Snow and ice removal activities on OGFC surfaces require special care and generally an increase in the use of de-icing chemicals.
- Premature deterioration of OGFC surfaces in the form of raveling and reduction in permeability has been experienced.
- During maintenance activities such as patching and crack sealing, the lateral movement of water through the OGFC should not be disrupted.
- Rehabilitation of a deteriorated OGFC involves removal by milling to below the OGFC, placement of a dense-graded AC layer, application of a seal/tack coat, and the placement of a new OGFC.
- The problem of stripping in the underlying AC base courses is being overcome by the use of anti-stripping additives in the underlying layers and improvement in sealing the surface prior to placing the OGFC.

EVALUATION

The following points, based on the review of available literature, interviews with state highway personnel in northeastern and southeastern states, and personal observations should be addressed to minimize highway wet-weather skidding accidents and to optimize the use of OGFC.

- Agency policies limiting the use of OGFC are sometimes based on poor experience from a few test sections built more than 10 years ago.
- When adequate wet-weather friction values can be attained by dense-graded AC mixture design and careful selection of coarse aggregates, other OGFC benefits, such as reductions in splash and spray, water buildup on multilane highways, headlight glare in wet weather, and noise levels, are often not considered during selection of the pavement surface type.
- The use of OGFC surfaces in one state and dense-graded AC friction surfaces in an adjacent state with essentially identical climatic, traffic, material availability, and other conditions appears to be based on personal preference.
- Premature raveling and deterioration of underlying layers have been or are being overcome by improved mixture design, construction practices, and continuing research.
- Additional research and experience, taking advantage of European findings, as well as the Strategic Highway Research Program (SHRP) asphalt projects, should provide a strong basis for expanded OGFC use in the U.S.

INFORMATION GAPS

Gaps in current information and experience that should be subjected to further study and evaluation include the following:

Design Refinements

It has been observed that on multilane roadways, the 3/4-in. thickness of OGFC with air voids of 12 to 15 percent generally
used in the U.S. is likely to become flooded during moderate to heavy rain. The European and Oregon DOT experience with thicker OGFC surfaces and higher void contents demonstrates that such surfaces can be built and maintained. These thicker surfaces appear to improve noise reduction capabilities as well as internal drainage. With use of thicker OGFC surfaces, there should be consideration of the structural value contributed to the pavement. It seems apparent that a single mixture design and surface thickness would not be the optimum for all traffic volumes, climatic conditions, and roadway types. For example, the Oregon DOT uses a Class E mixture with a maximum aggregate size at ¾-in. in a 1-in. nonstructural overlay to improve friction and hydroplaning resistance. A Class F mixture with a 1-in. maximum aggregate size is used as a 2-in. structural overlay and as a wearing course on new pavement construction. Experience with the Class F mixture over five years and with sections subjected to more than 2.3 million ESALs has been very good. Further study to refine the OGFC design process, including mixture design, thickness, and cross slope, is recommended.

**Binder Properties**

One of the more serious causes of the early failure of OGFC is the oxidation and hardening of the thin binder films on the coarse aggregate. The combination of European research and experience with additives to increase binder film thickness and the research conducted by SHRP on use of additives to improve performance of asphalt cement should be very helpful in overcoming this problem. An effort to implement the findings of these activities should be supported.

**Maintenance**

Small areas damaged by snowplows and oil spills must be patched immediately, usually with a readily available dense-graded patch material creating dissimilar surfaces (Figure 11). Some maintenance activities, such as crack sealing and some striping activities, have been reported to disrupt the lateral drainage characteristics. Early failures have been reported in areas of high lateral forces such as intersections and interchange ramps. There is a need to collect and evaluate experience regarding these problems and to conduct research as required to develop solutions.

**FIGURE 11** OGFC patched with conventional mix producing uneven appearance and disruption of internal drainage. (Massachusetts I-495 by Smith)

**RECOMMENDATIONS**

OGFC can be a successful technology that provides desirable pavement surface characteristics not generally available with dense-graded AC and other surface treatments (e.g., chip seal coat). Information in this synthesis indicates that implementation of existing findings from research and experience will result in the beneficial use of OGFC surfaces. It is recommended that:

- A demonstration program on OGFC benefits, design, construction, and maintenance be conducted to emphasize successful OGFC experience.
- A study be undertaken to evaluate European research and experience and SHRP asphalt research results in the areas of asphalt binder properties and additives in relation to OGFC long-term durability.
- Research should be planned and conducted on the design of OGFC surfaces, including void content, surface thickness, binder characteristics, and cross slope, to determine desired designs for various combinations of climate, traffic, road geometrics, and other criteria such as traffic noise control, reduced splash and spray, and reduced wet pavement glare at night.
REFERENCES


8. *Asphaltic Concrete Friction Course Survey*, Louisiana Department of Transportation and Development (1983).


