Acta Scientiarum

http://periodicos.uem.br/ojs
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v45i1.59011

CIVIL ENGINEERING

Mix design of large-stone asphalt mixtures for heavy-traffic roads

Zila Maria Garcia Mascarenhas[1*], Igor Amorim Beja[2], Kamilla Lima Vasconcelos[1] and Liedi Legi Bariani Bernucci[1]

[1]Departamento de Engenharia de Transportes, Escola Politécnica, Universidade de São Paulo, Avenida Professor Almeida Prado, 83, 05508-070, São Paulo, São Paulo, Brazil. [2]Departamento de Engenharia Civil e Ambiental, Universidade de Brasília, Brasília, Distrito Federal, Brazil. *Author for correspondence. E-mail: zila.mascarenhas@gmail.com

ABSTRACT. Heavy traffic and high temperatures are a common cause of rutting in paved areas, which reduces the time needed between pavement maintenance interventions. Large-stone asphalt mixtures (LSAMs) can reduce rutting when used as intermediate layers in pavement rehabilitation. LSAM is asphalt concrete with a nominal maximum aggregate size of at least 25 mm. In this study, we provide a brief literature review of the historical use of LSAMs, as well as the relevant characteristics of LSAM design. Three LSAMs were designed using different compaction methods: (i) Marshall compaction; (ii) rolling compaction; and (iii) Superpave gyratory compaction (SGC) by varying the compaction energy in 75, 100, and 125 gyrations. Depending on the mix design method used, the designed asphalt content ranged from 3.0 to 4.3%. The locking point from the SGC was evaluated at different gyratory compaction energies, which were related to the porosity of the dominant aggregate size range. These parameters are considered to be of great value when evaluating the LSAM design.

Keywords: LSAM; asphalt mix design; compaction methods; locking point.

Received on May 1, 2021.
Accepted on October 25, 2021.

Introduction and background

Hot mix asphalt (HMA) has been extensively used as the surface course of pavements worldwide, as it can provide good road infrastructure conditions to transport people and goods. Currently, this material is also applied to lower layers of pavement structures for the prevention of damage caused by increasing traffic volumes and overloaded vehicles that have increased tire inflation pressure.

In 1980, in the USA, the increase of distress in pavements became an issue that turned the pavement engineer's attention to the search for more durable solutions. The need for resistant pavement structures has led to the development of large-stone asphalt mixture (LSAM) technology. LSAM is defined as asphalt concrete with a nominal maximum aggregate size (NMAS) ⩾ 25 mm (Kandhal, 1990; National Cooperative Highway Research Program [NCHRP], 1997; United States Army Corps of Engineers [Usace], 2000). It has not been widely studied, and is mostly evaluated as a technique for reducing permanent deformation in the wheel path and improving the durability of pavements.

It is believed that LSAMs can present both technical and economic advantages when subjected to very heavy traffic, particularly by avoiding premature rutting. The National Cooperative Highway Research Program (NCHRP) project 4-18 indicates the benefits of LSAMs (NCHRP, 1997): (i) the use of a lower design asphalt binder content for mixture homogenization with complete aggregate coating when compared to conventional mixtures; (ii) the requirement of less crushing energy to meet the aggregate design parameters; (iii) better resistance to rutting; (iv) the need for a thin surface course over the LSAM when it is used as a base course; (v) good resistance to thermal cracking; and (vi) greater service life of LSAM pavements under heavy-duty traffic.

The conventional Marshall mix design procedure, commonly used in Brazil, limits the mineral aggregate to a maximum aggregate size (MAS) of 25 mm owing to the use of a 100 mm diameter compaction mold. This is the main difficulty in studying LSAMs in countries that still use the Marshall design method. However, there are other test procedures that can be used for LSAM design, such as rolling compaction, gyratory compaction, and a modified Marshall design method with 150 mm diameter specimens. The latter one was developed specifically for testing LSAMs, owing to the resistance of most American agencies to buy new equipment that was still expensive and unusual for conventional mixture design (Kandhal, 1989).

In this study, we present the evaluation of the LSAM design with different compaction methods: (i) Marshall compaction; (ii) rolling compaction; and (iii) Superpave (superior performing asphalt pavements) gyratory compaction (SGC) with different compaction energies of 75, 100, and 125 gyrations. The locking point (LP) from the SGC was evaluated at different gyratory compaction energies, which were related to the porosity of the dominant aggregate size range (DASR). This analysis was considered as an additional parameter for the LSAM design. Results of rutting depth from the Laboratoire central des ponts et chaussées (LCPC) permanent deformation tests were presented to validate these data.

LSAM overview

LSAMs have been applied as a structural layer of the so-called 'Bitulithic pavement' since the 1900s by the Warren Brothers Company in the USA. They were the first to use aggregate gradation with particle dimensions varying from 37.5 to 50 mm. Remarkable pavement resistance characteristics that can withstand traffic conditions have been observed. The motor vehicle became the dominant road user requiring better quality roads than those previously needed for horses and carriages (Warren Brothers Company, 1912; The Cambridge Tribune, 1916). Since then, LSAMs have been used more frequently by North American highway agencies. NCHRP project 4-18, with a final report published as NCHRP Report 386 (NCHRP, 1997), showed that 30 of 52 state highway agencies in the USA had constructed LSAM pavements. The primary states with LSAM experience were Kentucky, Pennsylvania, and Iowa.

