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13. Abstract
Open-Graded Friction Course (OGFC) is a specialized asphalt concrete mixture used for thin-wearing courses, offering significant safety, economic, and environmental benefits. The porous structure of OGFC enhances drainage, reduces hydroplaning, and improves road visibility, particularly during wet weather conditions. Despite its potential advantages, OGFC has faced challenges in the past, including performance issues and limited maintenance practices. Recent research has focused on understanding and addressing these limitations. This study aimed to review current practices for constructing and maintaining OGFC pavements. Key findings include the widespread use of PG 76-22 binder and additives such as styrene-butadiene (SB), styrene-butadiene styrene (SBS), and ground tire rubber (GTR) in OGFC. Granite is the most widely used aggregate in OGFC, while various tests are conducted to ensure the suitability of different aggregates for OGFC applications. Maintenance of OGFC pavements is challenging due to their porous nature, which can lead to raveling, delamination, clogging, and debonding. Many agencies adopt a “do nothing” approach, as distresses in OGFC are

often localized and do not pose a significant safety risk. However, preventive maintenance, such as cleaning the voids to maintain permeability, is critical for ensuring the long-term performance of OGFC pavements. Overall, this research highlights the need for continued efforts to improve OGFC maintenance practices and ensure its long-term viability. By addressing challenges and implementing effective maintenance strategies, OGFC can continue to provide valuable benefits for roadways, enhancing safety, reducing costs, and promoting environmental sustainability.

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Each research project will have an advisory committee appointed by the LTRC Director. The Project Review Committee is responsible for assisting the LTRC Administrator or Manager in the development of acceptable research problem statements, requests for proposals, review of research proposals, oversight of approved research projects, and implementation of findings.

LTRC appreciates the dedication of the following Project Review Committee Members in guiding this research study to fruition.

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Implementation Statement

Based on the findings of this research and two supporting studies, a comprehensive guideline will be developed to address design, performance, and maintenance strategies for Open-Graded Friction Course (OGFC) pavements. The proposed guideline will include techniques for using epoxy-modified OGFC and a new generation of OGFC mixtures with enhanced durability and functional performance.

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Introduction

Open-Graded Friction Course (OGFC) mixtures, sometimes referred to as Permeable Friction Course (PFC) mixtures, are porous, gap-graded asphaltic concrete mixtures. These mixtures, which are primarily used as thin-wearing course layers, provide safety, economic, and environmental benefits. OGFC mixtures contain a high percentage of interconnected air voids, which aids in the drainage of water and the preservation of surface friction. This improved drainage and friction reduces hydroplaning and splash-and-spray while enhancing roadway visibility and skid resistance in wet conditions. OGFC also provides improved pavement smoothness and reduced tire noise [1, 2].

The experimental application of permeable thin asphalt overlays on dense-graded mixtures began in the 1940s. The first applications aimed to offer a superior alternative to chip seals. In the U.S., California pioneered the construction of OGFC pavements. Plant seal mixes, typically used in California, were applied in a thin layer with a smaller nominal aggregate size and additional binder content compared to the conventional dense-graded mixtures [3]. This approach offered benefits similar to chip seals, along with reduced road noise, increased durability, and improved ride quality [4]. In the 1970s, the Federal Highway Administration (FHWA) initiated the Skid Accident Reduction Program, which resulted in the increased use of OGFC pavements. However, during the 1980s, many states discontinued OGFC usage due to performance issues. The most critical shortcomings of OGFC mixtures included durability problems (e.g., raveling and stripping due to aging) and maintenance challenges (e.g., clogging of voids by dirt), resulting in a shorter service life and higher maintenance costs. To address these issues, agencies in Georgia, Texas, and Oregon experimented with modifications such as adding polymers and fibers, increasing binder content and air voids, and using more durable aggregates [5].

The Louisiana Department of Transportation and Development (DOTD) began developing Open-Graded Friction Course (OGFC) mixtures in the late 1960s and 1970s. However, a moratorium was imposed in the 1980s due to early failures primarily caused by moisture and temperature issues, leading to premature raveling and stripping, as well as construction difficulties. In the 1990s, the National Center for Asphalt Technology (NCAT) proposed a new generation of OGFC mixtures, renewing interest in its use. With this renewed interest, DOTD conducted a comprehensive evaluation of Louisiana OGFC mixtures in the 2000s. This research, which evaluated several OGFC pavements based on their laboratory and field performance, concluded that the selected OGFC mixtures had the potential to meet current

DOTD specifications, along with the various performance standards established by previous studies [1].

Literature Review

Open-Graded Friction Course (OGFC) presents a variety of maintenance issues that can be difficult to address. The porous nature of the pavement can lead to a variety of issues, including raveling and delamination, premature oxidation and hardening, clogging of pores, and debonding in the presence of water. A survey conducted by Cooley et al. for NCHRP Report 640 revealed that no state highway agency has developed regular maintenance practices specifically for OGFC pavements. Additionally, no state reported using any maintenance techniques to unclog OGFC pavements, and only one state employs field tests to determine when general maintenance is needed [6]. In a related study, Putnam noted that transportation departments often adopt a “do nothing” approach to OGFC maintenance, as issues such as raveling or delamination are usually localized and the thin OGFC layers rarely pose a safety risk [3].

Raveling and delamination were the most commonly reported maintenance issue in Cooley’s NCHRP survey of state agencies [6]. The porous nature of OGFC pavements makes them particularly susceptible to premature oxidation due to increased exposure to corrosive elements such as water, air, and ultraviolet radiation [7]. Over time, oxidation can cause the asphalt binder to become brittle, leading to raveling [6]. To address these issues, effective corrective surface maintenance is essential. This includes proper mill and inlay techniques for OGFC pavements, as they require repairs to potholes and delaminated areas. Using conventional HMA for patching can hinder the lateral flow of water through the pavement layer, potentially causing water damage to the base. One essential maintenance task for OGFC is cleaning or declogging the voids. These voids can become clogged with dirt and debris, reducing permeability and drainage capacity over time. This can shorten the service life of the porous base layer. Preventing clogging is challenging, and restoring permeability after it occurs is costly [3].

These maintenance issues may result in a shorter service life and higher maintenance costs over the pavement’s lifespan. A 2009 survey revealed that the average service life of PFC pavements was between eight and ten years [6]. Moreover, OGFC pavement sections in Alabama have been shown to exhibit premature distress after only six to seven years [8]. As OGFC mixtures become more common in Louisiana, durability and maintenance concerns have emerged. To address these issues, the Louisiana Department of Transportation and Development (DOTD) aims to investigate the maintenance practices of other states and nations. This research seeks to identify the most cost-effective, safe, and efficient options for maintaining OGFC pavements.

For OGFC pavements to continue functioning as intended, preventive maintenance is essential. One of the primary challenges to the long-term performance of OGFC pavements is the clogging of voids due to the accumulation of dust and debris. Studies in Japan and Canada have shown that exposure to real-world conditions can reduce the permeability of OGFC pavements over time. This clogging leads to a loss of permeability, which requires maintenance [9, 10, 11]. Common maintenance methods to restore permeability include cleaning the pavement with a high-pressure hose or a specialized cleaning vehicle. While pressure washing and vacuuming are sometimes used, there is concern that these methods might be detrimental to OGFC pavements. To address this issue, Liu et al. recently conducted a research project in China. Researchers evaluated the effectiveness of using a specialized cleaning vehicle equipped with a high-pressure water and vacuum system to restore permeability. The cleaning process involves spraying water in various directions to loosen debris within the pores, followed by the use of a vacuum system that removes the water and debris mixture. The wastewater is collected, filtered, and reused in the cleaning process. The study found that the specialized cleaning vehicle was effective in clearing clogged OGFC pavements. However, permeability restoration was higher in non-wheel paths compared to wheel paths. For heavily clogged traffic lanes, the pavement might need to be cleaned three to four times to be effective. It is important to note that the cleaning operations did not cause any raveling damage to the OGFC pavement [9]. In a related study, Isenring et al. [12] highlighted the difficulty of cleaning heavily clogged pavements. The researchers recommended initiating maintenance cleaning while the pavement still retains permeability. This proactive approach can preserve permeability for a longer period of time.

Asphalt binder in OGFC pavements is more susceptible to oxidation due to increased exposure to harmful elements. Fog seal application is one technique used to address oxidation issues in OGFC pavements. Highway agencies in Oregon, South Carolina, New Mexico, and Wyoming have applied fog seals as a preventive maintenance measure for their OGFC pavements. Fog seals, which are a mixture of asphalt, water, and an emulsifier, are believed to extend the service life of OGFC pavements by providing a thin film of unaged asphalt at the surface. However, quantitative information on their effectiveness is limited [13]. One concern with the application of fog seals is that they might reduce porosity and pavement friction. Research by Rogge on PFC pavements has shown that fog seals can maintain porosity and macrotexture, which are essential for reducing the risk of hydroplaning [13]. While pavement friction may decrease immediately after fog seal application, it typically recovers significantly within the first month due to traffic [14]. Chip seal application is another technique for sealing the surface of OGFC pavements when water damage to underlying layers is a problem. Some agencies also use seal coats to temporarily stop raveling and maintain pavement serviceability until more extensive repairs can be executed [13].

When repairs are needed for delaminated or potholed sections of OGFC pavements, another OGFC mixture should be used if the section is large enough to justify the OGFC production. However, dense-graded HMA can be used for smaller patches that may not significantly disrupt water flow through the OGFC layer [13]. The California Department of Transportation (CalTrans) recommends that patches be diamond-shaped and oriented at a 45-degree angle to allow water to drain along the patch [15]. A light emulsion tack coat should be applied to the edge of the OGFC patch to prevent the drainage from being blocked. When repairing cracks in OGFC pavements, it is critical to avoid impeding the lateral flow of water. Transverse cracks can be sealed using the standard techniques without obstructing the flow of water. However, longitudinal cracks can be problematic, as they can block drainage in the top layer of the OGFC pavement. One potential solution to this problem is to mill the cracked strip of pavement and replace it with a new OGFC mixture [3]. The South Carolina Department of Transportation published supplemental specifications for using maintenance OGFC mixtures in limited patching applications. These specifications provide construction guidelines and mixture compositions for OGFC mixtures. The specification recommended using a PG 64-22 binder instead of a polymer-modified PG 76-22 binder due to the relatively small production quantities. Additionally, the specifications required the use of crushed stone that met the agency's gradation requirements [16]. In the event that cracking in an OGFC pavement becomes too excessive, rehabilitation is the only option [17]. Studies have shown that placing a dense-graded HMA layer over an OGFC pavement at the end of its service life can trap water, leading to deterioration [17]. Therefore, it is recommended to mill the existing OGFC before replacing it with a new OGFC or HMA layer.