APPENDIX A

FHWA TECHNICAL ADVISORY T5040.31, 1990
Technical Advisory

OPEN GRADED FRICTION COURSES

Classification Code  Date
T 5040.31  December 26. 1990

Par. 1. Purpose
2. Cancellation
3. Background
4. Recommendations

1. PURPOSE. To provide technical guidance on the use of open graded friction courses (OGFC), also known as plant mix seal courses, to develop good friction characteristics for pavement surfaces.


3. BACKGROUND

a. Open graded friction courses constructed with high quality, polish resistant aggregates have an outstanding capacity for providing and maintaining good frictional characteristics over the operating range of speeds on high speed highways. Their macrotexture facilitates drainage of water from the tire/pavement interface, improving tire contact with the pavement and reducing the potential for hydroplaning.

b. Open graded friction courses have generally provided good performance for 7 to 10 years under a range of traffic conditions. When failures have occurred, many were resolved by making minor refinements to the mix design and construction procedures to adjust for local conditions.

c. When compared to other high type surfaces, open graded friction courses have demonstrated the following advantages:

   (1) provide and maintain good high speed, frictional qualities (the frictional characteristics are relatively constant over the normal range of operating speeds);

   (2) reduce the potential for hydroplaning;

   (3) reduce the amount of splash and spray;
(4) are generally quieter, often providing a 3 to 5 decibel reduction in tire noise;

(5) improve the wet weather, night visibility of painted pavement markings; and

(6) conserve high quality, polish resistant aggregates, which may be scarce in some areas, because they are placed only as a surface layer, up to 3/4 inch thick.

d. Open graded friction courses exhibit the following limitations:

(1) increase the potential for stripping of the surface and underlying pavement (they do not seal the underlying pavement against moisture intrusion);

(2) require special snow and ice control methods and generally remain icy longer;

(3) require special patching and rehabilitation techniques;

(4) do not add structural value to the pavement (their performance is governed by the condition of underlying pavement); and

(5) may ravel and shove when used at intersections, locations with heavy turning movements, ramp terminals, curbed sections and other adverse geometric locations.

4. RECOMMENDATIONS. In selecting an OGFC, a number of factors should be considered, such as the environmental conditions, alignment, accident rates and the frictional properties of the State's standard surface mixes. Some locations or pavements may not be appropriate for an OGFC and therefore proper project selection must be considered. For an OGFC to perform as intended, it must be properly designed, constructed, and maintained.

a. An OGFC should only be placed on structurally sound pavements that have minimal cracks, ruts, bleeding and depressions. Pavement cracks are as likely to reflect through an OGFC as with any other thin asphalt course. The high air voids content in an OGFC will allow water to drain into it and attempt to flow laterally. Ruts in the underlying pavement may inhibit lateral flow and cause water to pond in the ruts, promoting separation of the OGFC from the underlying pavement. An OGFC placed on a bleeding pavement may lose its drainage characteristics (close up) due to the migration of the free asphalt from the underlying pavement.
b. The underlying pavement should be sealed with a 50 percent diluted asphalt emulsion, applied at a rate of 0.05 to 0.10 gallons per square yard. An OGFC will increase the amount of time that the underlying pavement will be wet. If the underlying pavement has a high air voids content, stripping potential is increased.

c. Specifications should require the coarse aggregate to be polish resistant and 100 percent crushed material. Carbonate aggregates should not be used. Certain slags and lightweight aggregates have demonstrated satisfactory performance. The frictional qualities of an OGFC are affected by the microtexture of the coarse aggregate. It is poor practice to construct a premium friction course and then have its effectiveness lost due to polishing.

d. An OGFC should be designed in accordance with the mix design procedures included as the Attachment to this Technical Advisory. The basic steps in this procedure determine asphalt content, mixing temperature, air voids, and moisture damage susceptibility.