In Kentucky, the laboratory investigation of LSAMs was complemented by the construction of test sections on the Louisa Bypass highway (Lawrence County) and Mountain Parkway (Powell County). A dense LSAM, with a 37.5 mm NMAS and non-modified asphalt binder classified as AC-20, was considered as the base course in the pavement structure. It was suggested in Kentucky that LSAMs can be designed as a conventional mixture with some modifications to existing procedures for plants and pavers (Mahboub, 1990).

In China, Cao, Yao, Shang, Li, and Yang (2011) reported the use of a large stone mixture as an open-graded mixture for a porous layer (13 to 18% air voids), which has been denominated as a 'large stone porous asphalt mixture' (LSPM). A rehabilitated pavement with an LSPM was evaluated over five years, presenting good resistance to rutting, fatigue cracking, and reflective cracking for the mixture applied as the leveling course. The other pavements, which were composed of LSPM as the surface course, exhibited good resistance to the same distresses but showed rougher final macrotexture issues due to the large dimensions of the aggregates (Mascarenhas, Gaspar, Vasconcelos, Bernucci, & Bhasin, 2020).

In South Africa, the increase in traffic volume and axle loads culminated in traffic-loading conditions beyond the current road design class. The Southern African Bitumen and Tar Association (Sabita) conducted a study to search for cost-effective asphalt layers for heavy-duty pavements. The technology of large aggregate mixes for bases (LAMBS) was considered for pavement rehabilitation on the M2 Motorway in Johannesburg. Several sections have been constructed. The initial ten sections were analyzed using different grading curves, and the last three sections were constructed as fully instrumented test sections (Emery, 1996).

In the UK, the use of large stone mixtures is considered efficient, and it has been denominated as 'dense bituminous macadam' (DBM) with aggregate dimensions above 37.5 mm (Carswell & Gershkoff, 1993; Mascarenhas et al., 2020). The 'grave-bitume' (GB) from France, is an asphalt concrete with significant concentrations of coarse aggregates and good stone-on-stone contact between these particles. However, these large mixtures are limited to an NMAS of 19 mm because the French technicians believe that dimensions outside this will cause serious problems with segregation (Hingley, Peattie, & Powell, 1976).

The closest to LSAM in Brazil is the *pré-misturado a quente*, which is specified by some departments of transportation agencies, such as *Departamento de Estradas de Rodagem do Estado de São Paulo* (DER/SP) and *Departamento Estadual de Infraestrutura de Santa Catarina*. The maximum particle size of this mixture was limited to 38 mm. Recently, Mascarenhas et al. (2020) reported an experimental test site as one of their first experiences using LSAM in Brazil, which showed almost no permanent deformation after two years under very heavy traffic. Table 1 summarizes the worldwide use of mixtures with large stones and their relevant characteristics.

Table 1. Characteristics of asphalt mixtures more similar to LSAM.

Country	Author	Definition for asphalt mixtures with large stones	Aggregate sizes	Mixture gradation
USA	Warren Brothers Company (1912)	Bitulithic	37.5 ≤ MAS ≤ 50 mm	Dense graded
	Mahboub (1990)	LSAM	25 ≤ MAS ≤ 50 mm	Dense graded
China	Cao et al. (2011)	LSPM	25 ≤ MAS ≤ 63 mm	Open graded
South Africa	Emery (1996)	LAMBS	37.5 ≤ MAS ≤ 53 mm	Dense graded
UK	Carswell and Gershkoff (1993)	DBM	MAS ≤ 37.5 mm	Uniform graded
France	Hingley et al. (1976)	GB	NMAS ≤ 19 mm	Dense graded
Canada	Badeli, Carter, and Doré (2018)	GB	NMAS ≤ 19 mm	Dense graded
Brazil	DER/SP (2006)	*Pré-Misturado a Quente*	MAS ≤ 38 mm	Open graded

Note: DBM: dense bitumen macadam; GB: grave-bitume; LAMBS: large aggregate mixes for bases; LSAM: large-stone asphalt mixture; LSPM: large stone porous mixture.

Material characteristics

The LSAM can have different types of mixtures depending on the pavement structure objectives that determine where the desired application is on the grading curve. These types may be dense, stone-filled, or an open graded mixture. The dense mixture is characterized as a highly stable material with an air void content varying from 4 to 8% and a well-graded curve, which can develop resistance to load application through both aggregate interlock and the viscosity of the cohesive material. This has been referred to as the asphalt binder (Mascarenhas et al., 2020). The stone-filled mixture has small top-sized aggregates combined with large single-size aggregates, which can develop resistance strength through the aggregate-bridging effect. The open graded mixture is characterized by large top-sized aggregates, a lower asphalt content, and a high air void content varying from 15 to 30%. Thus, this mixture exhibits high permeability and develops strength from direct stone-on-stone contact (Newcomb, Wei, & Stroup-Gardiner, 1993). It can also delay reflective cracking when applied as a base course in pavement structures (Cao et al., 2011). However, care is needed when used in cold climate conditions, because the open-graded mixtures are more sensitive to freeze-thaw cycles due to the high content of open and connected air voids (Chen, Yao, Wang, Ding, & Xu, 2018).

It is believed that the dense LSAM can resist a very heavy traffic scenario, minimizing plastic deformation and, consequently, premature rutting in the wheel paths. However, the aggregate grading composition should ensure a coarse aggregate interlock with good stone-on-stone contact. In addition, it is important to use the cubic aggregate shape, rough surface texture, high abrasion resistance, and volumetric characteristics of the mixture (absorption of asphalt by aggregates, proportion of fine aggregates, voids in mineral aggregates [VMA], and voids filled with asphalt [VFA] – NCHRP, 1997).

