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Functional and Durability Properties of Open-Graded Asphalt Mixtures: A Review

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ABSTRACT

There is a growing concern over the use of Open-Graded Asphalt (OGA) mixes as a material for the wearing surface. This is due to the many advantages that may be acquired in terms of safety, economy, and the environment. In order to successfully remove water from the surface of the pavement in a short time, the OGA mix is particularly formulated to have high air void contents. A growing number of organizations and companies all around the entire world are beginning to acknowledge the benefits of these distinctive mixes. However, there is still some cause for worry about the possible detrimental effects that surface water that has invaded the groundwater might have on the groundwater below. During the last three decades, a significant amount of research has been carried out on OGA mixes. The purpose of this paper was to examine certain issues related to design, construction, and performance that might maximize the benefits connected with the use of OGA mixes while simultaneously minimizing the negative consequences that are often associated with their utilization. It was decided to undertake a comprehensive analysis of the literature on OGA mix applications from all around the globe. Additionally, specifications for OGA mix from all over the world were assessed. As a result of the many advantages that OGA pavements offer, there is a great deal of opportunity for further studies to improve knowledge of the process, which will ultimately lead to it becoming a potential sustainability-oriented pavement material in the future. Providing a baseline for improvement of the existing design and conception of OGA mixes, the features that were summarized give directions for certain future research advances and provide a foundation for potential improvements.

1. Introduction

Open-graded friction coarse (OGFC) is a kind of asphalt mixture that is applied over conventional pavements to improve friction, safety, and the environment. The following characteristics of the OGA mixes are listed [1]:

1. Elevated and interconnected air void (AV) contents ranged from 15 % to 22%.
2. Open graded aggregate gradation.
3. Compared to the conventional DGA mixtures, these mixtures have higher binder contents and binders that are more rigid.

In this type of mixes, the mixture achieves great permeability due to its raised and linked air gaps. The interlinked air spaces facilitate water infiltration into the layer's structure, enabling lateral drainage to the underlying pavement layer and subsequently to the pavement's edge, where a sub-surface drain is constructed [2]. The distinct attributes of OGA mixtures may be classified into three categories based on several benefits: Safety, Driving, and Environmental [3]. Figure (1) illustrates the flow of water inside an OGA pavement construction. In dense graded pavements, the surface is engineered to be impermeable, necessitating that water be directed to the road's edge by a little cross slope included into the pavement.

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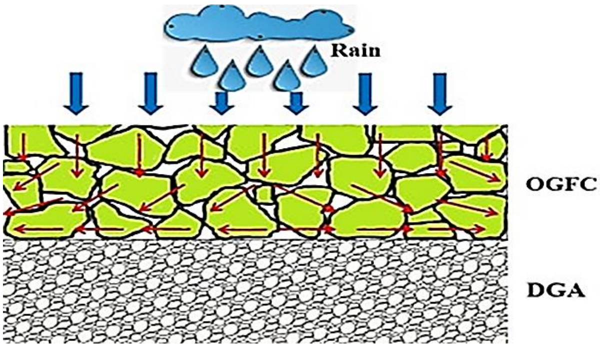

Figure (1) Movement of water within an OGA pavement structure [5].

In 1944, California became the first state in the United States to implement OGA mixtures on its roadways. The use of OGFCs became prevalent in the United States throughout the 1970s due to the Federal Highway Administration's (FHWA) initiative to enhance skid resistance on highways [2, 4].

Researching the evolution of subsequent generations of OGA and the efficacy of the modified OGA is beneficial, given the poor performance of the conventional, unaltered OGA prior to the 1990s. As a result, not all the examined studies are up to date. There has been a recent rise in the use of OGA, as several of the studies that were examined focused on its performance in the laboratory environment. Many laboratory tests have been conducted on OGA mixtures, including permeability, drainage, Cantabro, tensile strength ratio, abrasion test, etc., with the help of different additives. In the following paragraphs, the most important research works in this field are listed.

2. Differences between OGA and DGA mixes

Total air voids (AV) in OGA mixtures are larger and more extensive than in traditional DGA mixes; their composition ranges from 18% to 22%. Thinner layers are also used for OGA mixes instead of the traditional DGA mixtures. These qualities are achieved because of the open aggregate gradation in OGA blends. Alvarez-Lugo et al. [6] compared the internal structure of a traditional OGA mixture with a DGA mixture in a grayscale picture, which is shown in Figure (2).

Due to its specific internal structure, the linked AV content (i.e., the ratio of AV in the mixture that is accessible to water) in OGA mixes surpasses that of traditional dense-graded HMA. Prior studies indicated that the ratios of linked air voids in OGA mixtures varied from 65% to 100% [7]. The highly interconnected AV content and layer thickness (30 to 50 mm) facilitate noise reduction and enhance permeability for OGA mixes, while also achieving a pronounced surface texture [8-9].

When contrasted with traditional pavement, porous asphalt mixes often include more coarse aggregate and less fine aggregate. Conventional penetration-grade asphalt cannot be used in OGA mix due to the low viscosity characteristics. Additives have been added to address this issue [10].

3. Advantages and disadvantages of open mix asphalt

3.1 Benefits of Porous Asphalt

One of the main benefits of porous asphalt is the reduced amount of water that gets trapped on the road surface due to its increased permeability, which is a result of its high air void content. The following advantages may result from the pavement's high water drainage rate:

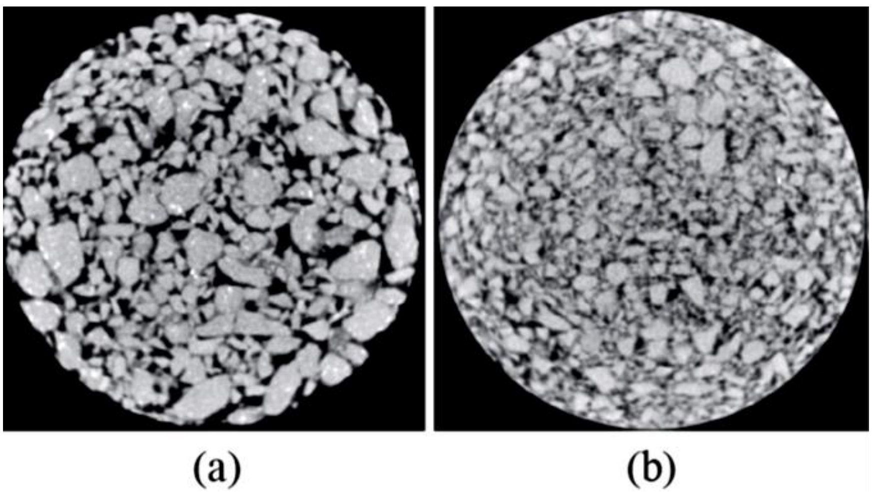

Figure (2) Difference of the internal structure of: a) An OGA mixture and b) A DGA mixture [6].

A. Safety enhancement

To enhance safety, hydroplaning is effectively mitigated with the use of OGA mixtures, even under almost saturated circumstances [11]. Reduction in spray and splash is about 90–95% compared to DGA mixtures. Furthermore, sight is enhanced by about 2.7 to 3.0 times [2]. Moore et al. [12] demonstrated enhanced visibility of road markings and decreased glare at night using this sort of mixture, as seen in Figure (3).