(1) An OGFC generally has a higher asphalt content than a dense graded mix and uses an equal or harder grade of asphalt. A very heavy asphalt film on the aggregate is essential for longevity. The film helps to resist stripping and oxidation of the asphalt cement. Typical dense graded mixes achieve a 4-6 micron average film thickness, whereas an OGFC requires a 8-11 micron average film thickness. The OGFC has a black shiny appearance and appears to have excessive asphalt when compared to a dense graded mix. It is critical that no reduction in asphalt content be made based on the appearance of the OGFC. Excessive drain down of asphalt in the haul trucks can usually be corrected by lowering the mixing temperature or correcting deficiencies in the mixing and handling procedures. The combined handling and hauling of the mix should be limited to 40 miles or 1 hour.

(2) To ensure that a heavy asphalt cement film is actually obtained, the mixing temperature should correspond to the asphalt viscosity in the range of 700 to 900 centistokes from the temperature-viscosity curve for the asphalt cement. Higher mixing temperatures can cause the asphalt cement to flow off the aggregate. This may result in some areas of the mat having excessive asphalt, others not enough. A range of 2 to 5 percent minus 200 material in the mix will help achieve a thick asphalt cement film. A number of State and local agencies have successfully used latex modified asphalt and other additives to improve OGFC performance.
(3) The air voids analysis is not necessarily required for each project. However, it should be conducted when developing master gradation bands for open graded mixes or when considering new aggregate sources.

(4) An OGFC should be tested for moisture susceptibility because its high air voids content increases the potential for stripping. The mix should be tested for retained coating (AASHTO T 182) and retained strength (modified AASHTO T 165 and T 167). If stripping is observed, the mix design must be revised. The aggregates may be changed or an asphalt cement additive selected. Additional tests should be performed using the revised mix design.

e. One ounce of silicone should be added to every 5000 gallons of asphalt cement. This additive will improve mix workability and reduce the potential of tearing the mat under the paver screed. It also improves mix discharge from the truck beds.

f. An OGFC is placed as a thin lift and loses heat quickly. An OGFC should only be placed when the underlying pavement surface and ambient temperature have reached 60° F, otherwise raveling may result. Late season placement of an OGFC may prevent adequate curing of the asphalt cement and should be discouraged.

g. An OGFC should be placed full width, from outside edge to outside edge of the shoulders, to provide a cross-section with uniform frictional properties. As a minimum, it should extend 3 feet onto the shoulder. Do not place dense graded mix or curb and gutter adjacent to an OGFC. This will obstruct the lateral flow of water.

h. Handwork during placement should be minimized to avoid roughening of the surface. Rolling of an OGFC should be limited to one or two passes of an 8 to 10 ton static steel wheel roller to seat the mix. Longitudinal and transverse joints should be kept to a minimum. Joints should be butted rather than lapped.

i. Maintenance on roadways surfaced with an OGFC should avoid any activities which may obstruct the lateral flow of water through the OGFC.

(1) Traffic striping may inhibit lateral water flow if the stripe material is applied at a heavy rate or an excessive amount of reflective beads are used.
(2) Snow and ice control should be limited to plowing and chemical deicers. The use of sand or other abrasive to improve traction must be avoided.

(3) All crack and joint sealing should be performed prior to placing OGFC. When sealing is required on reflective cracks through an OGFC, only transverse joints should be sealed.

(4) Only small dense graded patches which allow for lateral flow of water through the OGFC should be considered. When larger areas of patching are involved, OGFC should be replaced with OGFC.

(5) A fog coat can be applied to an OGFC to extend the life of the asphalt binder. The fog coat is a 50 percent dilution of asphalt emulsion applied in two passes at a rate of 0.05 gallons per square yard for each pass. The use of rejuvenating agents should be avoided.

(6) When any additional overlay is required on the pavement, the existing OGFC surface must be removed.

Anthony R. Kane
Associate Administrator for Program Development

Attachment
OPEN GRADED FRICTION COURSE (OGFC)  
FHWA MIX DESIGN PROCEDURE

This document combines and updates the design procedure found in Federal Highway Administration Report No. FHWA-RD-74-2, Appendix A and B and Supplements 1 & 2 to the report which were distributed by FHWA Bulletin, dated July 11, 1975. The procedure has been expanded to consider alternative equipment. A suggested laboratory report form is included at the end of the design procedure.