A survey conducted by Cooley et al. for NCHRP Report 640 found that raveling was the most common reason for rehabilitating PFC pavements [6]. According to Rogge, there are three rehabilitation methods: mill and inlay, in-place recycling, and overlay application. However, Rogge notes that mill and inlay is typically used only when Oregon's F-mix (OGFC) is placed on shoulders [13] . Furthermore, Cooley et al. reported in a survey that most agencies milled and replaced their OGFC pavements with new OGFC or conventional HMA when the existing OGFC pavement reached the end of its service life or experienced excessive raveling [6].

Another rehabilitation option for OGFC pavements is to incorporate micromilling. When the OGFC pavement reaches the end of its service life but the underlying HMA layer is still in good condition, the common practice is to mill and replace both layers. This rehabilitation technique typically addresses two issues: (1) bonding issues between the OGFC and milled surfaces, and (2) the entrapment of water that passes through the permeable layer in the valleys created by milling. However, this procedure can be expensive. The Georgia Department of Transportation conducted research to validate their requirements for milled surface texture and smoothness. These requirements addressed variations in surface texture and smoothness, specifying a ridge and valley measurement difference of no more than 1/16 inch and a smoothness index of 825 mm/km. The research found that micromilling is a promising pavement preservation option for OGFC pavements with a sound underlying structure, offering significant cost savings. Additionally, the research made two key conclusions: (1) micromilling in combination with thin asphalt overlays is an effective pavement preservation treatment, and (2) variable-depth micromilling can achieve the required surface texture without compromising milled surface texture and smoothness [18].

Objective

The objectives of this study were to:

1. Review current practices for constructing and maintaining Open-Graded Friction Course (OGFC) pavements; and
2. Develop a comprehensive guide that addresses design, performance, and maintenance strategies for OGFC pavements, based on the findings of this study and two supporting studies.

This report focuses on the first of these objectives. The second objective is addressed in two other supporting studies: LTRC Projects 21-4B and 21-6B.

Methodology

To fulfill the objectives of the study, a comprehensive review of published literature focusing on current and proposed maintenance methods for Open-Graded Friction Course (OGFC) mixtures was conducted. Additionally, a multi-state survey was administered to gather information about OGFC construction and maintenance practices, as well as the durability issues most frequently encountered by state agencies. The survey was distributed to DOTs from all 50 U.S. states and five additional districts and territories. A copy of the multi-state survey questionnaire is provided below.

- Q1—Select the type of asphalt binder grade specified for use in OGFC mixtures:
  ☐ PG 70-22
  ☐ PG 76-22
  ☐ PG 70-28
  ☐ PG 76-28
  ☐ Other, specify

- Q2—Provide the type of additives/modifiers specified/allowed for use in OGFC mixtures.

- Q3—List aggregate types specified/allowed for use in OGFC mixtures.

- Q4—Select aggregate property tests and performance criteria specified/allowed for OGFC mixtures:
  ☐ ASTM D6928—Micro Deval Test, Maximum % Loss
  ☐ ASTM D4791—Flat and Elongated Particles, Dimensional Ratio, % Maximum
  ☐ ASTM D5821—Coarse Aggregate Angularity, % One-Fractured Face (min.), % Two or More Fractured Faces (min.)
  ☐ AASHTO T176—Sand Equivalent Test, % Minimum
  ☐ AASHTO T304—Fine Aggregate Angularity, % Minimum
  ☐ Aggregate Friction Rating Test
  ☐ Other, specify

- Q5—Please list other aggregate tests and properties evaluated for OGFC mixtures.

- Q6—List % passing range for aggregate gradation specified/allowed for use in OGFC mixtures.

- Q7—What design method does your agency follow for OGFC mixtures?

- Q8—Does your agency have experience using epoxy asphalt in OGFC mixtures? If so, please provide information on the specific epoxy asphalt source, type, and any additional relevant details.

- Q9—What mechanical performance tests are used to evaluate OGFC mixtures?

- Q10—What are the most frequent maintenance problems you encounter with OGFC pavements?

  ☐ Clogging/Unclogging

  ☐ Raveling/Delamination

  ☐ Other, please explain

- Q11—Do you perform regular maintenance activities for your OGFC roadways? If so, please describe the specific maintenance activities you employ.

  ☐ Yes

  ☐ No

  ☐ No, but we plan to

- Q12—Do you employ field tests to determine when maintenance activities are necessary? If yes, please give examples.

  ☐ Yes

  ☐ No

  ☐ No, but we plan to

- Q13 to Q14—Do you patch the OGFC pavements in your state?

  ☐ Yes

  ☐ No

If so, what type of mix do you use for patching?
☐ Dense-graded (DG) HMA
☐ OGFC
☐ Other, specify

- Q15—Are OGFC pavements more expensive to maintain compared to other types of pavements?
  ☐ Yes
  ☐ No
  ☐ Not sure

  If yes, by approximately what percentage?
  ☐ 1-5%
  ☐ 6-10%
  ☐ 11-15%
  ☐ 16-20%
  ☐ More than 20%

- Q16—What type of distress most often triggers the need for OGFC pavement rehabilitation?
  ☐ Raveling, pot holes, delamination
  ☐ Loss of permeability
  ☐ Safety issues (e.g., reduced friction, tire spray, noise)
  ☐ Other, specify

- Q17—How are the OGFC pavements rehabilitated?
  ☐ Mill and overlay
  ☐ Micromill
  ☐ In-place recycling
  ☐ Full-depth reclamation
  ☐ Shot blasting
  ☐ Vacuuming
  ☐ Other, specify

- Q18—Do you place OGFC on milled surfaces?
  ☐ Yes
  ☐ No
  ☐ We used to, but we don't anymore

- Q19—What type of mix is typically selected as an overlay for milled OGFC roadways?
  ☐ OGFC
  ☐ Dense-graded (DG) mix
  ☐ Stone Matrix Asphalt (SMA)
  ☐ Other, specify

- Q20—What problems, if any, have you encountered with your rehabilitated OGFC roadways?

- Q21—Do you require a tack coat prior to placing the OGFC? If yes, what kind (hot-applied, emulsion, etc.)?
  ☐ Yes
  ☐ No

- Q22—Do you have a minimum ambient or surface temperature requirement for laying OGFC? If yes, what is it?
  ☐ Yes
  ☐ No

- Q23—Do contractors in your state find it more difficult to construct OGFC pavements compared to conventional asphalt mixtures? If yes, could you please elaborate on the specific challenges they face?
  ☐ Yes
  ☐ No
  ☐ Not sure

- Q24—How do you specify compaction requirements for OGFC mixtures?

The responses from the survey questionnaires were analyzed to evaluate construction, maintenance practices, and durability issues associated with Open-Graded Friction Course (OGFC) pavements. An interim report was prepared to compile the findings of the two tasks performed as part of this study: the review of current literature, and the administration of the multi-state survey.

Two supporting studies were conducted as part of this research. The first study aimed to design and evaluate a new generation of Open-Graded Friction Course (OGFC) mixtures featuring enhanced durability while also maintaining their functional benefits. The second study assessed the impact of various asphalt binder additives and modifiers on OGFC mixture performance. The findings and recommendations from both support studies were documented in separate final reports. Based on the combined findings and recommendations of this primary study and the two support studies, a draft standard practice document will be developed for the design, construction, and maintenance of OGFC pavements in Louisiana.

Discussion of Results

The responses to the survey questionnaires were collected and analyzed by the research team. These results are detailed in the following sections of this chapter.

Figure 1 summarizes the responses to survey questions Q1 and Q2 regarding the asphalt binder and additive types used in OGFC mixtures. Twelve responses were submitted. PG 76-22 is the most commonly used asphalt binder for OGFC mixtures, with 58% of respondents utilizing it; see Figure 1a. In addition to conventional performance grade binders, unconventional binders such as highly-modified asphalt (HiMA), crumb rubber (8% by weight of binder) plus styrene-butadiene styrene (SBS)-modified PG 70-22 TR+ and PG 76-22 TR+, and a highly modified PG 64E-22 with 4.9–6.0% polymer (for extremely heavy traffic) are also utilized in some OGFC mixtures; see Figure 1a.

Based on the responses to Q2, styrene-butadiene (SB), SBS, and ground tire rubber (GTR) are the most commonly used additives in OGFC mixtures. Other frequently used additives include fibers, hydrated lime, polyphosphoric acid (PPA), and styrene-butadiene rubber (SBR). Additionally, warm mix asphalt (WMA) and various anti-strip additives are also utilized in OGFC mixture production.