The most common binder used for LSAM production is petroleum asphalt cement (AC) with a high viscosity, usually without modification (Kandhal, 1990; Mahboub, 1990; NCHRP, 1997). An adequate asphalt film thickness can ensure the workability and durability of the LSAM, and it is possible to control it by means of the asphalt content and filler in the mineral aggregate. The asphalt content must be convenient for maximum field density without an excessive reduction of air voids in the mixture (Kandhal, 1990). However, some researchers have recommended the modified asphalt binder rather than conventional asphalt binders as appropriate for LSPM, owing to its better resistance to moisture damage (Zhao & Huang, 2010). The use of styrene butadiene styrene polymer-modified binders was also reported by researchers to enhance the performance of large-stone dense asphalt mixtures (Mascarenhas et al., 2020).

Mix design methods

Asphalt mixture design methods have been developed to enhance material properties and improve field performance. The selection of the design procedure depends on the type of mixture, local traditional methods used, and equipment available. The proportion of each material used for the asphalt mixture is chosen from the design procedure. The aggregate grading curve is selected according to the final purpose, which should ensure mixture stiffness, stability (resistance to permanent deformation), resistance to fatigue cracking and to moisture damage, durability, and workability (National Asphalt Pavement Association [Napa], 2002; Bernucci, Motta, Ceratti, & Soares, 2010).

Marshall compaction

Marshall mix design was used extensively in 76% of the states in the USA, according to a survey conducted in 1984 (Kandhal, 1990; Anwar, 2014). For large stone mixtures, this conventional design procedure limits the aggregate dimensions by specifying a compaction mold of 100 mm, which is appropriate for asphalt mixtures with an NMAS of up to 25.4 mm (*Departamento Nacional de Estradas de Rodagem* [DNER], 1995). Therefore, new methods are needed to enable LSAM investigation and use.

Several design studies on large aggregate mixes have used the Marshall method, with some adaptations. Most LSAM projects in the USA were designed using the Marshall modified compaction mold developed by Kandhal (1990) with diameters corresponding to 152 and 85 mm height. The Marshall hammer mass increases (from 4.5 to 10.2 kg) and the number of blows (from 75 to 112 blows for heavy duty pavements) was necessary to ensure the same compaction energy per unit volume to the new specimen dimensions. Most agencies believe that the modified procedure design could save costs compared with purchasing new equipment for mixture design (Kandhal, 1990; Newcomb et al., 1993; Price & Aschenbrener, 1994).

Gyratory compaction

The densification of asphalt mixtures has been extensively studied by technicians and engineers specializing in asphalt pavements because the final volumetric characteristics are affected by compaction. After 30 decades in Texas, gyratory laboratory compaction was considered the best method for reproducing field compaction. The difference in densification can be clearly observed by comparing the impact and shear compaction methods (Cominsky, Leahy, & Harrigan, 1994).

The Superpave mix design was developed from the Strategic Highway Research Program using SGC, which is the design method most used in the USA. The Superpave design method (AASHTO M 323/13, American Association of State Highway and Transportation Officials [AASHTO], 2013) limits the maximum aggregate dimensions to 37.5 mm, and is reported as the most appropriate design method for asphalt mixtures (Buchanan & Brown, 2001). Preliminary studies have been conducted using the asphalt-aggregate mix analysis system from the NCHRP (Von Quintus, Scherocman, Hughes, & Kennedy, 1991), which indicates that gyratory compaction is better than impact compaction in simulating the particle orientation in the field. In addition, the gyratory compactor can produce LSAM samples using molds with larger dimensions (150 mm in diameter).

The NCHRP Report 386 (NCHRP, 1997) presents the compaction conditions used for the LSAM design and sample evaluation in the NCHRP Project 4-18/1997. The design procedure was fully compatible with the conventional HMA Superpave design method with respect to specimen preparation, compaction, and mix analysis. For densification, the Texas DOT gyratory compactor was used with an inclination angle of 5°, 120 gyrations, 0.5 Hz, and 375 kPa. Other options for compaction angle and force were investigated in this study to achieve satisfactory density without an excessive number of gyrations, which may cause aggregate breakage (NCHRP, 1997). The report recommended the use of SGC or rolling wheel compaction as the standard practice of LSAM design, considering Marshall modified compaction as the last choice if the other two are not available.

Additionally, determining the LP from the SGC during the design procedure is considered important to avoid over compaction of the asphalt mixture samples (Vavrik & Carpenter, 1998). The LP is the number of gyrations at which the internal aggregate structure is locked and further compaction has little effect on the densification. This might result in greater potential for aggregate breakage, compromising the mechanical behavior of the asphalt mixture (National Cooperative Highway Research Program [NCHRP], 2007; Watson, Moore, Heartsill, Jared, & Wu, 2008).

Rolling compaction

The need to create representative laboratory specimens similar to field specimens has led to the development of rolling wheel compaction. Rolling compaction uses the pressure distribution arising from the contact between a pneumatic, or a metallic wheel, and the pavement surface. Mixtures with large aggregate sizes can be easily accommodated in roller compaction molds compared to conventional Marshall molds (Swiertz, Mahmoud, & Bahia, 2010). The rolling compaction design procedure is related to the analysis of the volumetric properties, as previously mentioned. The specimens are prepared with different asphalt contents and applied to the same aggregate grading curve. After compaction, the cylindrical specimens are extracted from the slabs and used to determine their volumetric properties.