1.0 Material Requirements

Definitions. The grading terminology used in this design procedure is defined as follows:
Coarse Aggregate Fraction - the aggregate from each source or combined job mix formula (JMF), which ever is specified, that is retained on a No.8 sieve.
Fine Aggregate Fraction - the aggregate from each source or combined JMF, which ever is specified, that passes a No.8 sieve.
Predominant Aggregate Fraction - the aggregate from the combined JMF that passes a 3/8" sieve and is retained on a No. 4 sieve.

1.1 Aggregate. Use high quality, polish resistant aggregate with a capacity to provide and maintain good frictional characteristics. It is recommended that relatively pure carbonate aggregates or any aggregates known to polish be excluded from the coarse aggregate fraction. 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 Mineral Filler. Mineral filler as specified in AASHTO M 17 or as specified in the State's Standard Material Specifications is suitable for OGFC design.

1.3 Gradation. The recommended gradation for OGFC is as follows:

<table>
<thead>
<tr>
<th>U.S. Sieve Size</th>
<th>Percent Passing (by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2&quot;</td>
<td>100</td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>95-100</td>
</tr>
<tr>
<td>#4</td>
<td>30-50</td>
</tr>
<tr>
<td>#8</td>
<td>5-15</td>
</tr>
<tr>
<td>#200</td>
<td>2-5</td>
</tr>
</tbody>
</table>
1.4 Asphalt Cement. The recommended grade of asphalt cement is AC-20, AASHTO M 226 Table 2. Other grades of asphalt should be considered when local conditions indicate a necessity or when an improved performance can be achieved.

1.5 Asphalt Additives. Additives may be required to improve the properties of the asphalt binder to resist stripping, retard oxidation (aging) or improve temperature susceptibility. Additives routinely used by the highway agency should be acceptable for OGF mixes. Additives which have not been previously used should be considered experimental features and examined accordingly. In either situation, all additives required for the mix must be incorporated in the mix design.

2.0 Preliminary Data

2.1 Gradation. Test the aggregate from each source, as received for the project, for gradation. If mineral filler is submitted as a separate item, it should also be tested for specification compliance. Analyze the gradation results to determine the JMF that will meet the specification limits of Section 1.3.

2.2 Specific Gravity. Separate the coarse and fine aggregate for each aggregate source and determine the bulk and apparent specific gravity of the coarse and fine aggregate fractions for each source of material submitted. Utilizing the information verified in Section 2.1, mathematically compute the bulk specific gravity ($SG_b$) for the coarse and fine aggregate fractions for the proposed JMF gradation. If the bulk specific gravities of the aggregate sources are significantly different, a gradation analysis based on aggregate weight will not reflect the actual particle size distribution. Re-examine the gradation of the aggregate blend on a volume basis for compliance with Section 1.3.

Compute the apparent specific gravity ($SG_a$) of the predominant aggregate fraction based on the proportion of predominant aggregate from each source and utilizing the specific gravity information obtained above.

2.3 Viscosity. Test the asphalt cement to be used for specification compliance with AASHTO M 226. The asphalt cement binder used for the temperature-viscosity data should include all additives proposed for the mix.
3.0 Asphalt Content

3.1 Surface Capacity. Determine the surface capacity of the predominant aggregate fraction in accordance with the following procedure (AASHTO T 270):

3.1.1 Quarter out a 105 gram sample of the predominant aggregate. Dry the sample on a hot plate or in an oven (230 ± 9°F) to a constant weight and allow the sample to cool to room temperature.

3.1.2 Reduce the sample to approximately 100.0 grams (measured to 0.1 gram) and place the sample in a metal funnel with a piece of screen (No. 10 sieve) fastened above the orifice. The suggested funnel size is top diameter 3-1/2 inches, height 4-1/2 inches, orifice 1/2 inch.

3.1.3 Completely immerse the specimen in S. A. E. No. 10 lubricating oil for 5 minutes at room temperature. [If highly absorptive aggregate is being used, immerse the specimen for 30 minutes.]

3.1.4 Drain the sample in the funnel for 2 minutes. Place the funnel containing the sample in an oven (140 ± 5°F) for 15 minutes of additional drainage.