Figure 1. Responses to (a) Q1—binder and (b) Q2—additive types used in OGFC

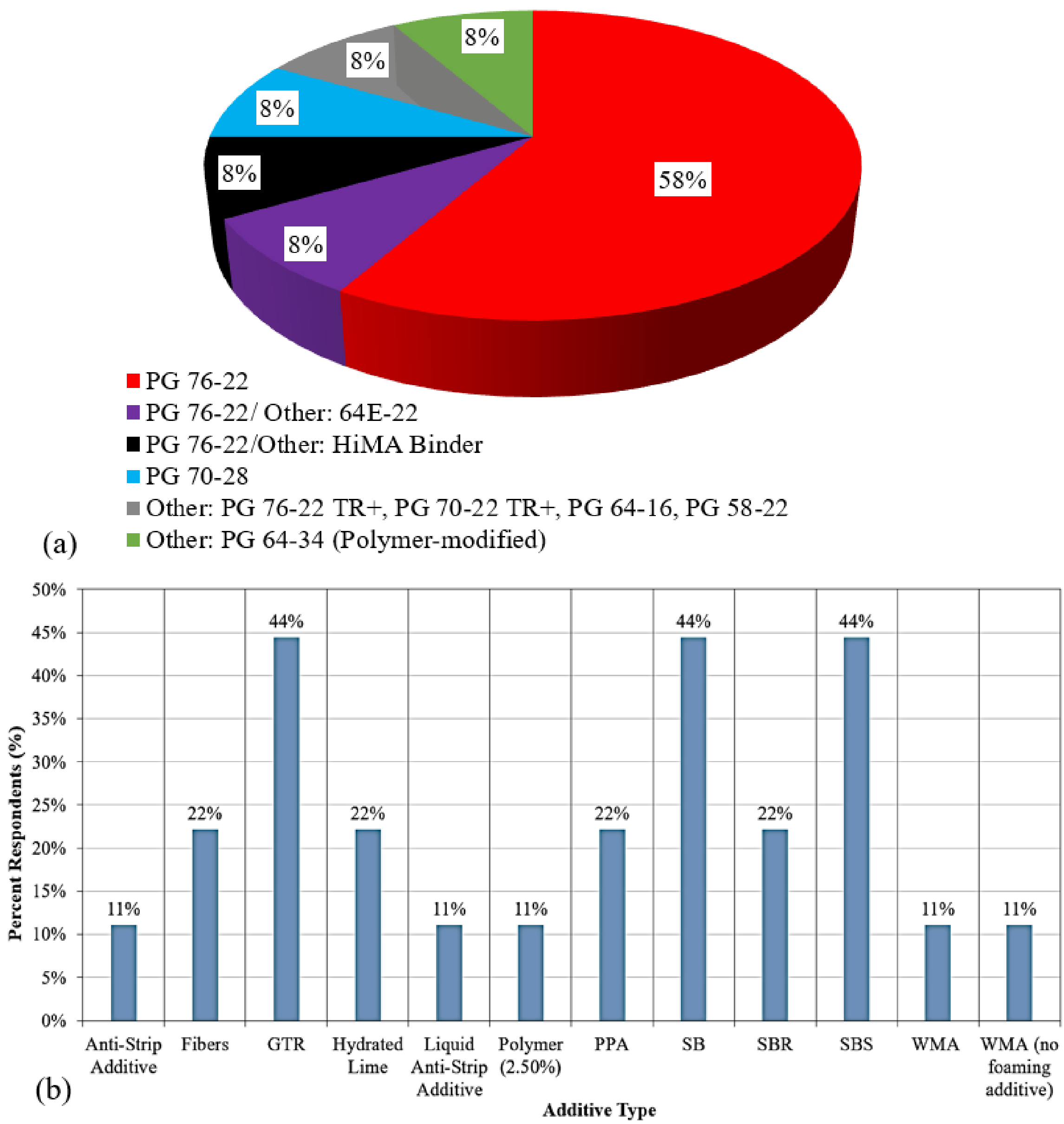
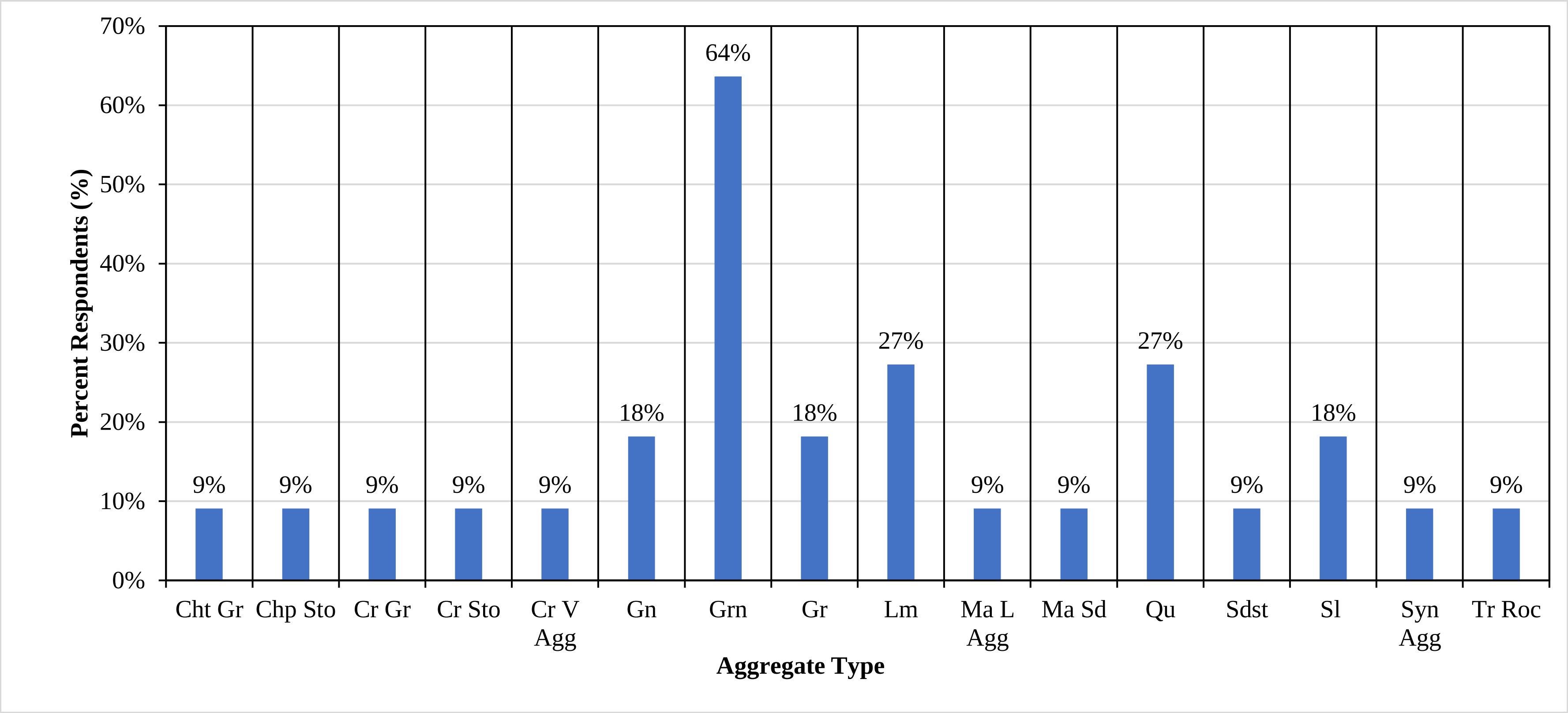


Figure 2 illustrates the aggregate types commonly used in OGFC mixtures, as reported by survey respondents. Granite (Grn) is the most widely used aggregate, followed by limestone (Lm) and quartzite (Qu). Slag is an example of an unconventional aggregate that is permitted by the Alabama and Utah DOTs for OGFC mixture production.

Figure 2. Responses to Q3—aggregate types used in OGFC mixtures



Note: Cht Gr = Chert Gravel; Chp Sto = Chip Stone; Cr Gr = Crushed Gravel; Cr Sto = Crushed Stone; Cr V Agg = Crushed Virgin Aggregates; Gn = Gneiss; Grn = Granite; Gr = Gravel; Lm = Limestone; Ma L Agg = Manufactured Light Weight Aggregate; Ma Sd = Manufactured Sand; Qu = Quartzite; Sdst = Sandstone; Sl = Slag; Syn Agg = Synthetic aggregate; and Tr Roc = Trap Rock

Table 1 presents a summary of the aggregate tests typically performed on OGFC mixture aggregates and their corresponding performance criteria specified by the various state agencies. Based on the survey responses, a dimensional ratio of 5:1 is most commonly specified for flat and elongated particles using the ASTM D4791 test. The maximum allowable percentage of elongated particles typically ranges from 10% to 20%. For coarse aggregate angularity, a high percentage of fractured faces (85-100%) is generally required. The fine aggregate angularity is often specified with a minimum percentage of 45%. Some states also require additional tests, such as sodium sulfate soundness, LA abrasion, and aggregate polishing. Moreover, individual states may have unique testing requirements, as demonstrated by the Broken Stone-NJDOT A-3 test for New Jersey.

Table 1. Aggregate property tests and performance criteria

State	ASTM D6928—Micro Deval / Max. % loss.	ASTM D4791—Test for Flat and Elongated particles/ Dimensional Ratio / %Max.	ASTM D5821—Coarse Aggregate Angularity / % One-Fractured Face (min.)/ % Two or More Fractured Faces (min.)	AASHTO T176—Sand Equivalent Test/ % Min.	AASHTO T304—Fine Aggregate Angularity/ % Min.	Aggregate Friction Rating Test	Other Aggregate Tests / Specified Max or Min.
FL	NP	NP	NP	NP	NP	NP	NP
SC	RQ / 15	RQ / 5:1 /10	RQ / NP / 90	NP	NP	NP	Sodium Sulfate Soundness & LA Abrasion
AZ	NP	NP	RQ / 92 / 85	RQ / 55	NP	NP	NP
TN	NP	RQ / 5:1 / 20	RQ / 100 / 90	NP	NP	NP	NP
MS	NP	RQ / 3:1 / 20	RQ / NP / 90	NP	NP	NP	NP
WY	NP	RQ / 5:1 /10	NP	RQ / 45	RQ / 45	NP	Sodium Sulfate Soundness & LA Abrasion
AL	NP	RQ/3:1/20	RQ/ 100/ 90	NP	NP	NP	NP
UT	NP	NP	RQ / 95 / 90	RQ / 60	RQ / 45	Aggregate Polishing Test (ASTM D3319)	LA Abrasion / 30% Max.
NC	RQ / 18	RQ /5:1 / 10	RQ / 100 / 100	RQ / 45	RQ / 45	NP	NP
HI	NP	NP	NP	NP	NP	NP	NP
GA	NP	RQ / 5:1 / 10	NP	NP	NP	NP	NP
NJ	NP	RQ / 5:1 / 10	NP	NP	NP	NP	Broken Stone- NJDOT A-3

Note: NP = Information not provided or test not required; RQ = Test required; min. = minimum specification value; max = maximum specification value.

Table 2 summarizes other aggregate performance properties evaluated for OGFC mixtures, along with their corresponding specified criteria. Survey respondents reported a wide range of aggregate tests and properties. Aggregate physical properties typically evaluated for OGFC mixture production include specific gravity, water absorption, flakiness index, carbonates, abrasion, friction, limestone content, hydrated lime, soundness, LA abrasion, polishing test, plasticity index, clay lumps, natural fines, and mica schist content. Aggregate durability properties commonly assessed include weathered and deleterious stone, broken stone, absorption, sodium sulfate soundness, and adherent fines. The number of aggregate property measurement criteria varies by state. For instance, Arizona has criteria for multiple properties, while Utah focuses on a more limited set. Additionally, specific numerical values for each criterion can differ significantly between states. For example, Arizona has a maximum allowable flakiness index of 25%, whereas New Jersey has no specified limit.