Material and methods

Materials

Three continuous grading curves of granite aggregate were selected for the design evaluation of LSAMs. The mix grading curves have an MAS starting from 25 to 37.8 mm, considering the gradation limits from the Asphalt Institute (2001) specifications for NMAS 25 and NMAS 38 mm (Figure 1 and Table 2). The grading curves for LSAM 1 and LSAM 2 correspond to mixtures with an NMAS of 25 mm, but from different quarries. LSAM 3 is a mixture with a higher NMAS (32 mm) and is from the same quarry as LSAM 2. The physical and mechanical characteristics of the aggregates were also evaluated, which were in accordance with specifications from the Brazilian National Department of Transportation Infrastructure and met the Superpave specifications. It was necessary to add 1.5% of hydrated lime to enhance the adhesion between the asphalt binder and the aggregates (a common practice used by Brazilian agencies). The hydrated lime can enhance the asphalt mixture anti-stripping ability, and the resistance to moisture damage (Little & Epps, 2001; Al-Qadi, Abauwad, Dhasmana, Coenen, & Trepanier, 2014).

A neat asphalt binder from the Paulínia petroleum refinery (Brazil) with penetration grade 30/45 (AC 30/45) and performance grade (PG) 58V-XX or PG 64S-XX, according to ASTM D 6373 (American Society for Testing and Materials [ASTM], 2016), was used for the selected grading curves (low-grade testing was not performed because low-temperature cracking is not an issue in Brazil). This binder is not recommended for the surface course for locations with pavement temperatures at 70°C or above, even for standard traffic. However, researchers usually report LSAM as a binder or base course (Mahboub, 1990; Cao et al., 2011), which are usually subjected to lower temperatures. This study supports the design of the LSAM applied to a Brazilian highway described by Mascarenhas et al. (2020). Table 3 summarizes the physical properties of the neat asphalt binder.

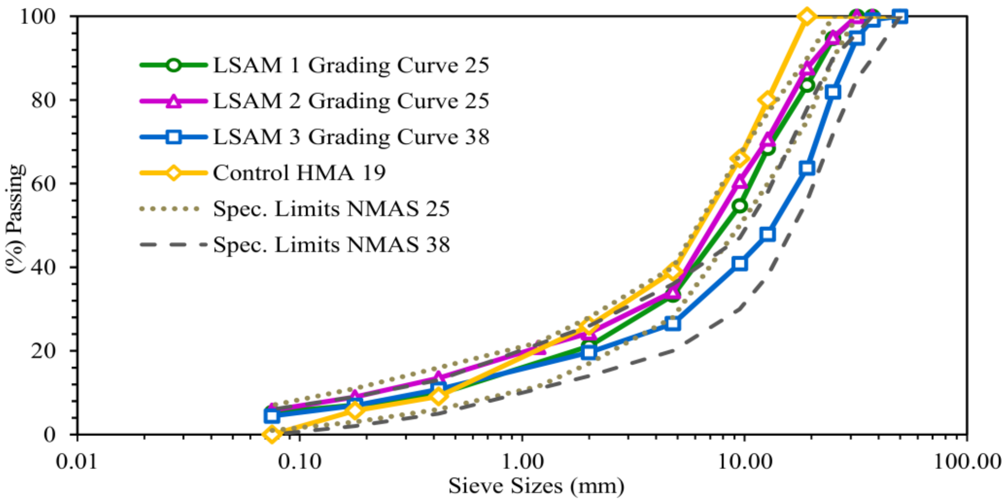

Figure 1. Aggregate grading curves.

Table 2. Aggregate gradations.

Sieve (mm)	Spec. Limits NMAS 25		LSAM 1	LSAM 2	Spec. Limits NMAS 38		LSAM 3
50	100	100	100	100	100	100	100
37.5	100	100	100	100	90	100	99
32	100	100	100	100	85	96	95
25	90	100	95	95	72	90	82
19.1	75	90	84	84	56	78	64
12.7	60	77	68	68	38	58	48
9.5	50	67	55	55	30	47	41
4.76	28	40	33	33	20	36	27
2	17	28	21	21	14	26	20
0.42	6	16	10	10	5	13	11
0.177	3	11	7	7	2	9	7
0.075	1	7	5	5	0	6	4

Table 3. Physical properties of neat asphalt cement.

Property		ASTM standard	Requirements	Units	AC 30/45
Penetration		D 5	30 to 45	0.1 mm	34
Density				-	1.007
PG		D 6373		-	PG 58V-XX or PG 64S-XX
Softening Point		D 36	> 52	°C	52.6
Solubility in Trichloroethylene		D 2042	> 99.5	% mass	99.9
	135°C	D 4402		cP	425
Brookfield Viscosity*	150°C	D 4402		cP	210
	177°C	D 4402	76 to 285	cP	76

*Spindle 21 and 20 rpm

Mixture design

LSAMs were designed using different compaction procedures to evaluate their influence on volumetric properties. The mixtures were designed with 4% air voids, in accordance with the requirements of VFA from 70 to 80% for heavy traffic, and VMA at 12% for mixtures with NMAS 25 mm, and 11% for mixtures with NMAS 37.5 mm, from the Asphalt Institute (2001). The design binder content and mixture volumetric parameters were evaluated for the different compaction methods: (i) impact compaction with 75 blows per face using a 100 mm diameter mold (conventional Marshall mix design without replacement of aggregates with dimensions higher than 19 mm); (ii) rolling compaction using equipment created by the Technology Development Center - Arteris S.A. (*Recursos para Desenvolvimento Tecnológico* [RDT], 2014), in which the densification process simulates the smooth wheeled or static rollers in field compaction; and (iii) gyratory compaction (Superpave mix design) with a 150 mm diameter mold varying the compaction energy by means of the number of gyrations. The specimens prepared with impact compaction had a diameter of 100 mm and a height of approximately 63 mm, which were the same dimensions as the specimens extracted from slabs prepared with the rolling compactor. The other specimens from gyratory compaction had a diameter of 150 and height of approximately 115 mm.