3.1.5 Pour the sample from the funnel into a tared pan, cool to room temperature, and reweigh the sample to the nearest 0.1 gram.

3.1.6 Compute the percent oil retained (POR) using the following equation:

\[
POR = \frac{SG_a}{2.65} \times \frac{(B-A)}{A} \times 100
\]

where \(SG_a\) = apparent specific gravity of the predominant aggregate
\(A\) = oven dry weight of the sample (Step 3.1.2)
\(B\) = coated weight of the sample (Step 3.1.5)

3.1.7 When using the procedure for highly absorptive aggregate, after determining the POR, pour the sample onto a clean dry absorptive cloth and obtain a saturated surface dry condition.

3.1.8 Pour the sample from the cloth into a tared pan and reweigh the sample to the nearest 0.1 gram.

3.1.9 Compute the percent oil absorbed (POA) using the following equation:

\[
POA = \frac{(C-A)}{A} \times 100
\]

where \(A\) = dry weight of the sample (Step 3.1.2)
\(C\) = saturated surface dry weight of the sample (Step 3.1.8)

Determine the percent (free) oil retained (POR) using the following equation:

\[
POR_f = POR - POA
\]
3.1.10 Compute the surface constant value \( (K_c) \) for the predominant aggregate using the following equation or use Figure 1 below:

\[
K_c = 0.1 + 0.4(POR)
\]

When using the procedure for highly absorptive aggregate, the equation for the \( K_{ca} \) value is:

\[
K_{ca} = 0.1 + 0.4(POR_a)
\]

Figure 1 SURFACE CAPACITY \( (K_c) \) GRAPH
3.2 Asphalt Content. Compute the required JMF asphalt content \( AC_{\text{JMF}} \) which is based on the weight of aggregate from the following equation. The asphalt content computed from this formula is the same regardless of the asphalt grade or viscosity.

\[
AC_{\text{JMF}} = (2(K_c) + 4.0) \times \frac{2.65}{SG_a}
\]

When using the procedure for highly absorptive aggregate, determine the required asphalt content \( AC_{\text{err}} \) as follows:

Compute the effective asphalt content \( AC_{\text{err}} \) from the following equation:

\[
AC_{\text{err}} = (2(K_c) + 4.0) \times \frac{2.65}{SG_a}
\]

Complete Section 4.0 and 5.0, then continue with the determination of the asphalt content as follows:

Prepare a trial mixture using an asphalt content equal or somewhat greater (estimate amount that will be absorbed) than the effective asphalt content \( AC_{\text{err}} \) determined above and using the aggregate gradation as determined in Section 5.2.

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).

Determine the JMF asphalt content \( AC_{\text{JMF}} \) of the absorptive mixture using the following equation:

\[
AC_{\text{JMF}} = AC_{\text{err}} + \text{actual asphalt absorbed}
\]

4.0 Void Capacity of Coarse Aggregate

4.1 Unit Weight. Determine the unit weight of the coarse aggregate fraction of the proposed JMF by either of the following procedures (FHWA-RD-72-43 or ASTM D 4253 modified).

4.1.1 Apparatus

Compaction Mold. - A 6 inch nominal diameter solid-wall metal cylinder with a detachable metal base plate. A detachable metal guide-reference bar as shown in Figure 2 is required for Method 1.

Vibratory Compactor

Method 1. Rammer. - A portable electromagnetic vibrating rammer as shown in Figure 3, having a frequency of 3,600 cycles a minute, suitable for use with 115-volt alternating current. The rammer shall have a tamper foot and extension as shown in Figure 4.

Wooden Base. - A plywood disc 15 inches in diameter, 2 inches thick, with a cushion (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.
Figure 2  COMPACTION MOLD

Figure 3  VIBRATORY COMPACTION ASSEMBLY

Figure 4  TAMPER FOOT
Method 2 (experimental) Vibrating Table. - A vibrating table capable of inducing a vibratory force to the sample at 3,600 cycles a minute and at an amplitude of (0.013 ±0.002 inch). (Soiltest CN-166 or equivalent)

Confining Load. - A circular steel disc weighing 60 pounds with a diameter of 5 7/8 inches. (Soiltest CN-167 or equivalent)

Timer. - A stopwatch or other timing device graduated in divisions of 1.0-second and accurate to 1.0-second, and capable of timing the unit for up to 2 minutes. An electric timing device or electrical circuits to start and stop the vibratory compactor may be used.