Table 2. List of other aggregate properties evaluated for OGFC mixtures

State	Aggregate Property / Test	Criteria
Arizona	Combined Bulk Oven Dry Specific Gravity	2.350 – 2.850
	Combined Water Absorption	0-2.5%
	Flakiness Index	25% Max
	Carbonates	20% Max
	Abrasion	100 Rev.: 9% Max and 500 Rev.: 40% Max
Tennessee	Friction approved by silica dioxide content (ASTM C25) or performance under traffic with a test strip (AASHTO T 242)	-
Mississippi	Limestone content	Less than 50% of aggregate blend for friction
	Hydrated lime required	1% of total dry aggregate weight.
Wyoming	Soundness	18% Max
	LA Abrasion	35% Max
Alabama	LA Abrasion	48% Max
	Soundness	T104 sodium sulfate 5 cycle coarse and fine 90% min retained
Utah	Polishing Test	T278 and T279, 31 min.
	Plasticity Index	0
	Clay Lumps and Friable Particles	2% Max
	Natural fines	none
	Soundness	5 Cycles, 12% Max
Georgia	AASHTO T96 (% Abrasion Loss Value)	0-50%
	ASTM C294: Mica Schist Content	5% Max
New Jersey	Weathered and Deleterious Stone	5% Max
	Broken stone other than that approved classification	5% Max
	Absorption No. 9 and Larger, Stone sand only (No. 10)	1.8%, 2.0% max
	Sodium Sulfate Soundness, % Loss	10% Max
	Adherent Fines in Coarse Aggregates	1.5% Max
	LA Abrasion Test Surface/ Intermediate or Base Course	40% / 45% Max

Figure 3 presents plots of the average percent passing values calculated from the data provided by respondents regarding aggregates used in OGFC mixtures. The complete range of percent passing values for each sieve size is detailed in Appendix A. Among the 14 aggregate gradation plots analyzed, the aggregates used in Arizona (AZ) and Wyoming (WY) were determined to be the finest. Conversely, the 12.5-mm porous European mixture (PEM) utilized by Georgia DOT exhibited the coarsest gradation among all the OGFC mixture gradations examined. The nominal maximum aggregate size (NMAS) for the gradation values reported by the respondents varied from 9.5 to 12.5 mm.

Figure 3. Gradation plots for OGFC mixtures

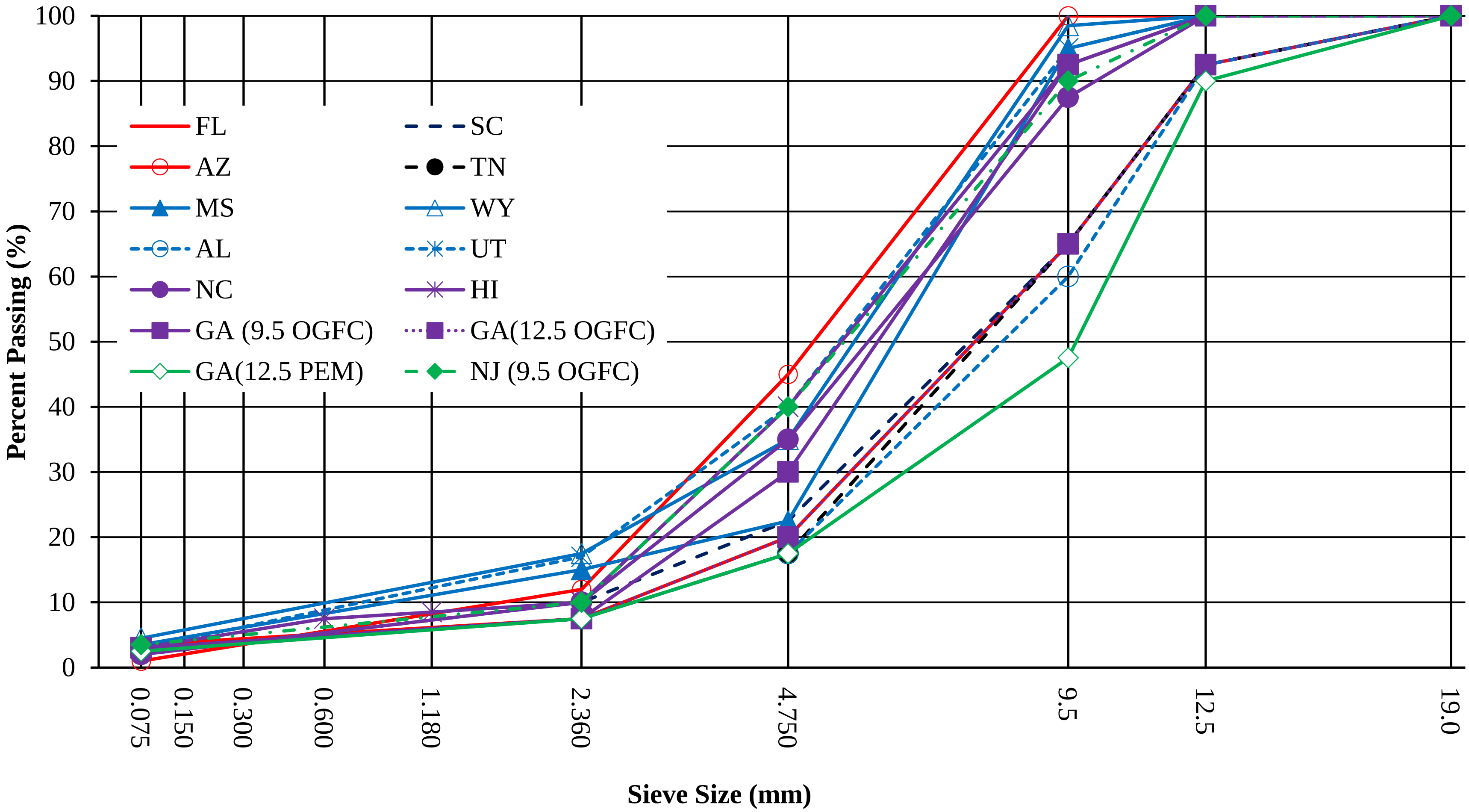


Figure 4 summarizes the responses concerning the use of epoxy asphalt in OGFC mixture production. Of the 12 respondents, 11 (92%) indicated that they had no experience with epoxy asphalt in this context. Only one respondent (Florida DOT) reported that their agency is currently investigating the potential of using epoxy asphalt in OGFC mixtures, in collaboration with the National Center for Asphalt Technology (NCAT).

Figure 4. Responses to Q8—use of epoxy asphalt in OGFC

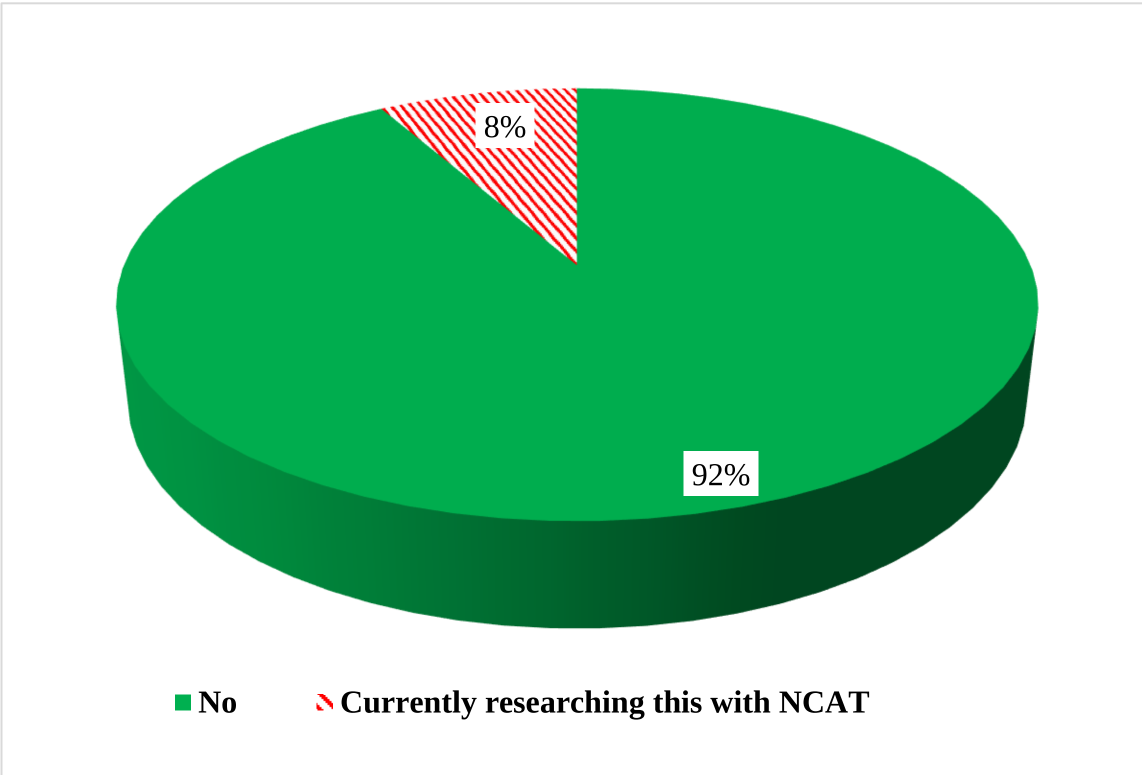


Figure 5 shows a summary of the responses to survey questions about the types of laboratory-mechanical tests used to evaluate OGFC mixture performance. A significant portion of respondents (58%) indicated that they do not conduct any mechanical tests on OGFC mixtures. Among those who do perform mechanical tests, the Cantabro test is the most popular, with 38% of respondents utilizing it for laboratory performance assessment. Other commonly employed tests include the boil test, proctor test, and modified Lottman test (TSR).

Figure 5. Responses to Q9—mechanical tests for OGFC mixtures

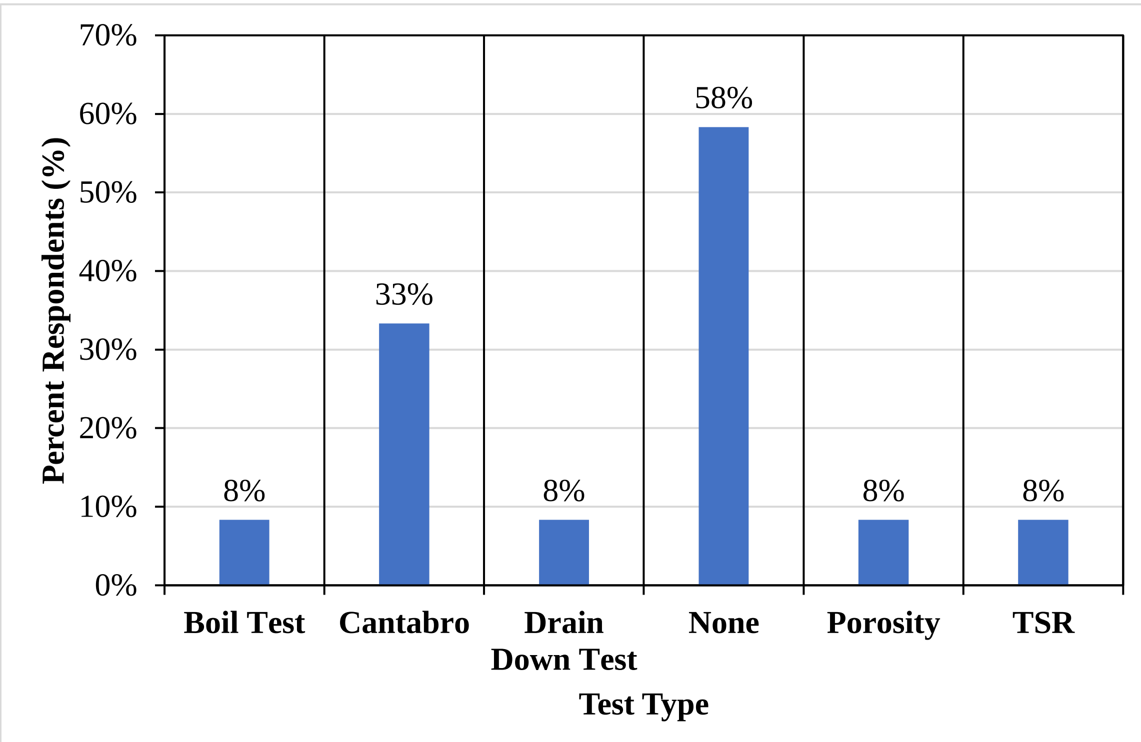


Figure 6 summarizes the responses to the survey question regarding common maintenance issues associated with OGFC pavements. The most frequently reported issue was raveling or delamination, selected by 87% of respondents. The second most common issue was clogging or unclogging, reported by 27% of respondents. Other maintenance issues associated with OGFC pavements included freeze-thaw damage and snowplow damage or gouging.