Moreover, it was observed that the pavement's friction with OGA markedly enhanced, particularly in inclement weather [11]. These advantageous conditions led to an overall reduction in accidents associated with inclement weather. Research conducted at 213 areas in Japan identified as prone to rain-related incidents revealed an 85% reduction in vehicle accidents after the application of OGA mixes as surface friction layers [13].

Furthermore, a complete reduction (100%) in deaths and a decrease of (76%) in accidents was reported in Louisiana with the use of the OGA mixture [15]. In San Antonio and Texas, days with precipitation saw a reported decrease of 51% in serious accidents [16]. The primary rationale for using this sort of blend is the enhancement of safety.

Figure (3) Water draining ability of porous asphalt [14].

B. Driving Quality

This sort of blend demonstrated enhanced average speeds and increased traffic capacity, contributing to improved quality advantages [8]. Additionally, improvements in pavement smoothness [17], and a decrease in fuel consumption were documented [17-18].

C. Environmental advantage

Improving water runoff quality and mitigating noise pollution are critical concerns for the environmental advantages of OGA mixtures. The total suspended particles and lead in the water runoff were decreased by almost 90% in this mixture compared to the runoff produced by typical mixes [12, 19]. The application of OGA mixes as a surface layer resulted in a noise level reduction of approximately 3-6 dB for passing vehicles [8, 18, 20, 21], and a decrease of 5.5-10.5 dB when compared to Portland Cement Concrete (PCC) surface layers [20], as illustrated in Figure (4). The primary motive for using OGA mixes, as shown in several research studies across various European nations, is their environmental advantages. Van der Zwan [22] indicated that using OGA mixtures as a surface layer in the Netherlands effectively mitigates noise throughout over 80% of the road infrastructure network. Countries such as France, Italy, Sweden, Austria, Switzerland, Denmark, Belgium, Germany, and the United Kingdom have also reported use this sort of mixture for analogous objectives [2, 16].

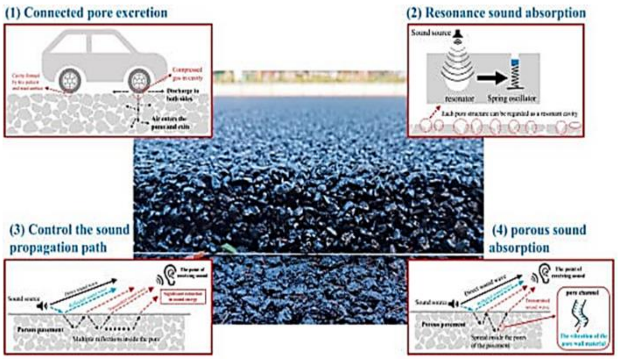

Figure (4) The noise reduction mechanism in porous pavement [23].

3.2 Disadvantages of OGA mixes

When it comes to environmental protection and safety, OGA mixtures are great. But there are still major problems with functionality and durability that prevent its broad usage. According to Wu et al. [24], this section laid out various obstacles and suggested future directions for OGA mix research and applications.

Raveling is considered the primary issue with lifespan. Raveling and aging often happen at the same time and often promote each other. To guarantee raveling resistance, high-quality raw materials are required. On the other hand, investing in premium raw materials will definitely drive-up prices. Using OGA mixes would be made much easier and more widespread with the right maintenance procedures put in place [16]. Researchers see OGA upkeep as a promising area for further investigation. However, in order to guarantee maintenance efficiency, treatment timing and procedures should be selected with caution. Conversely, OGA mix functionality may be temporarily or permanently altered by these typical maintenance procedures. Another major factor preventing OGA mixtures from being widely used is the upkeep required throughout winter. The decreased heat conductivity of OGA compared to DGA is a result of its greater air void content. Because of this, frost and ice tend to build on OGA pavement more often and early. The ride quality of OGA mixtures is often maintained by applying additional deicing agents and performing maintenance procedures more frequently. Nevertheless, these actions increase unit costs even more. Furthermore, it is currently unclear how deicing chemicals, such salt, affect the mechanical and durability of OGA mixtures [5].

In certain road conditions, the porous asphalt layer becomes unsuitable because of the following conditions [25]:

1. The skeletal strength of the pavement is inadequate. This is due to the fact that porous asphalt serves as a nonstructural layer.
2. Significant traction occurs owing to unexpected acceleration, deceleration, and turning maneuvers, particularly at essential intersections. The reason for this is the possibility of the aggregates being removed from the surfaces.
3. The road shoulders are not suitable for free drainage.
4. The roadways are shorter than one hundred meters. Reason being, there's a good chance that splash and spray will be transported over from nearby surfaces. The efficiency of porous asphalt in decreasing splash and spray might be quite poor if the route is fewer than 100 meters.
5. Traffic volume: A roadway exhibiting a traffic volume above 4,000 commercial vehicles per lane daily. The porous asphalt surface is vulnerable to degradation under intense traffic situations.
6. Highways having a speed limit of less than 40 kilometers per hour are considered slow. This is due to the fact that the consequences of the porous asphalt's inability to reduce spray and noise become negligible at this speed.
7. Porous asphalt should not be used in areas that undergo small radius turns or areas with intense turning motions. Parts of these places include junctions, parking lots, truck stops, weigh stations, and ramp terminals.
8. Porous asphalt is not recommended for use in locations prone to muddy or sandy conditions, since they may be carried onto the pavement from unpaved side roads. This includes routes that see heavy agricultural traffic, as well as those close to beaches and sand dunes. Fine sand and mud particles may clog the pores of porous asphalt, making it less effective in draining water.
9. Porous asphalt should not be utilized in regions where slow or stopped cars might spill oil or gasoline, since this could quickly weaken and damage the surface.
10. Overlays made of porous asphalt are not suitable for use on bridge decks.
11. Designated zones for removal and replacement: Porous asphalt must not be installed in locations susceptible to the formation of a bathtub effect. Conventional pavement must be used as a replacement material when parts are removed, prior to covering with porous asphalt.
12. In cold climatic regions, porous asphalt should not be installed during low temperatures. Porous asphalt with a polymer-

modified binder is required when the ambient temperature is below 5°C or when the minimum mix laydown temperature cannot be attained with traditional (unmodified) binders.

4. Historical Review of Porous Asphalt Systems

Current procedures in OGA mix design and construction, as well as their performance in the lab and on the job site, have been extensively studied. The previous 30 years have seen changes, such as the introduction of polymer-modified asphalt and other methods using OGA mixtures. There is a wide range in the expected lifespan of OGA pavements as a result of environmental factors, traffic loads and volumes, design principles, and building methods. A thorough and critical evaluation of the existing uses of OGA mixtures in pavement construction is necessary to improve the present state-of-the-art OGA standards and address local material and climate issues. Table (1) provides a brief review of some previous studies that dealt with open-graded asphalt systems.