Dial Indicator - A dial indicator graduated in 0.001-inch with a travel range of 3.0 inches.

4.1.2 Sample. Select a sample of the coarse aggregate fraction (approx. 5 lb.) from the proposed JMF as verified in Section 2.1. If the bulk specific gravity of the coarse aggregate is less than 2.0, reduce the size of the sample to approximately 3.5-lb. Weigh the sample to the nearest 0.1 pound.

4.1.3 Procedure

Method 1. Pour the selected sample into the compaction mold and place the tamper foot on the sample. Place the guide-reference bar over the shaft of the tamper foot and secure the bar to the mold with the thumb screws.

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

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 0.01 inch.

Method 2. (experimental) Pour the selected sample into the compaction mold and place the surcharge base plate on the sample.

Lower the surcharge weight onto the surcharge base plate and vibrate the assembly for 2 minutes.

Remove the surcharge weight and brush any fines from the top of the surcharge base plate. Measure the thickness (t) of the compacted material to the nearest 0.01 inch.
4.1.4 Calculation. Calculate the vibrated unit weight \( X \) (in pounds per cubic feet) as follows:

\[
X = \frac{6912 \, w}{\pi \, d^2 \, t}
\]

Where
- \( w \) = weight of coarse aggregate fraction (pounds)
- \( d \) = diameter of compaction mold (inches)
- \( t \) = thickness of compacted specimen (inches)

4.2 Void Capacity. Determine the void capacity of the coarse aggregate (VCA) as percent of total volume using the following equation:

\[
VCA = \left( 1 - \frac{X}{U_c} \right) \times 100
\]

Where
- \( X \) = vibrated unit weight from step 4.1.4
- \( U_c \) = bulk dry solid unit weight of the coarse aggregate fraction (pcf).

5.0 Optimum Content of Fine Aggregate

5.1 Compute the optimum fine aggregate content with the following relationship:

\[
Y = \frac{VCA - V - \frac{(AC_{JMF}) \, (X)}{U_a}}{(VCA - V) + \frac{X}{U_f}} \times 100
\]

Where
- \( Y \) = percent of fine aggregate by weight of total aggregate
- \( VCA \) = voids in the coarse aggregate (percent)
- \( V \) = design percent air voids = 15.0 percent
- \( AC_{JMF} \) = asphalt content for the JMF (percent by weight of aggregate) (when using the procedure for highly absorptive aggregate, use \( AC_{ot} \) from Section 3.2, not \( AC_{ot} \))
- \( X \) = vibrated unit weight of coarse aggregate (pcf)
- \( U_a \) = unit weight of asphalt cement (pcf)
- \( U_f \) = bulk dry solid unit weight of fine aggregate (pcf)

5.2 Compare the optimum fine aggregate content \( Y \) determined in Section 5.1 to the amount passing the No. 8 sieve of the proposed JMF. If these values differ by more than 1 percentage point, revise the JMF using the value determined for optimum fine aggregate content. Recompute the proportions of coarse and fine aggregates (as received) to meet the revised JMF. If the proposed and revised JMF gradations are significantly different, it may be necessary to rerun portions of this procedure.
6.0 Optimum Mixing Temperature

Prepare a sample of aggregate (approximately 1000 grams) in the proportions determined under Section 5. Mix this sample with the proposed asphalt cement at the asphalt content (AC_{inf}) determined under Section 3.2 at a mix temperature corresponding to an asphalt viscosity of 800 centistokes determined under Section 2.3. When the aggregate is completely coated, transfer the mixture to a pyrex glass plate (8-9 in. diameter) and spread the mixture with a minimum of manipulation. Place the plate with the sample in the oven at the mixing temperature. Observe the bottom of the plate after 60 minutes. A slight puddle of asphalt cement at the points of contact between the aggregate and the glass plate, as shown in Figure 5, is suitable and desirable after the 60 minute period. Otherwise, repeat the test at a higher or lower mixing temperature to achieve the desired contact area. If asphalt drainage occurs at a mixing temperature which is too low to provide for adequate drying of the aggregate (typically not lower than 225°F), an asphalt of a higher viscosity should be used.