Figure 6. Responses to Q10—common maintenance issues associated with OGFC pavements

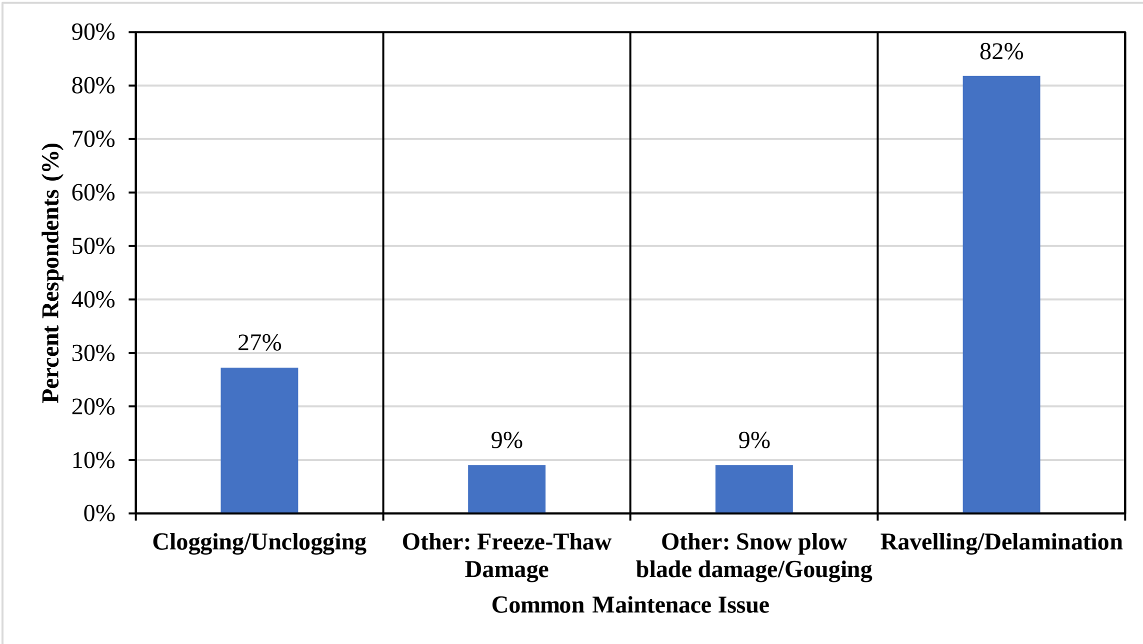


Figure 7 presents a summary of the responses to the survey question about the conduct of regular maintenance activities on OGFC pavement sections. A significant majority of respondents (91%) indicated that they do not perform any maintenance activities on OGFC pavements. Only one respondent (Georgia DOT) reported conducting limited maintenance activities, specifically applying fog seal as a treatment.

Figure 7. Reponses to Q11—performance of regular maintenance activities on OGFC

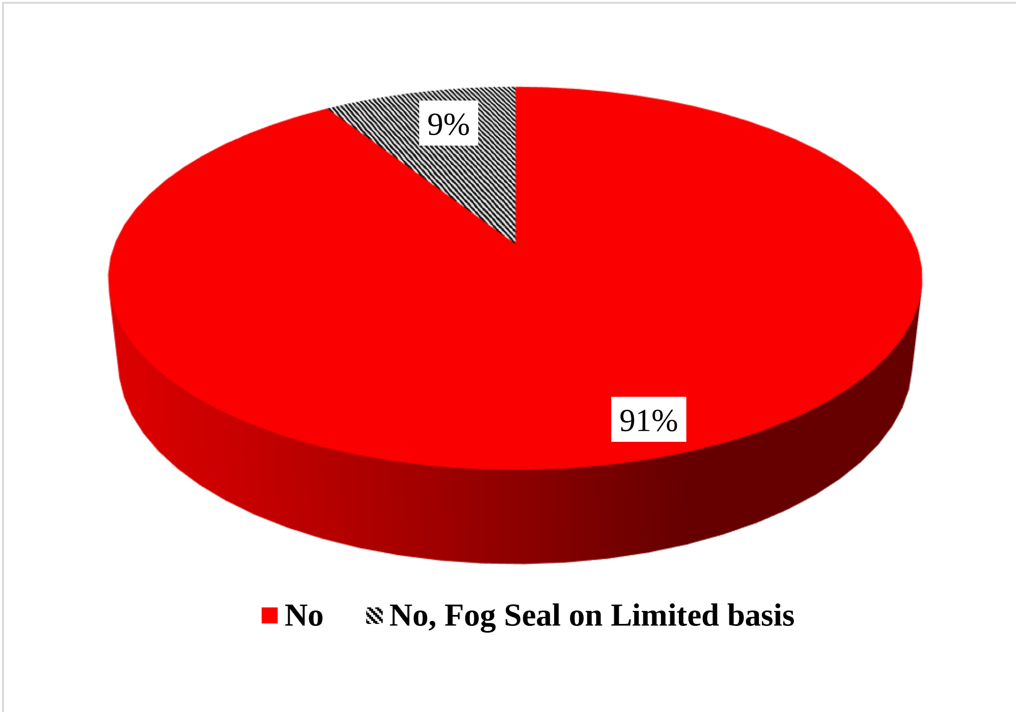


Figure 8 summarizes the responses to the survey question regarding the use of field tests to initiate maintenance on OGFC pavement sections. A significant majority of respondents (91%) reported that they do not conduct any field tests to determine the need for maintenance. Conversely, 9% of respondents indicated that they require roughness measurements using a laser profiler before initiating any maintenance treatments.

Figure 8. Responses to Q12—field testing requirement for initiating maintenance treatments

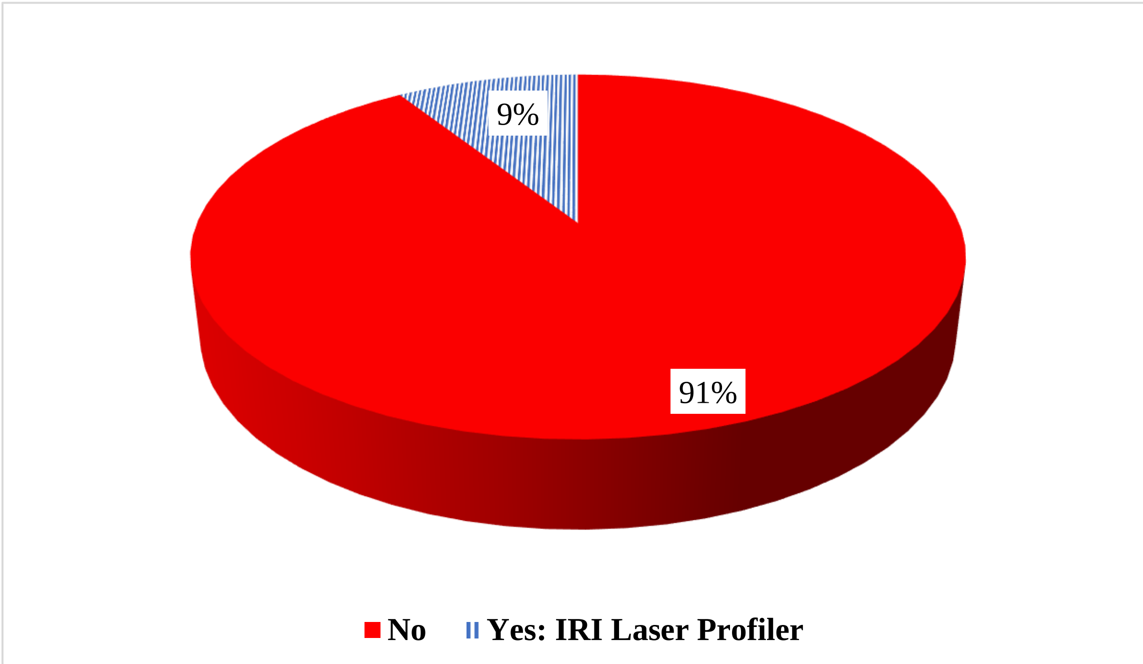


Figure 9 presents a summary of the responses of survey participants regarding patching activities on OGFC pavement sections and the types of mixtures used. The majority of respondents (58%) reported using dense-graded mixtures for patching OGFC sections. Additionally, a sizeable number (25%) indicated using OGFC mixtures for patching existing OGFC sections. Some respondents also reported occasionally using cold and open-grade cold mixtures for patching these sections.