5. Porous Asphalt Materials

The first step in designing a porous asphalt mixture, which includes aggregate type, the asphalt binder and manufacturer, and any necessary modifiers or stabilizing additives is to choose the components. The correct operation of the combination depends on knowing the physical and chemical characteristics of each component.

5.1 Aggregates

Aggregates (mineral aggregates) are solid inert substances that, when appropriately combined in the exact ratios with the asphalt binder, provide an acceptable asphalt mixture. Aggregates serve as the primary load-bearing elements of OGA pavement [42]. In OGA mixtures, aggregates may be categorized into three kinds based on their size, as outlined below [43]: Fine aggregates are defined as those that pass through a 4.75mm sieve and are retained on a 0.075mm screen. Coarse aggregates are often characterized as those that remain on the 4.75mm sieve. Mineral filler is characterized as the fraction of the aggregate that passes through the 0.075 mm sieve. Mineral filler is an extremely thin substance like flour, sometimes known as mineral dust or rock dust.

A substantial proportion of coarse aggregate and little fine aggregate should be used in the porous asphalt mix to achieve a high air void percentage. Table (2) presents examples of design gradations for porous asphalt surface courses.

5.2 Asphalt Binder (Bitumen)

Asphalt binders have been used in road building for millennia owing to their viscosity and the substantial residue left after the refinement of crude oil, which cohesively binds particles in asphalt mixtures. While natural sources of asphalt exist, the majority of asphalts used today are derived from the processing of crude oil. Asphalt is a robust cement that exhibits significant adhesion and exceptional waterproofing properties [51]. The physical characteristics of asphalt binders fluctuate considerably with temperature. At subzero

Table 1: The review of explanatory and latent variables in previous research

	Author	Objective/s	Laboratory Experiments
1	Cooley et al. [26].	To evaluate the use of cellulose fibers within OGA mixtures.	Water Absorption, Tensile Strength Ratio, Rut Testing
2	Kline [4]	The goal is to evaluate and contrast the several mix design approaches utilized for open-graded asphalt courses in the US today.	- Drain-down, Specimen Compaction, Specific Gravity, Porosity, Permeability, Cantabro Abrasion
3	Jeong et al. [27]	To evaluate the rutting resistance of Open Graded Asphalt Mixes made with different polymer modifiers and coarse aggregate sizes.	- Rutting potential,
4	Lu and Harvey [28]	To investigate the effects of several common combinations of binder type and additive on noise reduction and durability properties of a small aggregate	- Air void

		size, open-graded asphalt mix.	
5	King et al. [15]	To comprehensively evaluate Louisiana's OGA mixtures on the basis of their laboratory and field performance.	- Acoustic absorption, texture, resistance to ravelling, moisture sensitivity, permeability, friction, resistance to permanent deformation, and resistance to reflective cracking.
6	Xiao et al. [29]	To investigate moisture and rutting resistance characteristics of low Los Angeles (L.A.) Abrasion aggregate compared to high L.A. Abrasion aggregates in terms of three gradations and two PG 76-22 binders.	- Permeability, drain-down, tensile strength ratio, and wheel tracking test.
7	James et al. [30]	To address the raveling and cracking distresses commonly seen by adjusting the asphalt and dust content of OGA mixes to improve durability.	Moisture susceptibility and rut depth
8	Al-Jumaili [31]	To compare the influence of two modifier types, Styrene-butadiene-styrene (SBS) and Propylene (PP), on an OGA mixture performance.	
9	Aljawad [3]	To assess the efficiency of employing Polymer Modified Asphalt (PMA) with developed Styrene Butadiene Styrene (SBS).	- Cantabro, Permeability, Tensile strength ratio, and Hamburg wheel tracking test.
10	Ma et al. [32]	The purpose of this laboratory performance test is to examine several methods for making porous asphalt mixtures work better, as well as to determine the impact of different additives.	- Marshall Test, Cantabro Abrasion Loss Test, Drain-down Test, Air Void Analysis, Permeability, Moisture Sensitivity, and Wheel Tracking.
11	Anusha et al. [33]	To evaluate the performance studies of open graded friction course mixes with replacement of recycled asphalt pavement and addition of Arbocell fiber to the mix.	Draindown test, Falling-head permeability test, Cantabro test, tensile strength ratio (TSR), Wheel tracking test, Dynamic stability test, Marshall stability and flow, and Skid resistance test.
12	Tanzadeh et al. [34]	To study the effect of basalt and glass fibers on behavior of open-graded friction course asphalt modified with nano-silica.	- Strength test, binder drain-down, Cantabro abrasion, moisture susceptibility, rutting test, thermal stress restrained test, and permeability test.
13	Asmael [35]	To determine if modified OGFC mixes with different polymers and fibers have comparable performance.	- Air void content, Drain-down test, Cantabro test, Permeability test, Indirect tensile strength, Fatigue test, and Resistance to rutting.
14	Chen et al. [36]	To evaluate the pore characteristics and water flow pattern of the OGA mixture using image analysis and numerical simulation.	- The tests include moisture susceptibility, drain-down, Cantabro, permeability, and indirect tensile strength.
15	Mohammed et al. [37]	To study and improve the properties of OGA mixtures using SBS polymer.	- Drain-down test, Marshall test, indirect tensile strength, Cantabro test, and wheel track test.
16	Mungathia et al. [38]	To determine how sisal fiber can be used to reduce bitumen drain-down and effectively utilize waste plastics in the construction of flexible pavement to improve strength and performance capabilities.	- CT scan test and Permeability
17	Wu et al. [24]	To investigate the mechanical properties of OGA containing two different fiber types (lignin and mineral fiber).	- Permeability, Cantabro loss, drain-down, and indirect tensile ratio.
18	Muhammed [39]	To investigate the probability of using Cellulose Fiber as a modifier to improve the properties of the OGA mixture.	- Drain-down, Air voids, Stability test
19	Kamboozia et al. [40]	To evaluate the effect of the different percentages of nano-ZnO (NZ) on OGA mixes' intermediate-	- Marshall Stability, Moisture Susceptibility, Drain-down,

		temperature cracking behavior and rutting performance under various conditions.	Dynamic Stability, and TSR
20	Balreddy et al. [41]	To enhance the properties of the OGA mix with fibers.	- Air Voids, Cantabro Abrasion Loss, Drain down, and Permeability

Table (2): Different recommended design gradations for porous asphalt surfaces.

Sieve size, mm	Sieve No.	%Passing						
		NCHRP 2011, [44]	NAPA 2003, [45]	Cahill 2003, [46]	FHWA T 5040.31 [47]	ASTM D 7064 2013a, [48]	NZTA P11: 2023 PA 7 HS, [49]	NCAT [50]
37.5	3/2"	-	-	-	-	-	-	-
19	3/4"	100	100	-	-	100	-	100
12.5	1/2"	80-100	85-100	100	100	85-100	-	85-100
9.5	3/8"	35-60	55-75	95	95-100	35-60	100	55-75
4.75	#4	10-25	10-25	35	30-50	1.-25	25-55	10-25
2.36	#8	5-10	5-10	15	5-15	5-10	20-30	5-10
1.18	#16	-	-	10	-	-	-	-
0.6	#30	-	-	2	-	-	-	-
0.075	#200	0-4	2-4	-	2-5	2-4	2-5	2-4

temperatures, asphalt binder may become very brittle, yet at higher temperatures, it exhibits a fluid fluidity akin to that of oil. At ambient temperature, the majority of asphalt binders have a consistency similar to that of pliable rubber. A significant number of asphalt binders include minor proportions of polymer to enhance their physical characteristics; these substances are referred to as polymer-modified binders. The majority of asphalt binder standards were established to regulate variations in consistency due to temperature [52].