Additional parameters: LP and DASR Analysis

There are different definitions for determining the LP from the SGC data. This study uses the one developed by Vavrik and Carpenter (1998) to determine the LP as the first gyration in the first occurrence of three gyrations of the same height preceded by two sets of two gyrations of the same height.

With an appropriate design, the use of large aggregates can result in high direct stone-on-stone contact, creating good resistance to rutting under traffic (Yue & Morin, 1996; NCHRP, 1997). Another quantitative method used to ensure the maximization of stone-on-stone contact is the DASR analysis, and its porosity based on the range of interactive particle sizes, which must be lower than 50%, preferably outside the range of 48 to 52%, to guarantee the stone-on-stone contact (Greene, Chun, & Choubane, 2014). The porosity of DASR can be used as an additional parameter to design rutting resistant mixtures from analyzing the aggregate structure (Roque, Birgisson, Kim, & Guarin, 2006; Kim, Roque, Birgisson, & Guarin, 2009). This approach has been validated by many researchers as a tool to evaluate the coarse aggregate structure of asphalt mixtures (Guarin, Roque, Kim, & Sirin, 2013; Ferreira, Soares, Bastos, & 2016). Additionally, the LSAM was characterized by means of the LCPC permanent deformation test with the specimen prepared by rolling compaction according to European specification EN 12697-33 (*Comité Européen de Normalisation* [CEN], 2003), which was submitted to the traffic simulator according to the specification EN 12697-22 (*Comité Européen de Normalisation* [CEN], 2004). The rutting depth was determined by measuring 15 points on the loaded area over the slab when 30,000 cycles were reached.

Results and discussion

The following sections present comparisons between the volumetric parameters for the mixture design and the design binder content obtained. The parameters presented are air voids percentage (Va), bulk specific gravity of the compacted asphalt mixture (Gmb), VMA, and VFA.

Gyratory versus rolling compaction

Gyratory compaction at different compaction energies (75, 100, and 125 gyrations) with a 150 mm diameter mold and rolling compaction were used to evaluate the LSAM 1 (NMAS of 25 mm) mix design (Figure 2). The designed asphalt binder contents for the gyratory compaction at 75, 100, and 125 gyrations were 4.2, 3.6, and 3.0%, respectively. For rolling compaction, the design binder content was 3.5%.

Different asphalt contents were obtained from the change in the compaction method and effort for the same LSAM 1 grading curve. The mixtures prepared with 75 gyrations for N_{design} presented a higher design asphalt binder content than the upper gyration levels, as expected. If the number of gyrations during compaction is higher, the mixture undergoes more compressive effort and requires a lower asphalt content to lubricate the aggregate particles to obtain the desired air voids to meet the design specification.

Watson et al. (2008) observed the same in mixtures with an NMAS of 25 mm, concluding that as the gyratory level increased, the design binder content decreased. The authors reported a 23% decrease when the number of gyrations changed from 35 to 110 using the SGC. An inappropriate design procedure may culminate in issues related to field compaction and premature distress in the surface asphalt layer caused by an excess or lack of asphalt binder.

The volumetric requirements were not respected from the mixture designed for the gyratory compactor with 125 gyrations at the design binder content determined by 4% air voids. It is likely that the compaction energy was high, resulting in lower VMA and unsatisfactory VFA. A lower VMA can be associated with good permanent deformation resistance, but it could indicate insufficient space between particles to accommodate the asphalt binder, compromising the mixture stability (Ferreira et al., 2016, Mascarenhas et al., 2020).

The volumetric design curves from rolling compaction were more sensitive to variations in the asphalt content when compared to gyratory compaction. The engineering principles of wheel rolling compaction were based on creating specimens that are more representative of mixtures compacted in the field using a pneumatic roller compactor. However, the compaction procedure and specimen sizes may not ensure the homogeneity of the material over laboratory slabs (Swiertz et al., 2010). This is a concern when designing an asphalt mixture because of the large amount of material necessary for slab compaction. There is no consensus regarding which method is the best for simulating field conditions. The volume of specimens could be identical even with varying laboratory compaction methods, but they might be mechanically different (Georgiou, Sideris, & Loizos, 2016).