Figure 9. Responses to Q13 and Q14—patching activities and mixture types used

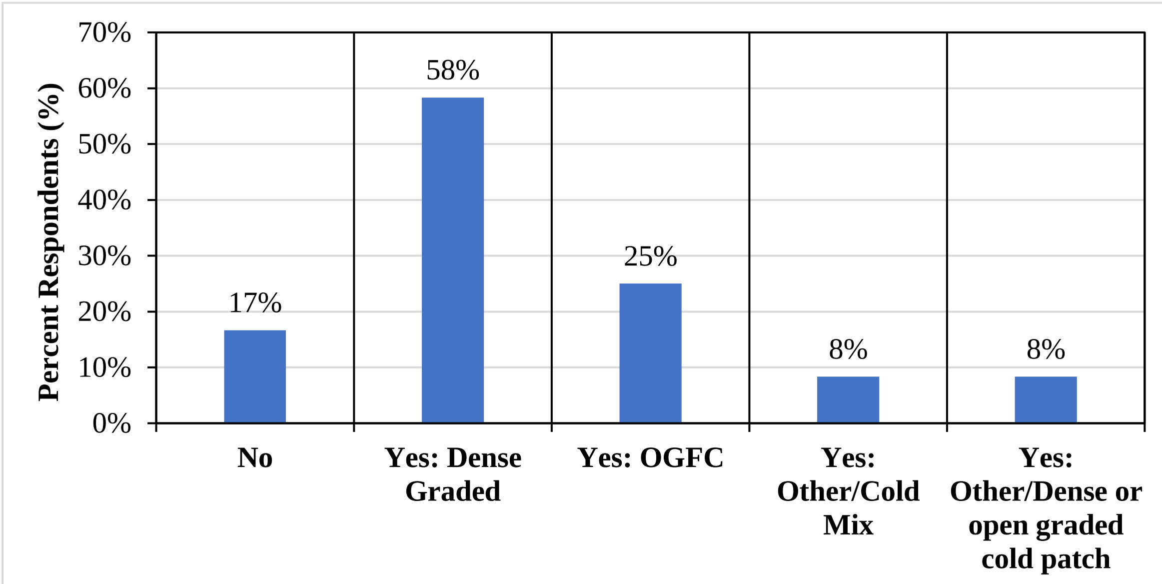


Figure 10 shows a summary of survey responses regarding the maintenance costs of OGFC and other pavement types. A significant portion of respondents (55%) expressed uncertainty about whether OGFC sections are more expensive to maintain. Approximately 18% believed that OGFC sections were not more expensive to maintain than other pavement types, while another 18% reported that OGFC sections were 20% or more expensive to maintain. Additionally, 9% indicated that OGFC sections were 11% to 15% more expensive to maintain than other pavement types.

Figure 10. Responses to Q15—comparative maintenance costs of OGFC pavements

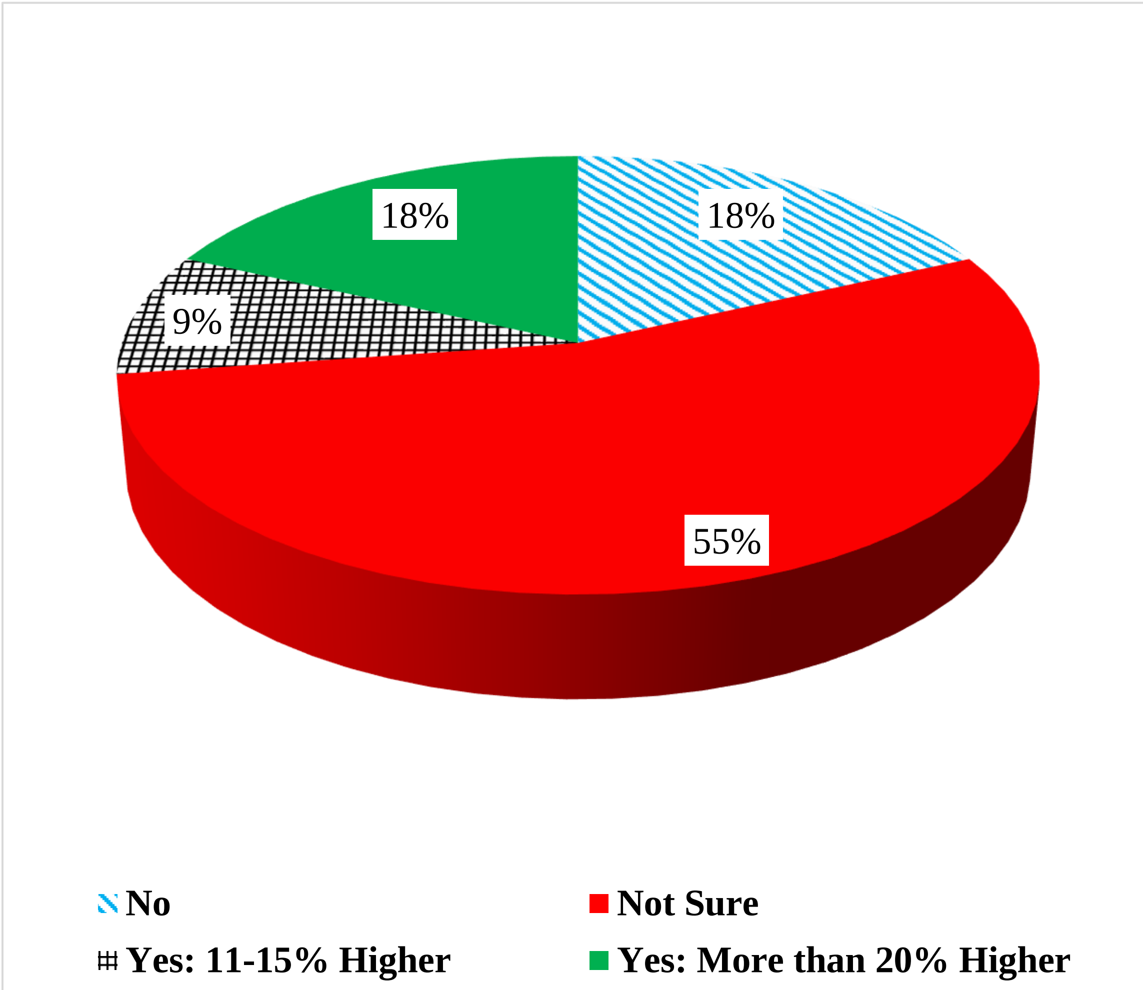


Figure 11 presents a summary of the survey responses concerning the types of distress in OGFC pavements that commonly trigger rehabilitation activities. All respondents indicated that maintenance is initiated when distresses such as raveling, potholes, or delamination are observed. Additionally, approximately 9% of respondents reported that rehabilitation is initiated when safety concerns arise due to reduced friction, tire spray, or noise in OGFC pavement sections.

Figure 11. Q16—distresses that trigger OGFC rehabilitation activities

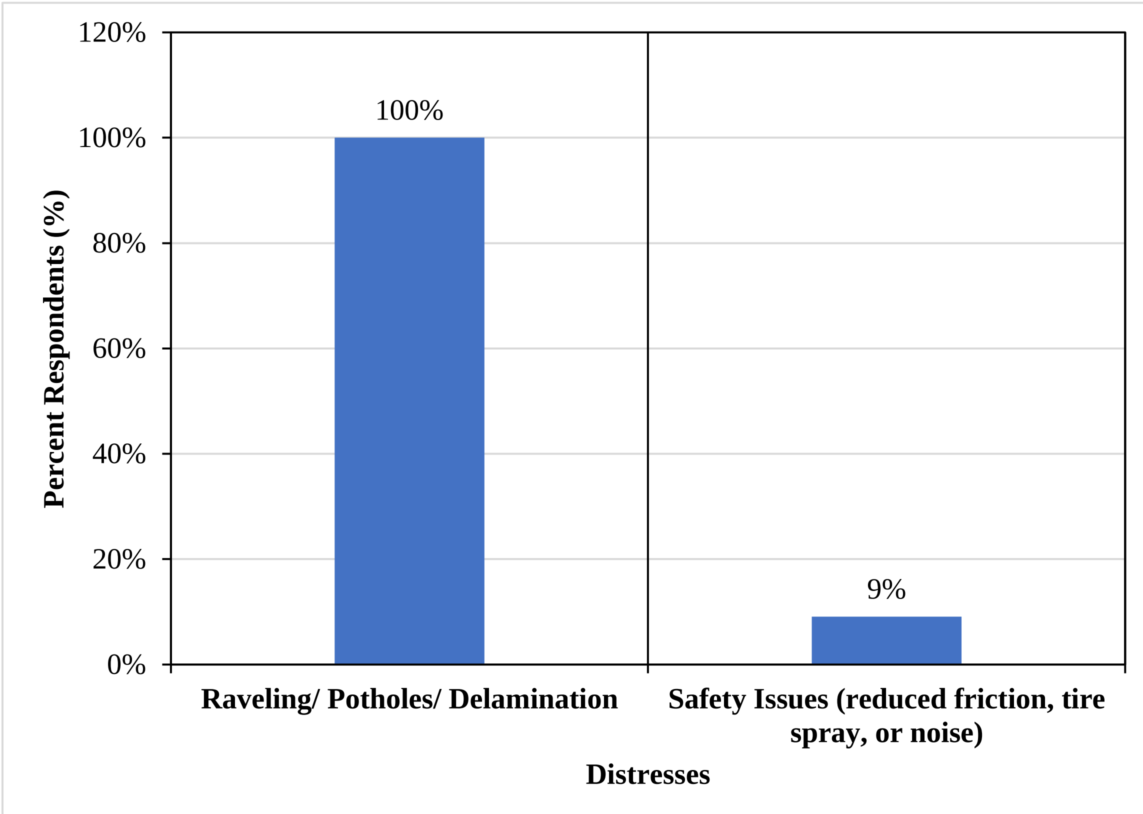


Figure 12 summarizes the techniques used for rehabilitating OGFC pavement sections, as reported by survey respondents. The most common technique is mill and overlay, used by 91% of respondents. Micromilling is also used by a significant number (36%). Some agencies (9%) employ a two-step approach: micromilling in the first rehabilitation cycle followed by full-depth milling in the second. Another 9% of agencies use a combination of patching, slurry seal, and a 1-inch high-performance thin overlay treatment.