6. Properties Related to Open-Graded Asphalt Mix Testing

6.1 Void in coarse aggregate

To offer sufficient resistance to both raveling and permanent deformation, porous asphalt mixes must have stone-on-stone contact in the course-aggregate portion [53]. An extreme quantity of fine aggregate blocks the interaction of course-aggregate particles in the matrix and reduces the density of OGA mixes, which in turn leads to bad stone-on-stone contact due to unacceptable gradation [2].

Inadequate seating and interlocking of aggregates due to low density makes the mixture more susceptible to shear stresses caused by traffic loads; as a result, the asphalt's cohesiveness determines how well the mixture responds. Consequently, there has to be a dependable technique for quantifying stone-on-stone contact in OGFC mixtures that have been compacted. By comparing the voids in coarse aggregate (VCA) in the dry-rodded condition (VCADRC) and the VCA in the compacted mixture (VCAMIX), the National Center for Asphalt Technology (NCAT) suggests that the mix design of the next generation of OGFC should be verified to ensure stone-on-stone contact. In this approach, stone-on-stone contact is achieved by an OGA mixture at what time the VCA_{mix}/VCA_{DRC} ratio is one (1.0) or below, as stated by [2,54].

6.2 Asphalt Binder Drain-down

During the production and construction stages and when the mixture is exposed to elevated temperatures of about (135–177°C), the drain-down could happen. Drain-down is the migration of asphalt binder or mastic from the aggregate skeleton. The result could be a binder content that is not evenly distributed [55]. The primary focus of drain-down has been on porous asphalt mixtures, such as SMA and open-graded asphalt (OGA). The AASHTO T305 [56], and the ASTM D6390 [57] provide detailed descriptions of the drain-down test. Because the extra bitumen is located lower in the asphalt structure, it may clog these layers, leading to a gradual decline in the porous asphalt's permeability rates and major issues with drain-down in OGA mixes [58]. According to Lyons and Putman [59] and Shankar et al. [60], stabilizing additives like as polymers, rubber, and fibers may be used to reduce the quantity of drain-down in this asphalt mixture. In order to avoid problems with drain-down during manufacturing and construction, it is often important to evaluate the effectiveness of stabilizing additives at the mix design stage [61].

During the manufacturing as well as construction phases, drain-down phenomenon has been used in several investigations. According to their research, drain-down in OGA mixes happens gradually over time. Based on qualitative observations of the surface infiltration rate of a residential driveway made of porous asphalt, this theory was put in 1996 in Macon and Georgia [62]. The driveway's penetration began to decrease after four years of use, as seen by increased runoff. As the binder film covering the aggregate particles thinned off during the course of the pavement's 6-year lifespan, a black layer of the flowing binder became apparent in the pores, around 12.5 mm below the surface. During the warmer months in Georgia, the black material placed lower into the pores and actually consisted of asphalt cement combined with ground-up organic debris, which was the cause of the high temperatures. The black substance came from the binder flowing under the force of gravity when its viscosity decreased due to the increase in temperature.

The stated high asphalt contents (about 5.5–7 percent for OGA mix) may be the cause of this discrepancy in the design requirements of the OGA mix. Asphalt embrittlement and resistance to mixture disintegration by abrasion are not the primary issues with durability; rather, drain-down is. As a result, higher-penetration asphalts may not always respond as well as penetration asphalts. The asphalt concentration of mixes made in Japan and Europe is around 4-6% lower than that of US-made combinations. Rather than asphalt drain-down, the primary issue here is aggregate particle loss due to abrasion and impact (raveling), which compromises the pavement's resilience. So, because of their ductility and toughness, high penetration asphalts and particularly modified asphalts may show the right reaction to durability [6].

A study conducted by [37-38] investigated the feasibility of constructing stronger and more performance-oriented flexible pavement using sisal fibers and recycled plastics. The retention characteristic of asphalt concrete is enhanced when sisal fiber (SF) and waste plastics (WP) are combined. In contrast to the control mix's 6.5% and waste plastic's 0.8% drain-down, samples enhanced with sisal-plastic had no drain-down at all.

For optimal rheological characteristics and reduced asphalt degradation, Aljawad [3], used an OGA mix amended with Styrene Butadiene Styrene. A 377 percent increase in viscosity and a 98% reduction in drain-down were both achieved with the addition of 6 percent of the constructed polymer.

In 2016, Al-Jumaili [31], examined the effects of two kinds of modifiers on the performance of an OGA mixture: styrene-butadiene-styrene (SBS) and propylene (PP). The drain-down potential was higher in mixes lacking of polymers compared to additive-containing mixes. By incorporating PP into the mixture at a rate of 5% by weight of asphalt, the likelihood of drain-down was decreased by about 40%.

6.3 Moisture susceptibility

When environmental conditions and traffic loads interact, OGA's distinctive pore structure may cause micro-cracks to form. During the cycles of freezing and thawing, water seeps into the microscopic cracks. According to Moraes et al. [63], one of the main reason’s adhesives fail is because of moisture at the interface between the binder and the aggregate. Water expands in these cracks when subjected to the freeze-thaw cycle. The space where stones touch eventually fails as the frequency of frost-thaw cycles increases. In most cases, additional problems like raveling and ageing will appear with moisture damage. At the same time, raveling and ageing are made worse by moisture damage. One essential process outlined in standards is the study of moisture susceptibility [48].

A material's moisture susceptibility may be assessed by calculating its ITS and TSR, or tensile strength ratio. At a temperature of 25 C, the TSR is calculated by dividing the average ITS of the wet-conditioned subset by the average ITS of the unconditioned subset. For open-graded porous asphalt, the minimum TSR value that is permitted as 80% [48]. According to many studies [58,64, 65-66], OGA mixes made with polymer- or rubber-modified binders had higher TSR values and indirect tensile strengths than plain binders.

Using a recently developed machine, Hamzah et al. [67] studied the stripping of OGA mixtures in response to the dynamic influence of flowing water. In order to assess the stripping, tests were carried out in both dry and wet environments, and the ITS ratio was computed. As the conditioning period progressed, the data demonstrated a decrease in permeability and TSR. The resistances of OGFC mixes to moisture and rutting are affected by the aggregate gradations; nevertheless, from a laboratory moisture susceptibility standpoint, the Los Angeles abrasion does not play a major role [29]. Multiple studies have shown that OGA mixes may be made more resistant to moisture by adding hydrated lime and anti-strip additives [24, 68-69].