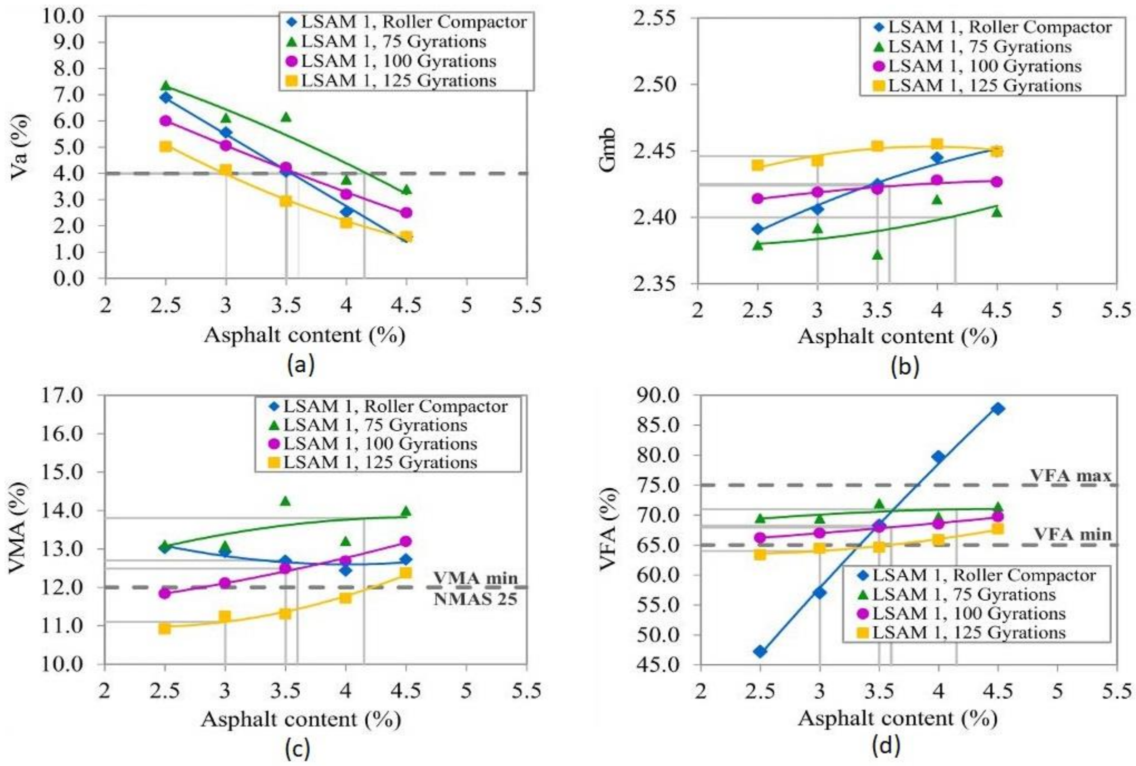

Figure 2. Volumetric parameters: gyratory versus rolling compaction (NMAS 25 mm).

Gyratory versus Marshall compaction

Gyratory compaction at 125 gyrations with a 150 mm diameter mold and Marshall compaction with 75 blows per face in a 100 mm diameter mold were used to evaluate the LSAM 2 (NMAS of 25 mm) mix design (Figure 3) and its sensitivity to different compaction procedures. The designed asphalt binder contents for the gyratory and Marshall compaction were 3.5 and 4.3%, respectively.

The LSAM 2 with NMAS 25 mm had been designed using the conventional Marshall mix design, presenting a design binder content 23% higher than that obtained by gyratory compaction with 125 gyrations. This occurred because of the different compaction principles (by impact and shear movement), which allows different orientations of aggregate particles into the compacted mixture. Consuegra, Little, Von Quintus, and Burati Jr. (1989) compared the gyratory compaction, the Marshall impact hammer, mobile steel wheel simulator, California kneading compactor, and the Arizona vibratory-kneading compactor, concluding that the gyratory compaction was the method that creates specimens more similar to the pavement samples. The same was reported by Yue and Morin (1996), who analyzed digital images to evaluate aggregate orientation in asphalt concrete mixtures. The Marshall hammer was defined as one with a lower probability of creating representative field samples. This procedure does not allow a partial free face to aggregate self-orientation, as occurs in field compaction.

25 versus 32 mm NMAS

Gyratory compaction at 100 gyrations with a 150 mm diameter mold was used to evaluate the LSAM 3 (NMAS of 32 mm) mix design (Figure 4).

The designed binder content of LSAM 3 for gyratory compaction was 3.6%. LSAM 3 with NMAS 32 mm was designed by gyratory compaction with a diameter of 150 mm owing to the mold capacity to accommodate large aggregates. After the design of previous large stone mixtures, the result analysis and experience made it possible to choose a suitable compaction to be used for the known materials and volumetric parameters desired.

The mixtures designed by gyratory compaction with 100 gyrations had the same asphalt binder content. However, LSAM 1 and LSAM 3 comprise the same mineral aggregate source from different quarries and different grading curves, presenting different densification at 4% of air voids (Gmb_{LSAM1} = 2.424, and Gmb_{LSAM3} = 2.499), which can explain the equal asphalt content for mixtures with different NMAS. The results of the design binder content for each design procedure are listed in Table 4.