Figure 12. Responses to Q17—techniques for rehabilitating OGFC pavement sections

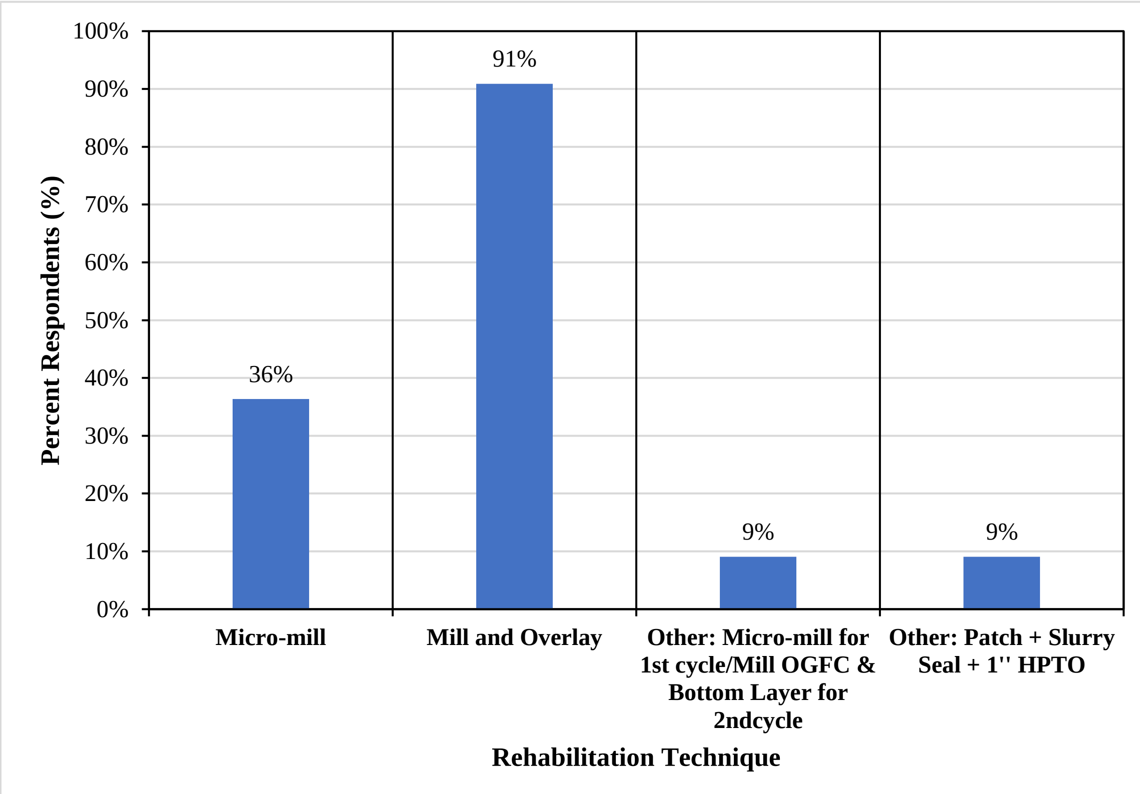


Figure 13 summarizes the responses of participants regarding whether OGFC mixtures are placed on milled surfaces. A substantial number of agencies (55%) indicated that OGFC mixtures can be placed on milled surfaces. However, another sizeable number (36%) reported that OGFC mixtures are not placed on milled surfaces. Additionally, approximately 9% of respondents indicated that OGFC mixtures are typically placed on micromilled surfaces.

Figure 13. Responses to Q18—placement of OGFC on milled surfaces

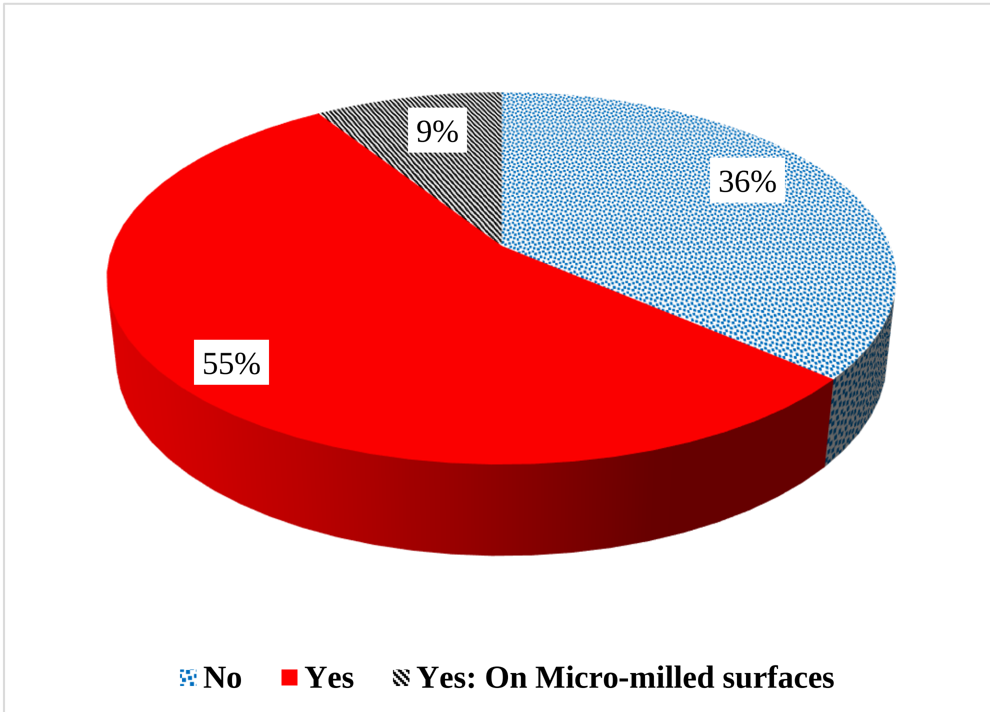


Figure 14 summarizes the responses regarding the types of mixtures typically used as an overlay for milled OGFC roadways. The majority of respondents (64%) indicated using OGFC mixtures as an overlay material. Approximately 36% and 18% reported using SMA and dense-graded (DG) mix, respectively. Other materials commonly used for overlay treatment, as reported by respondents, include dense-graded binder course (DGBC) followed by OGFC overlay, DG thin lift, or a combination of patching, slurry seal, and a 1-inch high-performance thin overlay (HPTO) treatment.

Figure 14. Responses to Q19—materials used for treating milled OGFC roadways

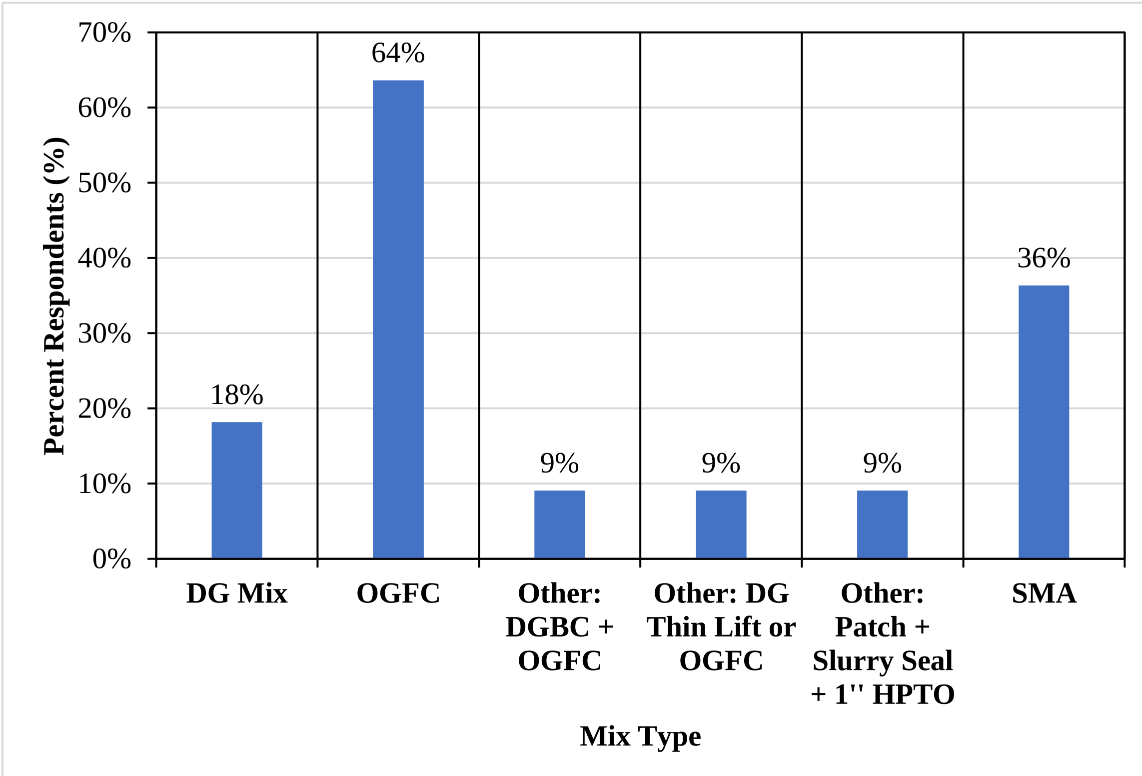


Table 3 summarizes the challenges and practices associated with OGFC pavement rehabilitation, as reported by survey respondents. States faced various challenges, including limited space, poor workmanship, and difficulties in assessing OGFC section conditions. Georgia DOT specifically noted raveling, ride quality, cracking, and delamination due to poor cleaning and tacking during rehabilitation. They also reported occasions when contractors failed to micromill the full depth of the OGFC, leading to issues. Texas DOT encountered problems with milling and replacing OGFC sections, such as unevenness, poor work quality, and incomplete removal. Florida, South Carolina, North Carolina, and Utah did not report any specific challenges or practices. The most common rehabilitation practice is mill and replace, although micromilling and patching are also used in some cases.

Table 3. Responses to Q20—challenges associated with OGFC rehabilitation

State	Response
Florida	None
South Carolina	None
Arizona	None
Tennessee	Very difficult to rehabilitate, mostly only mill and replace.
Mississippi	-
Wyoming	-
Alabama	OGFC roadways tend to hide cracking to a greater extent than SMA or other dense-graded mixes. This can cause issues in scoping projects later.
Utah	None
North Carolina	None
Georgia	Raveling, ride quality, cracking and delamination due to poor workmanship related to cleaning and tacking.
New Jersey	When micromilling, in some cases the contractor did not micromill the full depth of the OGFC. The remaining OGFC material raveled terribly and the stones damaged vehicle windshields. Emergency resurfacing was performed to remove the remaining OGFC and provide a suitable surface for traffic.

Table 4 summarizes the responses from various states regarding the requirement for tack coat application in OGFC pavement rehabilitation. All states surveyed indicated that they use tack coat in OGFC rehabilitation projects. The specific types of tack coats used vary by state, but common options include PG 64-22, UltraFuse Non-Tracking, emulsion, and hot-applied trackless tack coat. Overall, the data suggests that tack coat application is a widely adopted practice in OGFC rehabilitation.