6.4 permeability

Permeability is the main property of open asphalt mixtures; if achieved, the asphalt mixture will serve its purpose as a functional property. Even though, currently, measurement of the coefficient of permeability (or permeability) is not included in the mixture design phase, during the mixture design phase, most agencies do not evaluate permeability [53]. To apply the modern methodology used to evaluate permeability in OGA mix design, the permeability coefficient must be measured in the laboratory on compacted specimens, which are formed primarily using a Superpave Gyratory Compactor (SGC) or other suitable compactors. This is, of course, achieved by achieving the target total air void content of about 18 to 22% as an indirect indicator of adequate permeability coefficient [2]. The recommended minimum permeability coefficient is 100 m/day [5, 48, 70]. Discharge time is the standard for determining the permeability coefficient. As a result, American and European researchers have devised tools (called parameters in the literature) to determine the average rate of water discharge by computing the discharge duration of a given amount of water. Nevertheless, the discharge time serves as a valuable metric for comparing various performance attributes, including drain ability, across various mixes, phases, or locations of a project, as well as under varying compaction circumstances [53].

6.5 Rutting Resistance

The rutting potential of OGA mixes is generally determined by conducting any repeated loading mechanism tester like the Asphalt Pavement Analyzer (APA) or the loaded wheel test. According to AASHTO T 340-10 [71], the typical temperature ranges for conducting the rutting test is 40 to 60 °C. Research by Jiang et al. [72] and Song et al. [73] found that rutting depth at 10,000th cycles was often documented for comparative purposes. Due of the thin OGA layer and high air void content, there are no particular rutting-resistance specifications for OGA blends. According to Coleri et al. [74], the rutting performance is significantly impacted by the thickness of the OGA layer. In order to meet the requirements of AASHTO T 340-10, a complex specimen was created by [29]. This specimen had a total depth of 75 mm and comprised both the underlying DGA and the OGA layer. Additionally, rutting performance is affected by gradient. According to Xiao et al. [29], gradations that had a higher percentage of coarse aggregate in the OGA mix often exhibited better resistance to rutting.

According to Ali et al. [75], there are essentially three rutting mechanisms: (1) material loss, (2) densification, and (3) lateral plastic flow. Asphalt mixtures that are less robust and just cover a limited fraction of rutting tend to lose materials more quickly. The primary causes of pavement rutting in asphalt mixtures are densification and plastic flow. Densification, rather than shear-related deformation, was shown to be the primary rutting process in the OGA mix due to the aggregate skeleton's apparent interlock and the improved binder's performance [74]. Figure (5) shows that the rutting depth of OGA was half of the DGA mix, as previously reported [100]. Rutting depths for

OGA mixes with four different gradations were less than 5 mm, according to another study [54].

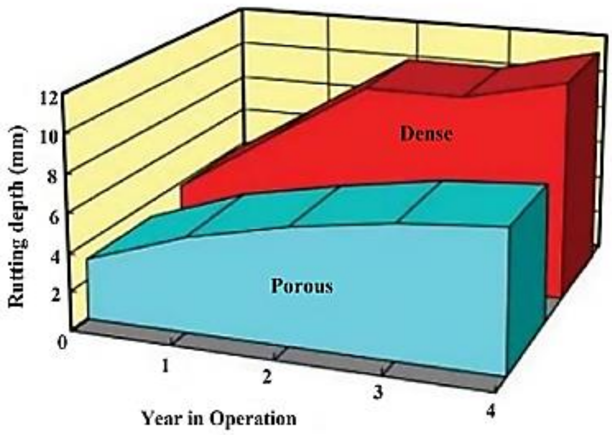

Figure (5) Rutting progress of porous asphalt and DGA (Takahashi [76].

6.6 Raveling

The loss of aggregate at the pavement's surface due to continuous abrasion by traffic, which is worsened by moisture, is known as raveling [77]. To determine how long OGA combinations last, many laboratory experiments have been suggested. Prior research provides a full inventory of these examinations [78]. Nevertheless, the Cantabro loss test created and standardized in Spain from 1978 to 1986 is the preferred method for determining an OGA mixture's resistance to disintegration [79]. Mix design and an extensive number of international studies on OGA mixes have made use of this test [6].

A number of factors, established by [54, 78, 80], have been identified as primary contributors to raveling. These factors include materials selection and reaction, as well as mix design: (1) moisture damage in the OGA mixture or in the underneath DGA layer, (2) asphalt oxidative ageing, (3) limited asphalt film thickness, (4) asphalt drain-down, (5) aggregate degradation during compaction, (6) lack or poor tack coat underneath the OGA mixture, (7) improper mixture compaction, and (8) the reduction of asphalt stiffness due to oil and fuel drippings in accidents zones and parking areas.

Ageing causes raveling phenomenon, according to Zhang and Leng [81]. However, compared to the OGA mixture with SBS-modified asphalt binder, the mixture with basic asphalt binder was more significantly affected by ageing in terms of raveling resistance. The abrasion resistance of the OGA mix was evaluated by Wu et al. [24] and Dong et al. [82] using a modified asphalt pavement analyzer (APA), in addition to the Cantabro loss test. The APA test was able to accurately replicate field raveling with studded wheels and higher wheel load.

7. Mixture design method

Once the appropriate materials have been selected for the mixture, the Optimal Binder Content (OBC) may be calculated. When made according to the correct method, OGA mixes typically have a binder percentage ranging from 5 to 7 percent by weight. The mixed-materials design process often begins with the compressed specimen technique. A set of three replicates is used for each asphalt binder content, and a range of three to five distinct contents are used to make the mixtures. When the components are mixed together, a Marshall compactor, or another suitable compactor, is used to compress the mixture. According to Aljawad [3], the compacted specimens are found to have the following volumetric properties:

1. Air void content (AV%).
2. Voids in the coarse aggregate in dry-roded condition VCA_{drc}.
3. Bulk specific gravity (Gmb).
4. Maximum theoretical specific gravity (Gmm).
5. Voids in the coarse aggregate in compacted mix condition (VCA_{mix}).

Several tests are performed on the specimens to specify the properties of the OGA mix after analyzing the volumetric properties. The most common design properties include the following:

1. Stone-on-stone contact evaluation by ensuring that the ratio of (VCA_{mix}/VCA_{drc}) is less than 1.0.
2. Potential drain-down estimated with the Wire Basket method described in ASTM D6390 [57]; NAPA [83].
3. Unaged specimens are tested for abrasion loss using the Cantabro abrasion test according to ASTM C131 [85]; NAPA [84].
4. The falling-head principle is used to evaluate the permeability, which is described in ASTM D5084 [86].

5. Performing moisture damage susceptibility, typically through the Tensile Strength Ratio (TSR) according to AASHTO T283 [87].

An OBC used in the OGFC mixture is chosen based on the asphalt binder content that meets the precise volumetric and performance property criteria specified by each specification, country, or agency [2]. Changing the stabilizer type or reducing the asphalt binder content may lower drain-down values. It is recommended to decrease the asphalt binder content if the AV content is below the stated value [2].

To address abrasion, it is advised to increase the asphalt binder concentration if the Cantabro loss for the unaged samples is more than the necessary value. Lastly, this approach recommends adjusting the chosen additives and raising the asphalt binder concentration if the mass loss of the aged specimens in the Cantabro test is more than what is needed by the standard [3].