An intermediate observation of the plate can be made at 15 minutes. If there is excessive drain down at the contact points, the sample can be discarded and the test repeated at a lower temperature.

**Figure 5** DRAIN DOWN CHARACTERISTICS
7.0 **Resistance to Effects of Water**

Conduct the Immersion-Compression Test (AASHTO T 165 and T 167) on the designed mixture. Prepare samples at the optimum mixing temperature determined in Section 6.0. Use a molding pressure of 2000 psi rather than the specified value of 3000 psi. Determination of the Bulk Specific Gravity is not required for this design procedure.

After 4-day immersion at 120°F, the Index of Retained Strength shall not be less than 50 percent unless otherwise permitted. Additives to promote adhesion that will provide adequate retained strength may be used when necessary.
OGFC MIX DESIGN REPORT

1.0 MATERIAL PROPERTIES

A. Proposed Aggregate Proportions (by weight)

B. Proposed Job-Mix Gradation (percent passing)

<table>
<thead>
<tr>
<th>Sieve Specification</th>
<th>Aggregate Sources</th>
<th>Job-Mix Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Limit</td>
<td></td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>95 - 100</td>
<td></td>
</tr>
<tr>
<td># 4</td>
<td>30 - 50</td>
<td></td>
</tr>
<tr>
<td># 8</td>
<td>5 - 15</td>
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</tr>
<tr>
<td>#16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#200</td>
<td>2 - 5</td>
<td></td>
</tr>
</tbody>
</table>

C. Specific Gravity - Unit Weight

COARSE AGGREGATE (Retained No. 8 Sieve)
Bulk Sp. Gr. (SGb)

FINE AGGREGATE (Passing No. 8 Sieve)
Bulk Sp. Gr. (SGu)

Bulk Solid Unit Weight (U_s) where U_s = 62.4(SG_u)

PREDOMINANT AGGREGATE (Passing 3/8" - Retained No.4)
Apparent Sp. Gr. (SGa)

ASPHALT BINDER
Specific Gravity @ 77.0°F.

Unit Weight (U_u)

2.0 ASPHALT CONTENT

Percent Oil Retained POR =
Surface Capacity K_s =
Asphalt Content ACaw = % wt aggr

3.0 VOID CAPACITY

A. Void Capacity of Coarse Aggregate

Vibrated Unit Weight X = pcf
Voids Coarse Aggregate VCA = %

B. Optimum Fine Aggregate Content

Where: X = pcf

U_s = pcf

U_y = pcf

ACaw = %

Specs. Limit 5 < Y < 15 Y = %

4.0 OPTIMUM MIXING TEMPERATURE

Asphalt Grade
<table>
<thead>
<tr>
<th>Viscosity (cSt)</th>
<th>Temperature (°F)</th>
<th>Observed Drainage</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Target Mixing Temperature "F

5.0 RESISTANCE TO EFFECTS OF WATER
(AASHTO T 165 & T 167, 2000 psi)

Air Dry Strength = psil
Wet Strength = psil (4 Days @ 120°F)
Retained Strength = % (50% Minimum)

6.0 DESIGN SUMMARY

Aggregate Proportions (by Weight)

JMF Gradation (percent passing)

Sieve Size JMF

1/2"          
3/8"          
No. 4          
No. 8          
No. 16         
No. 200        

Asphalt Grade

Asphalt Additives

Asphalt Content = % wt aggr

Mixing Temperature Range to "F

REMARKS:

Mix Design Recommendation Accepted ___ Rejected ___
APPENDIX B

EXCERPTS FROM FLEXIBLE PAVEMENT DESIGN MANUAL FOR NEW CONSTRUCTION AND PAVEMENT REHABILITATION, FRICTION COURSE POLICY, FLORIDA DEPARTMENT OF TRANSPORTATION

Friction Course Policy

The friction courses currently in use consist of two dense graded (FC-1 and FC-4) which are typically placed 1" thick and an open graded friction course (FC-2) which is placed 5/8" thick. A friction course will be placed on all roads with a design speed of 35 MPH or higher, except for low volume two-lane roads having a five year projected ADT of 3,000 vehicles a day or less. Figure 6 shows a summary of when the alternate friction courses may/will be used.