Table 4. Responses to Q21—tack coat application in OGFC rehabilitation

State	Response
Florida	Yes
South Carolina	Yes: PG 64-22 or UltraFuse Non-Tracking
Arizona	Yes
Tennessee	Yes: Typical Emulsion or Hot-applied trackless tack coat
Mississippi	Yes
Wyoming	Yes: Emulsion
Alabama	Yes: PG Asphalt for Trackless tack, or CQS-1hP
Utah	Yes: Emulsion
North Carolina	Yes: PG 64-22, PG 58-28, or hot-applied trackless tack coat
Hawaii	Yes
Georgia	Yes
New Jersey	Yes

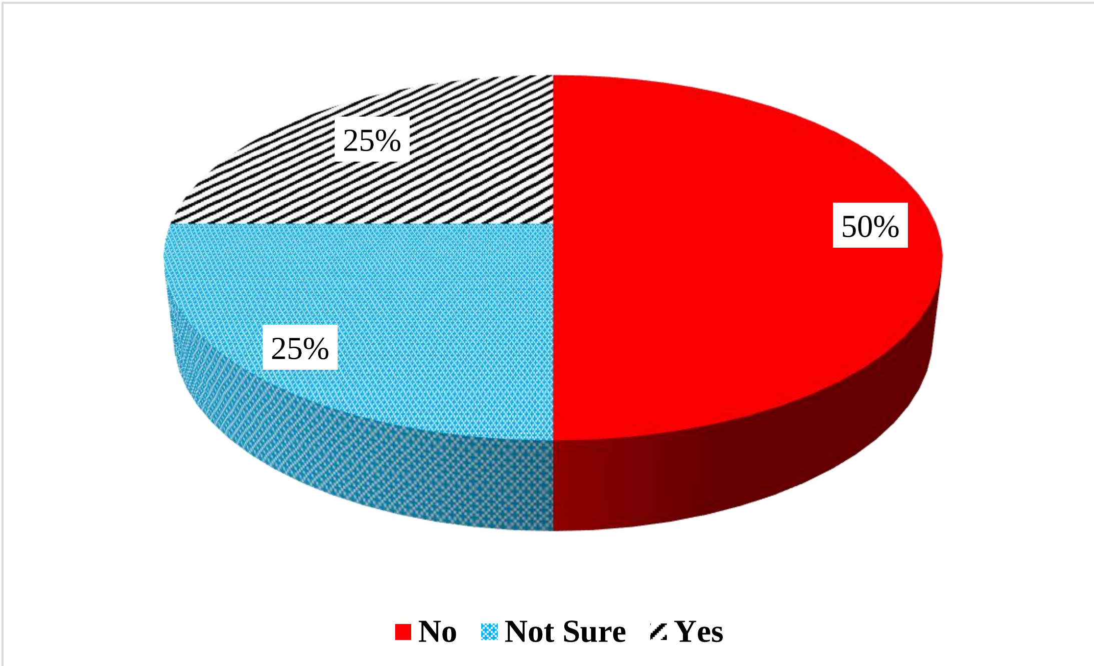
Table 5 summarizes the responses from various states regarding the minimum temperature requirements for laying OGFC pavement. All states surveyed have minimum temperature requirements in place. These requirements range from 40°F surface temperature in Alabama to 85°F surface temperature and 65°F ambient temperature in Arizona. Most states require a minimum ambient or surface temperature between 55°F and 65°F. However, some states, like Florida and Georgia, have exceptions or additional conditions for laying OGFC at lower temperatures. Overall, the data indicates that temperature is a critical factor in ensuring the successful placement of OGFC pavement.

Table 5. Responses to Q22—minimum ambient or surface temperature requirements for placing OGFC mixtures

State	Response
Florida	Yes: 65˚F, but there are some exceptions
South Carolina	Yes
Arizona	Yes: 85˚F surface temperature and 65˚F ambient temperature
Tennessee	Yes: greater than 55˚F
Mississippi	Yes: ambient and surface temperature equal to or greater than 55˚F
Wyoming	Yes: 60˚F
Alabama	Yes: 40˚F
Utah	Yes: surface temperature and temperature in the shade equal to 60˚F
North Carolina	Yes
Hawaii	Yes: 55˚F ambient temperature
Georgia	Yes: 55˚F with MTV, otherwise 60˚F
New Jersey	Yes: 50˚F

Figure 15 summarizes the responses from various states regarding the difficulty of placing OGFC compared to conventional mixtures. A significant number of surveyed states (50%) indicated that OGFC is not more difficult to place. Only Florida, Tennessee, and Wyoming reported challenges. Florida noted that OGFC mixtures are stiffer, cool faster, and are more prone to segregation and draindown, affecting their workability. Tennessee indicated that OGFC is less workable and requires careful placement on bridges. Wyoming reported that the stiffer mix of OGFC is more difficult to place compared to conventional mixtures. Overall, while some states may encounter minor challenges, contractors in most states can successfully place OGFC mixtures with minimal difficulty.

Figure 15. Responses to Q23—challenges associated with OGFC placement



Conclusions

Open-Graded Friction Course (OGFC) is a porous asphalt concrete mixture used for thin-wearing courses. It offers safety, economic, and environmental benefits by improving drainage, reducing hydroplaning, and enhancing road visibility. OGFC was first used in the 1940s and gained popularity in the 1970s due to the Federal Highway Administration's Skid Accident Reduction Program. However, performance issues led to its decline in the 1980s. To address these problems, agencies experimented with different modifications of OGFC mixtures. The Louisiana Department of Transportation and Development (DOTD) has a history of using OGFC, but faced challenges in the 1980s due to moisture and temperature issues. Research in the 2000s renewed interest in OGFC, and DOTD conducted evaluations to assess its suitability. OGFC maintenance is challenging due to its porous nature, which can lead to raveling, delamination, oxidation, clogging, and debonding. Many agencies adopt a "do nothing" approach to maintenance, as issues like raveling are often localized and do not pose a significant safety risk. Preventive maintenance is crucial for OGFC pavements. Cleaning or declogging the voids is essential to prevent permeability loss and maintain the service life of the porous base layer. However, such cleaning can be difficult and costly.

The goal of this research was to review current practices for constructing and maintaining OGFC pavements. A literature review and a multi-state survey were conducted to gather information about construction, maintenance practices, and durability issues associated with OGFC pavement sections. The survey was distributed to DOTs from all 50 U.S. states and five additional districts and territories. Based on the literature review and survey responses, the following key observations were made:

- The most commonly used asphalt binder for OGFC mixtures is PG 76-22, followed by unconventional binders like HiMA asphalt and crumb rubber.
- SB, SBS, and ground tire rubber (GTR) are the most common additives used in OGFC mixtures.
- Granite is the most widely used aggregate, followed by limestone and quartzite. Other unconventional aggregates, such as slag, are also used in some states.
- Various aggregate tests are performed on OGFC-mixture aggregates, including elongated particles, coarse aggregate angularity, fine aggregate angularity, and other

physical and durability properties. The specific tests and criteria for each aggregate property vary by state.

- The dimensional ratio specified for flat and elongated particles is typically 5:1, with a maximum allowable percentage of elongated particles ranging from 10% to 20%. A high percentage of fractured faces (85 to 100%) is generally required for coarse aggregate angularity, while fine aggregate angularity is often specified with a minimum percentage of 45%.
- The nominal maximum aggregate size (NMAS) for OGFC mixtures typically ranges from 9.5 to 12.5 mm.
- Only one respondent reported using epoxy asphalt in OGFC mixtures, and most respondents do not conduct mechanical tests on OGFC mixtures. The Cantabro test is the most common mechanical test used.
- The most common maintenance issue for OGFC pavements is raveling or delamination, followed by clogging or unclogging.
- Field tests are not conducted regularly to determine the need for maintenance, with only 9% of respondents using roughness measurements.
- Patching is a common maintenance activity, with dense-graded mixtures used most frequently.
- Maintenance costs for OGFC vary, with some states reporting higher costs compared to other pavement types.
- Rehabilitation is often triggered by raveling, potholes, delamination, or safety concerns. Mill and overlay is the most common rehabilitation technique. Micromilling is also used, sometimes in combination with full-depth milling or other treatments.
- Challenges faced by states in OGFC pavement rehabilitation include limited space, poor workmanship, and difficulties in assessing pavement conditions.
- Tack coat application is a widely adopted practice in OGFC rehabilitation, with various types of tack coats used.
- The minimum temperature requirements for laying OGFC pavement range from 40°F to 85°F, with most states requiring a minimum of 55°F to 65°F.

- While many states can place OGFC mixtures without difficulty, some states face challenges like stiffness, segregation, and draindown.

Recommendations

Based on the findings of the study, the following recommendations are made for Louisiana DOTD:

- Continue to conduct routine inspections of existing OGFC pavements to identify potential maintenance issues early.
- Prioritize preventive maintenance, such as cleaning voids and patching localized defects, to extend the service life of OGFC pavements.
- Explore and implement innovative maintenance techniques, such as specialized cleaning equipment or surface treatments, to improve efficiency and effectiveness.
- Provide comprehensive training and education programs for engineers, contractors, and maintenance personnel to enhance their knowledge and skills in OGFC pavement management.

Acronyms, Abbreviations, and Symbols

Term	Description
AASHTO	American Association of State Highway and Transportation Officials
cm	centimeter(s)
˚F	degrees Fahrenheit
DGBC	dense-graded binder course
DOTD	Louisiana Department of Transportation and Development
DOT(s)	Department(s) of Transportation
FHWA	Federal Highway Administration
ft.	foot (feet)
GTR	ground tire rubber
HiMA	highly-modified asphalt
HPTO	high-performance thin overlay
HMA	hot mix asphalt
in.	inch(es)
IRI	International Roughness Index
LTRC	Louisiana Transportation Research Center
MTV	material transfer vehicle
Max	maximum
m	meter(s)
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NMAS	nominal maximum aggregate size
OGFC	Open-Graded Friction Course
PFC	Permeable Friction Course
PPA	polyphosphoric acid
PEM	porous European mixture
lb.	pound(s)
PRC	Project Review Committee
SMA	stone matrix asphalt

Term	Description
SB	styrene-butadiene
SBR	styrene-butadiene rubber
SBS	styrene-butadiene styrene

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Appendix

Appendix A

Table 6. Specified aggregate gradation range for OGFC mixtures

Sieve Size	FL	SC	AZ	TN	MS	WY	AL	UT	NC	HI	GA (9.5 OGFC)	GA(12.5 OGFC)	GA(12.5 PEM)	NJ (9.5 OGFC)
19 mm	100	100	100	100	100	100	100	100	100	100	100	100	100	100
12.5 mm	85-100	85-100	100	85-100	100	100	85-100	100	100	100	100	85-100	80-100	100
9.5 mm	55-75	55-75	100	55-75	90-100	97-100	55-65	90-100	75-100	85-100	85-100	55-75	35-60	80-100
4.75 mm	15-25	15-30	35-55	10-25	15-30	25-45	10-25	35-45	25-45	33-47	20-40	15-25	10-25	30-50
2.36 mm	5-10	5-15	9-14	5-10	10-20	10-25	5-10	14-20	5-15	7-13	5-10	5-10	5-10	5-15
1.18 mm	-	-	0	-	-	-	-	-	-	6-11	-	-	-	-
0.6 mm	-	-	0	-	-	-	-	-	-	5-10	-	-	-	-
0.075 mm	2-5	0-4	0-2	2-4	2-5	2-7	2-4	2-4	1-3	2-4	2-4	2-4	1-4	2-5

FL: Florida; SC: South Carolina; AZ: Arizona; TN: Tennessee; MS: Mississippi; WY: Wyoming; AL: Alabama; UT: Utah; NC: North Carolina; HI: Hawaii; GA: Georgia; 9.5 and 12.5: 9.5-mm and 12.5-mm nominal maximum aggregate size; OGFC: Open-graded friction course; and PEM: Porous European mix.