8. Maintenance of Porous Asphalt Pavements

To keep porous asphalt mixes performing as expected, maintenance is essential. For the purpose of controlling maintenance activities, there are few established processes. Some US authorities have suggested these techniques. Various maintenance approaches for porous asphalt mixes, including clogging, winter, corrective, preventative, rehabilitative, and general maintenance, are briefly described along with their major methodologies. In order to determine how well maintenance operations for porous asphalt mixes met the requirements of ASTM D5084 [86] and ASTM D6390 [80], Fay and Akin [88], performed an investigation.

Porous asphalt repair may make use of the following methods Jendia and Krezem [52]:

1. Two times a year, Vacuum.
2. Two times a year, clean the inlets.
3. Maintain adjacent planted areas.
4. Unprotected pavement surfaces must not be used for construction staging.
5. When sand is not an option, use salt.
6. It is possible to recover, recycle, and re-lay porous asphalt if its permeability is significantly decreased due to an unknown cause.

9. Future Prospects for OGA Mixes

When it comes to practicality, standards should have a universal and consistent way to measure permeability. Precise permeability cannot be guaranteed by the current porosity assessment. When studying permeability in the vertical direction, the two most prevalent approaches utilized in laboratories and field tests nowadays are the falling head method and the constant head method. Even so, OGA pavement drainage combines lateral and vertical flow. It is advised to use a more thorough testing procedure that takes into account the water seepage from various angles. The current state of OGA's CBA is severely constrained due to the short data set. Because of the better-quality raw materials and more complex production methods used in OGA, the unit cost is greater than that of DGA. When considering the decrease of accidents, however, OGA offers better cost effectiveness. According to Wu et al. [24], the CBA of OGA is predicted to keep rising in the future due to its practicality and longevity.

10. Conclusion

Following is some of the aspects that may be emphasized based on the literature research that has been completed in this chapter:

1. Open-graded asphalt mix is a special mix that has an open nature that allows water to pass through it and has a special aggregate composition that allows this. This mix has advantages and disadvantages. Asphalt mixes may be suitable for use in certain areas depending on weather conditions and traffic volumes.
2. To improve environmental quality, pavement friction, and pedestrian safety, traditional pavements may be coated with thin layers of asphalt mixes, which are known as Open-Graded Asphalts (OGAs). Commonly utilized DGA mixes would not be able to provide such advantages.
3. It became clear that there are several ways to enhance the longevity and practicality of OGA mixes; for instance, by adding rubber, fiber, polymers, etc.

To make OGA more suitable for local highway roads in terms of performance, volumetric, functional qualities, and mechanical characteristics, this study suggested utilizing a binder modified with polymers.

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References

[1] Putman, B. J., & Kline, L. C. (2012). Comparison of mix design methods for porous asphalt mixtures. Journal of Materials in Civil Engineering, 24(11), 1359-1367.

[2] Kandhal, P. S. (2002). Design, construction, and maintenance of open-graded asphalt friction courses. National Asphalt Pavement Association.

[3] Aljawad, O. (2018). CHARACTERIZING OPEN GRADED FRICTION COURSE PERFORMANCE FOR HIGHWAY PAVEMENTS (Doctoral dissertation, University of Kerbala).

[4] Kline, L. C. (2010). Comparison of open graded friction course mix design methods currently used in the United States (Master's thesis, Clemson University).

[5] Wu, H., Yu, J., Song, W., Zou, J., Song, Q., & Zhou, L. (2020). A critical state-of-the-art review of durability and functionality of open-graded friction course mixtures. Construction and Building Materials, 237, 117759.

[6] Alvarez-Lugo, A. E., Reyes-Ortiz, O. J., & Miró, R. (2014). A review of the characterization and evaluation of permeable friction course mixtures. Ingeniare. Revista chilena de ingeniería, 22(4), 469-482.

[7] Alvarez, A. E., Martin, A. E., & Estakhri, C. (2010). Internal structure of compacted permeable friction course mixtures. Construction and Building Materials, 24(6), 1027-1035.

[8] Cooley, L. A., Brumfield, J. W., Mallick, R. B., Mogawer, W. S., Partl, M., Poulikakos, L., & Hicks, G. (2009). Construction and maintenance practices for permeable friction courses (Vol. 640). Washington, DC: Transportation Research Board.

[9] Ranieri, V., Ying, G., & Sansalone, J. (2012). Drainage modeling of roadway systems with porous friction courses. Journal of transportation engineering, 138(4), 395-405.

[10] Mansour, T. N., & [1]Putman, B. J. (2013). Influence of aggregate gradation on the performance properties of porous asphalt mixtures. Journal of Materials in Civil Engineering, 25(2), 281-288.

[11] Dell'Acqua, G., De Luca, M., & Lamberti, R. (2011). Indirect skid resistance measurement for porous asphalt pavement management. Transportation research record, 2205(1), 147-154.

[12] Moore, L. M., Hicks, R. G., & Rogge, D. F. (2001). Design, construction, and maintenance guidelines for porous asphalt pavements. Transportation research record, 1778(1), 91-99.

[13] Huddleston, I. J., Zhou, H. and Hicks, R. G. (1993) “Evaluation of Open-Graded Asphalt Concrete Mixtures Used in Oregon,” Transportation research record, (1427).

[14] Gul, M. A., & Alwi, M. M. A. (2024). Self-Healing Asphalt Using Steel Fibers: Induction Heating.

[15] King, W., Kabir, S., Cooper, S. B., & Abadie, C. (2013). Evaluation of open graded friction course (OGFC) mixtures (No. FHWA/LA. 13/513). Louisiana. Dept. of Transportation and Development.

[16] Hernandez-Saenz, M. A., Caro, S., Arámbula-Mercado, E., & Martin, A. E. (2016). Mix design, performance and maintenance of Permeable Friction Courses (PFC) in the United States: State of the Art. Construction and Building Materials, 111, 358-367.

[17] Bennert, T., Fee, F., Sheehy, E., Jumikis, A. and Sauber, R., 2005. Comparison of thin-lift hot-mix asphalt surface course mixes in New Jersey. Transportation research record, 1929(1), pp.59-68.

[18] Liu, Q., Schlangen, E. and van de Ven, M. (2012) Induction Healing of Porous Asphalt, Transportation Research Record: Journal of the Transportation Research Board. doi: 10.3141/2305-10.

[19] Roseen, R. M., Ballestero, T. P., Houle, J. J., Briggs, J. F., & Houle, K. M. (2012). Water quality and hydrologic performance of a porous asphalt pavement as a storm-water treatment strategy in a cold climate. Journal of Environmental Engineering, 138(1), 81-89.

[20] Freitas, E., Pereira, P., de Picado-Santos, L. and Santos, A., 2009. Traffic noise changes due to water on porous and dense asphalt surfaces. Road Materials and Pavement Design, 10(3), pp.587-607.

[21] Chu, L., Fwa, T. F., & Tan, K. H. (2017). Evaluation of wearing course mix designs on sound absorption improvement of porous asphalt pavement. Construction and Building Materials, 141, 402-409.