In general terms, FC-1 and 4 are designed to provide a riding surface with high friction numbers, a skid resistant surface. FC-2 is designed to provide for the rapid removal of water from between the tire and the pavement, a hydroplaning resistant surface. FC-2 is not allowed directly on top of Type II or III.

<table>
<thead>
<tr>
<th>Two Lane</th>
<th>Multi Lane</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 MPH thru 45 MPH</td>
<td>FC-1, FC-4; may use Alt. FC-2</td>
</tr>
<tr>
<td>50 MPH or greater</td>
<td>FC-1, FC-4, may use Alt. FC-2</td>
</tr>
</tbody>
</table>

Figure 6. Summary Asphalt Concrete Friction Course Selection Chart (required for 35 MPH or greater).

Low Volume - Two Lane Roads

- May use Type S surface course (no FC) if 5 year projected ADT is less than 3,000.
- May use FC-1 or FC-4 as both the structural and friction course if structurally adequate.

There are some limitations on the use of friction courses:

- FC-2 will not be placed directly on top of Type II or Type III asphalt. Type S-I or S-III asphalt concrete must be used under FC-2.
- FC-1 and FC-4 are allowed directly on top of Type II or Type III.
- Only one dense graded friction course (FC-1 or FC-4) is to be used throughout the limits of a project.
- FC-1 and FC-4 are considered part of the structural course and may be considered as both the structural and friction course if of adequate strength.
- FC-2 is not to be placed on intermediate median crossovers on multilane facilities. The FC-2 will terminate at the edge of the roadway pavement or the edge of the shoulder pavement, if provided. In the intermediate crossover, beyond the friction course surface, it is recommended that the last layer of the structural course be specified as Type S-III.
- Curb and gutter: The bottom of the FC-2 should be set at or above the lip of the curb on the low side of pavement.
- On nonlimited access facilities, the friction course is to be placed over the entire paved shoulder. On limited access facilities, the friction course is to extend one foot beyond the edge of the travel lane, onto the paved shoulder.
APPENDIX C

MARYLAND STATE HIGHWAY ADMINISTRATION, “PAVEMENT DESIGN CRITERIA—PLANT MIXED SEAL”

The primary function of Plant Mixed Seal is to minimize hydroplaning potential during rainstorms. Additional spinoff benefits include noise levels and reduced spray back. Plant Mixed Seal has a relatively uniform particle distribution size. The largest size aggregate is 3/8" and most of the material falls between 3/8" and the No. 4 sieve.

1.0 Plant Mixed Seal will be placed on roadways where:

a) Truck volumes are greater than or equal to 500 trucks per day in its 15th year of life.

and

b) Roadways with a posted speed limit of 50 mph or greater.

Note:

Trucks per day in 15th year calculation:

\[ \text{Trucks} = \text{ADTsy} \times \text{DS} \times \text{PT} \times (1 + \frac{(\text{GR}/100)\text{SY}}{(\text{YR}-\text{SY})})^{15} \]

where:  
\( \text{ADTsy} \) = Average daily traffic in the survey year of loadometer data,  
\( \text{DS} \) = Directional split of traffic (0-1.0)  
\( \text{PT} \) = Percent truck traffic (0-1.0)  
\( \text{GR} \) = Annual growth rate (see LCCP Guidelines)  
\( \text{YR} \) = Year when analysis period begins  
\( \text{SY} \) = Survey year of loadometer data

1.1 Plant Mixed Seal will not be placed on roadways where:

a) Truck volumes are less than 500 trucks per day in its 15th year of life.

or

b) Roadways with a posted speed limit less than 50 mph.

c) Low volume roads, intersections, bike paths and park and rides, but may be allowed where the profile is conducive to hydroplaning or poor transverse drainage.

d) Roadways with stop and go traffic.

2.0 The following is general information pertaining to the design and construction of Plant Mixed Seal:

a) Plant Mixed Seal will be extended to within 1 foot of the outside edges of the shoulders. (draft 10/87)

b) Plant Mixed Seal will be assigned a structural value equivalent to 1/2" of bituminous concrete. The structural layer coefficient equals 0.22 for a thickness of 0.75".

c) Plant Mixed Seal is not to be placed on a base course mix.

d) Except in unusual cases, Plant Mixed Seal is to be placed upon a surface course mix.

e) Do not use Plant Mixed Seal west of Washington County.