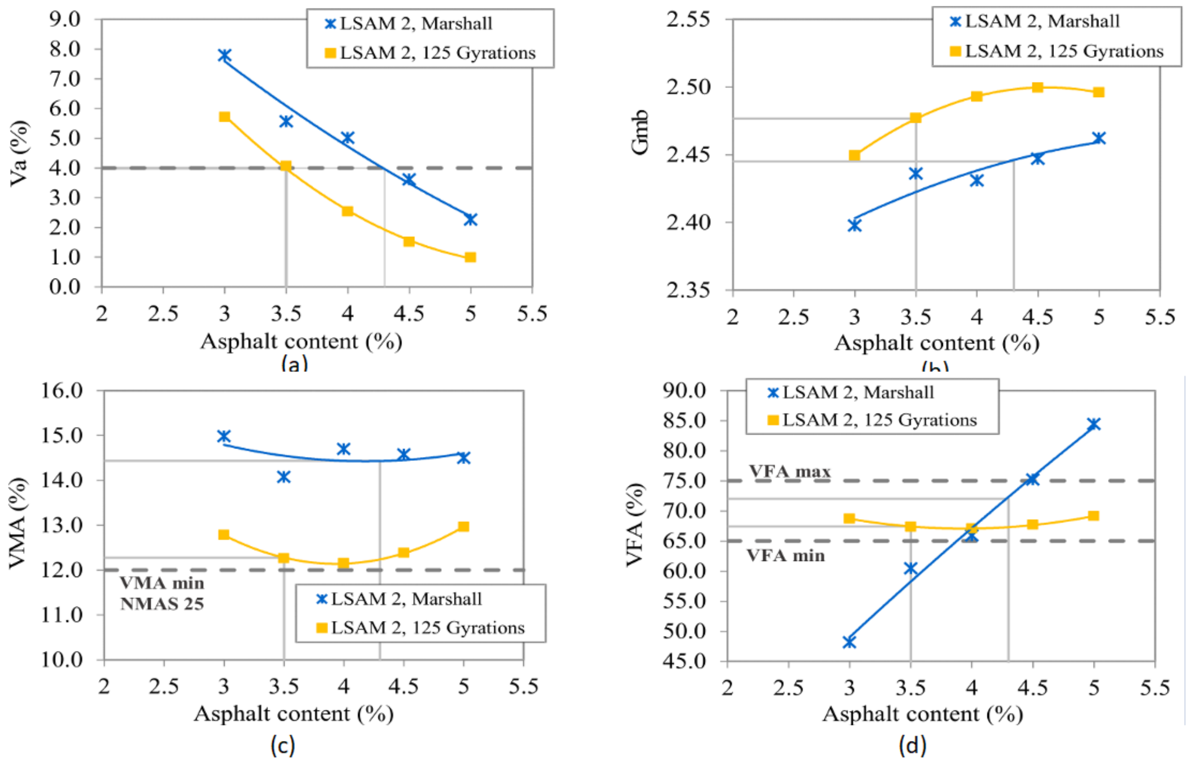

Figure 3. Volumetric parameters: gyratory versus Marshall compaction (NMAS 25 mm).

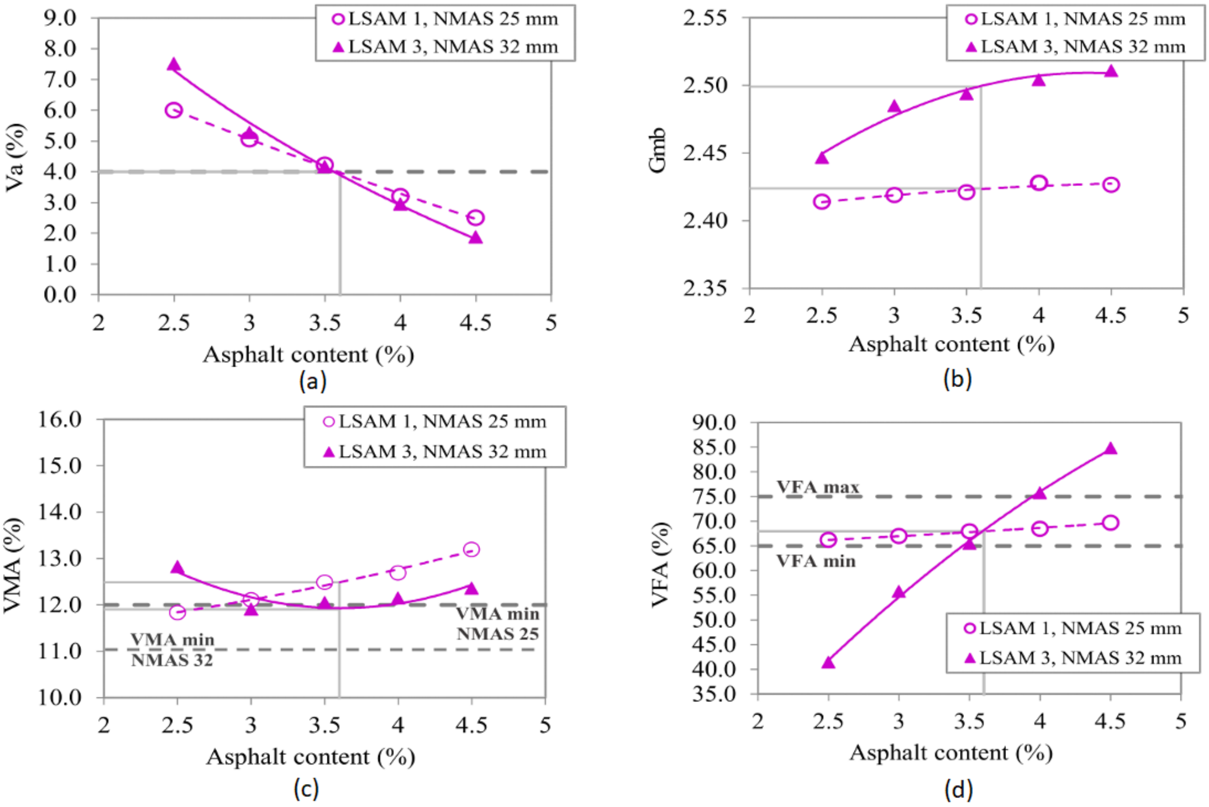

Figure 4. Volumetric parameters: 25 mm versus 32 mm NMAS using compaction at 100 gyrations.

Table 4. Effect of compaction method on design binder content.