[22] Van der Zwan, J. T. (2011). Developing porous asphalt for freeways in the Netherlands: Reducing noise, improving safety, increasing service life. TR News, (272).

[23] Ling, S., Yu, F., Sun, D., Sun, G., & Xu, L. (2021). A comprehensive review of tire-pavement noise: Generation mechanism, measurement methods, and quiet asphalt pavement. Journal of Cleaner Production, 287, 125056.

[24] Wu, H., Yu, J., Song, W., Zou, J., Song, Q., & Zhou, L. (2020). A critical state-of-the-art review of durability and functionality of open-graded friction course mixtures. Construction and Building Materials, 237, 117759.

[25] Ahmad, K. A., Abdullah, M. E., Hassan, N. A., Daura, H. A., & Ambak, K. (2017). A review of using porous asphalt pavement as an alternative to conventional pavement in stormwater treatment. World Journal of Engineering, 14(5), 355-362

[26] Cooley, L. Allen, Jr., E. Ray Brown, and Donald E. (2000). Evaluation of open-graded friction course mixtures containing cellulose fibers. Transportation Research Record, 1723(1), 19-25.

[27] Jeong, K. D., Hwang, S. D., Lee, S. J., & Kim, K. W. (2011). Investigation of rutting potential of open graded friction course (OGFC) mixes using asphalt pavement analyzer. KSCE Journal of Civil Engineering, 15, 1259-1262.

[28] Lu, Q., & Harvey, J. T. (2011). Laboratory evaluation of open-graded asphalt mixes with small aggregates and various binders and additives. Transportation Research Record, 2209(1), 61-69.

[29] Xiao, F., Herndon, D. A., Amirkhanian, S., & He, L. (2015). Aggregate gradations on moisture and rutting resistances of open graded friction course mixtures. Construction and Building Materials, 85, 127-135.

[30] James, T., Watson, D., Taylor, A., Tran, N., & Rodezno, C. (2017). Improving cohesiveness of porous friction course asphalt mixtures. Road Materials and Pavement Design, 18(sup4), 256-272.

[31] Al-Jumaili, M. A. H. (2016). Laboratory evaluation of modified porous asphalt mixtures. Appl. Res. J, 8, 2-3.

[32] Ma, X., Li, Q., Cui, Y. C., & Ni, A. Q. (2018). Performance of porous asphalt mixture with various additives. International Journal of Pavement Engineering, 19(4), 355-361.

[33] Anusha, T. M., Jagadeesh, H. S., & Sunil, S. (2019, October). Experimental investigation of Open Graded mixes using Reclaimed Asphalt Pavement. In IOP Conference Series: Materials Science and Engineering (Vol. 561, No. 1, p. 012061). IOP Publishing.

[34] Tanzadeh, R., Tanzadeh, J., & Tahami, S. A. (2019). Experimental study on the effect of basalt and glass fibers on behavior of open-graded friction course asphalt modified with nano-silica. Construction and building materials, 212, 467-475.

[35] Asmael, N. M. (2019). Investigate engineering properties of modified open-graded asphalt mixtures. Cogent Engineering, 6(1), 1678555.

[36] Chen, J., Wang, J., Wang, H., Xie, P., & Guo, L. (2020). Analysis of pore characteristics and flow pattern of open-graded asphalt mixture in different directions. Journal of Materials in Civil Engineering, 32(9), 04020256.

[37] Mohammed, H. H. (2021). Using of Open-Graded Bituminous Mixtures in Iraq. Turkish Journal of Computer and Mathematics Education (TURCOMAT), 12(11), 2443-2457.

[38] Mungathia, T., Gariy, Z. A., & Nyomboi, T. (2021). Analysis of Bitumen Draindown Characteristics of Sisal-plastic Modified Open Graded Asphalt. Journal of Agriculture, Science and Technology, 20(1), 94-106.

[39] Muhammed, A. J., Qasim, Z. I., & Al-Rubaee, R. H. (2022). Modifying the Properties of Open-Graded Friction Course by Adding Cellulose Fiber. Engineering and Technology Journal, 40(11), 1365-1375.

[40] Kamboozia, N., Mousavi Rad, S., & Saed, S. A. (2022). Laboratory investigation of the effect of nano-ZnO on the fracture and rutting resistance of porous asphalt mixture under the aging condition and freeze–thaw cycle. Journal of Materials in Civil Engineering, 34(5), 04022052.

[41] Balreddy, M. S., Nethra, P., & Naganna, S. R. (2023). Performance Evaluation of Open-Graded Bituminous Concrete Modified with Natural Fibers. Sustainability, 15(15), 11952.

[42] Matar, S. Y. F. (2017). Studying the Effect of Adding Glass Fiber on the Mechanical Properties of Asphalt Mixtures (Wearing Course Layer) (Master Dissertation, Gaza: The Islamic University).

[43] Schaus, L. K. (2007). Porous asphalt pavement designs: Proactive design for cold climate use (Master's thesis, University of Waterloo).

[44] NCHRP. (2011). A Manual for Design of Hot Mix Asphalt with Commentary (Vol. 673). Transportation Research Board. Washington, DC: The National Academies Press.

[45] NAPA. (2003). Porous asphalt pavement. National Asphalt Pavement Association, Lanham Maryland.

[46] Thomas H. Cahill, P.E., Michele Adams, P.E., and Courtney Marm. (2003). "Porous Asphalt: The Right Choice for Porous Pavements. Hot Mix Asphalt Technology" – September/October 2003. PP 26-40.

[47] FHWA, Open-Grade Friction Courses, in Technical Advisory T 5040.31. 1990, U.S. Department of Transportation

[48] ASTM-D7064 (2013). Standard Practice for Open-Graded Friction Course (OGFC) Mix Design. Annual book of ASTM standards.

[49] NZTA P11: 2023. Specification for Open-Graded Porous Asphalt.

[50] NCAT Report 00- 01. National Center for Asphalt Technology. Mississippi Department of

Transportation. (2005). Mix Design of Open Graded Friction Course Hot Mix Aspahlt (MT-83).

[51] Ashour, B., (2017), "The Relationship between Mechanical Properties and Initial Temperature of Compacted Asphalt Mixture of Binder Course", M.Sc Thesis: Islamic University of Gaza, Palestine.

[52] Jendia, S., & Krezem, M. (2019). Producing Porous Asphalt in Palestine According to ASTM D7064. Journal of Engineering Research & Technology, 6(1).

[53] Alvarez, A. E., Martin, A. E., Estakhri, C. K., Button, J. W., Glover, C. J., & Jung, S. H. (2006). Synthesis of current practice on the design, construction, and maintenance of porous friction courses (No. FHWA/TX-06/0-5262-1).

[54] Mallick, R. B., Kandhal, P. S., Cooley Jr, L. A., & Watson, D. E. (2000). Design, construction, and performance of new-generation open-graded friction courses. National Center for Asphalt Technology. Auburn, AL, USA.

[55] Huber, G. (2000). Performance survey on open-graded friction course mixes. Synthesis of Highway Practice. (Vol. 284). Transportation Research Board, National Research Council, Washington, D.C.

[56] AASHTO T305-2014, (2014), "standard method of test for determination of draindown characteristics in un compacted asphalt mixtures.

[57] ASTM (2011a) "D 6390 Standard Method of Test For Determination of Draindown Characteristics In Un-compacted Asphalt Mixtures," Annual Book of American Society for Testing materiasl ASTM Standards, pp. 6–8. doi: 10.1520/D639011.2.

[58] Lyons, K. (2012). Evaluation of rubber modified porous asphalt mixtures. M.Sc. Thesis. All Thesis, 1563. Clemson University. Lyons, Kimberly.

[59] Lyons, K. R., and Putman, B. J. (2013). "Laboratory Evaluation of Stabilizing Methods for Porous Asphalt Mixtures". Construction and Building Materials, 49, 772-780.

[60] Shankar, A. U., Suresha, S. N., and Saikumar, G. M. V. S. (2014). "Properties of Porous Friction Course Mixes for Flexible Pavements". Indian Highways, 42(3).

[61] Putman, B. J. and Amirkhanian, S. N. (2004) "Utilization of waste fibers in stone matrix asphalt mixtures," Resources, Conservation and Recycling, 42(3), pp. 265–274.

[62] Ferguson, B. K. (2010, June). Porous pavements in North America: experience and importance. In Novatech 2010-7ème Conférence internationale sur les techniques et stratégies durables pour la gestion des eaux urbaines par temps de pluie/7th International Conference on sustainable techniques and strategies for urban water management (pp. 1-6). GRAIE, Lyon, France.

[63] Moraes, R., Velasquez, R., & Bahia, H. U. (2011). Measuring the effect of moisture on asphalt–aggregate bond with the bitumen bond strength test. Transportation Research Record, 2209(1), 70-81.

[64] Luo, S., Lu, Q., & Qian, Z. (2015). Performance evaluation of epoxy modified open-graded porous asphalt concrete. Construction and Building Materials, 76, 97-102.

[65] Suresha, S. N., Varghese, G., & Shankar, A. R. (2009). A comparative study on properties of porous friction course mixes with neat bitumen and modified binders. Construction and Building Materials, 23(3), 1211-1217.

[66] Chen, J. S., Sun, Y. C., Liao, M. C., Huang, C. C., & Tsou, K. W. (2013). Evaluation of permeable friction course mixes with various binders and additives. Journal of materials in civil engineering, 25(5), 573-579.

[67] Sengoz, B., & Agar, E. (2007). Effect of asphalt film thickness on the moisture sensitivity characteristics of hot-mix asphalt. Building and environment, 42(10), 3621-3628.

[68] Hamzah, M. O., Hasan, M. M., Van De Ven, M. F. C., & Voskuilen, J. L. M. (2012). Development of dynamic asphalt stripping machine for better prediction of moisture damage on porous asphalt in the field. In 7th RILEM International Conference on Cracking in Pavements: Mechanisms, Modeling, Testing, Detection and Prevention Case Histories (pp. 71-81). Springer Netherlands.

[69] Mouillet, V., Séjourné, D., Delmotte, V., Ritter, H. J., & Lesueur, D. (2014). Method of quantification of hydrated lime in asphalt mixtures. Construction and Building Materials, 68, 348-354.

[70] Masri, K. A., & Arshad, A. K. (2015). Performance Tests of Porous Asphalt Mix—A Review. In InCIEC 2014: Proceedings of the International Civil and Infrastructure Engineering Conference 2014 (pp. 1231-1243). Springer Singapore.

[71] Watson, D. E., Cooley Jr, L. A., Ann Moore, K., & Williams, K. (2004). Laboratory performance testing of open-graded friction course mixtures. Transportation Research Record, 1891(1), 40-47.

[72] AASHTO T 340-10 (2015). Standard method of test for determining the rutting susceptibility of hot mix asphalt (HMA) using the asphalt pavement analyzer (APA). American Association of State Highway and Transportation Officials, Washington, D.C.

[73] Jiang, J., Ni, F., Dong, Q., Yao, L., & Ma, X. (2019). Investigation of the internal structure change of two-layer asphalt mixtures during the wheel tracking test based on 2D image analysis. Construction and Building Materials, 209, 66-76.

[74] Song, W., Huang, B., & Shu, X. (2018). Influence of warm-mix asphalt technology and rejuvenator on

performance of asphalt mixtures containing 50% reclaimed asphalt pavement. Journal of Cleaner Production, 192, 191-198.

[75] Coleri, E., Harvey, J. T., Yang, K., & Boone, J. M. (2013). Micromechanical investigation of open-graded asphalt friction courses' rutting mechanisms. Construction and Building Materials, 44, 25-34.

[76] Ali, Y., Irfan, M., Ahmed, S., & Ahmed, S. (2017). Empirical correlation of permanent deformation tests for evaluating the rutting response of conventional asphaltic concrete mixtures. Journal of Materials in Civil Engineering, 29(8), 04017059.

[77] Takahashi, S. (2013). Comprehensive study on the porous asphalt effects on expressways in Japan: Based on field data analysis in the last decade. Road Materials and Pavement Design, 14(2), 239-255.

[78] Arambula-Mercado, E., Hill, R. A., Caro, S., Manrique, L., Park, E. S., & Fernando, E. G. (2016). Understanding Mechanisms of Raveling to Extend Open Graded Friction Course (OGFC) Service Life [report].

[79] Alvarez, A. E., Martin, A. E., & Estakhri, C. (2011). A review of mix design and evaluation research for permeable friction course mixtures. Construction and Building Materials, 25(3), 1159-1166.

[80] Rubio, B., Jiménez, R., Pérez, F., & Martínez, A. (2009). Assessment of moisture effect on open graded mixes using water sensitivity and Cántabro after immersion tests. In Advanced Testing and Characterization of Bituminous Materials, Two Volume Set (pp. 287-298). CRC Press.

[81] Kabir, M. S., King Jr, W., Abadie, C., Icenogle, P., & Cooper Jr, S. B. (2012). Louisiana's experience with open-graded friction course mixtures. Transportation research record, 2295(1), 63-71.

[82] Zhang, Y., & Leng, Z. (2017). Quantification of bituminous mortar ageing and its application in ravelling evaluation of porous asphalt wearing courses. Materials & Design, 119, 1-11.

[83] Dong, Q., Wu, H., Huang, B., Shu, X., & Wang, K. (2013). Investigation into laboratory abrasion test methods for pervious concrete. Journal of Materials in Civil Engineering, 25(7), 886-892.

[84] NAPA (National Asphalt Pavement Association), (2002), "Design and Constructing SMA Mixtures – State-of-the-Practice", National Asphalt Pavement Association, Lanham, Maryland.

[85] ASTM (2003a) "C131 Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine."

[86] ASTM (2003c) "D5084 Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter."

[87] AASHTO T283-14, (2014), "Standard method of test for resistance of compacted asphalt mixture to moisture-induced damage", American Association of State highway and Transportation Officials, Washington. D.C.

[88] Fay, L., & Akin, M. (2014). Snow and ice control on porous and permeable pavements: literature review and state of the practice. Transportation Research Board 93rd Annual Meeting Transportation Research Board, (14-2839).