Mixture	NMAS	Quarry	Mineral Origin	Design Binder Content for 4% air voids (%)				
				Marshall	SGC 125 G	SGC 100 G	SGC 75 G	Roller
LSAM 1	25 mm	Mandirituba	Granite	-	3.0	3.6	4.2	3.5
LSAM 2	25 mm	Itapoá	Granite	4.3	3.5	-	-	-
LSAM 3	32 mm	Itapoá	Granite	-	-	3.6	-	-

Additional parameters: LP and DASR analysis

Table 5 presents the average values of the LPs obtained for compacted specimens of each asphalt content at different compaction energies in the SGC, associated with the varied DASR porosity at the design binder content as an additional parameter to evaluate their tendency toward permanent deformation. The results of rutting depth from the LCPC permanent deformation tests are also presented to validate the additional parameters used for LSAM designs.

Table 5. Average values of the locking point (LP), porosity of the dominant aggregate size range (DASR), and rutting depth during mixture design.

Asphalt Content (%)	LSAM 1 (NMAS 25 mm)			LSAM 2 (NMAS 25 mm)	LSAM 3 (NMAS 32 mm)
	75 G	100 G	125 G	125 G	100 G
2.5	Did not reach	91	94	-	71
3.0	Did not reach	89	89	76	92
3.5	Did not reach	91	92	74	84
4.0	Did not reach	92	89	70	82
4.5	Did not reach	90	86	76	86
5.0	-	-	-	73	-
Design binder content (%)	4.2	3.6	3.0	3.5	3.6
LP at design binder content	X	91	89	74	84
% Gmm estimated for design binder content	X	95.5	94.2	94.6	95.7
DASR Porosity (%)	31	30	29	34	36
Rutting depth (%) LCPC test	3.1	2.9	3.0	2.3	2.2

Note: Gmm - maximum specific gravity.

At the designed asphalt binder content, the average LP for LSAMs ranged from 74 to 91 gyrations, indicating that the compaction energy at 100 gyrations is suitable for designing all LSAMs considered in this study. Thus, a higher compaction energy (125 gyrations) may result in excessive compaction and aggregate breakage, which could change the grading curve. The use of 75 gyrations for LSAM 1 was insufficient to reach the LP for any asphalt content.

For 100 gyrations, LSAM 1 and LSAM 3 had similar densification values, which were represented by the percentage of maximum specific gravity (Gmm). However, the LP of LSAM 1 (91) was higher than the LP of LSAM 3 (84), indicating that LSAM 1 needed a greater number of gyrations to reach the same level of compaction. The workability in compaction is also related to several variables other than the NMAS, such as the aggregate crushing process, the aggregate properties, and the aggregate shape (Gudimettla, Cooley, & Brown, 2003), each producing different LP values. The quarry used for LSAM 1 was different from that used for LSAM 3. The difference in the aggregate source and properties might explain the results obtained.

For 125 gyrations, LSAM 1 and LSAM 2 also had close values of densification, where the LP of LSAM 1 (89) was higher than that of LSAM 2 (74), again indicating that LSAM 1 requires a greater number of gyrations to reach the same level of compaction. The main differences between the two aggregate skeletons are the grading curve and aggregate quarries, but both are from the same aggregate crushing process, which can influence the energy needed for densification.

For LSAM 1, LSAM 2, and LSAM 3, the resulting DASR porosities were between 29 and 36%, which are both less than the maximum porosity criterion of 50%, suggesting a good resistance to permanent deformation (Kim et al., 2009) for all mixtures designed by gyratory compaction. This was verified by the LCPC tests (EN 12697-22, CEN, 2004) in slabs compacted by LCPC rubber-tired compactor (EN 12697-33, CEN, 2003), and better field rutting performance (Chun & Kim, 2016). The specification limits the maximum deformation for a selected number of cycles, which varies according to the type of mixture. The French evaluation parameter for LSAM, GB is a maximum deformation between 5.0 and 10.0% at 30,000 cycles, depending on the traffic level the mixture will be exposed to, from heavy to heavy-duty traffic conditions (*Laboratoire Central des Ponts et Chaussées* [LPC], 2007).

Results showed low rutting depth for all the LSAMs, which was below the specification limit of 5% for a surface course under heavy traffic (LPC, 2007). This means that all these mixtures have a high resistance to permanent deformation. The LCPC permanent deformation test used 60°C as the set temperature. This can decrease the asphalt binder viscosity and requires a good aggregate skeleton interlock to resist permanent deformation (NCHRP, 1997). In the field, rehabilitation test sections in Brazil had shown minimal rutting after two years of pavement monitoring which was considered a successful strategy as a binder course under heavy traffic (Mascarenhas et al., 2020).

Conclusion

The LSAM design showed the following conclusions:

- Marshall compaction does not allow the correct accommodation of coarse aggregates into the specimen mold (limited to 100 mm in diameter), with insufficient compaction.
- Rolling compaction was inappropriate for LSAM design due to the material heterogeneity.
- For SGC, the LP is an additional tool for LSAM design, implying that 100 gyrations compaction can reach sufficient densification and have less propensity to aggregate breakage. In addition, the DASR porosity can be a permanent deformation indicator. Based on these results, gyratory compaction with 100 gyrations was suggested for the design of LSAM.

Acknowledgements

The authors acknowledge the financial support of the Brazilian Coordination for the Improvement of Higher Education Personnel (*Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* – Capes), the National Council for Scientific and Technological Development (*Conselho Nacional de Desenvolvimento Científico e Tecnológico* – CNPq), the National Land Transportation Agency (*Agência Nacional de Transportes Terrestres* – ANTT), and the Arteris Concessionary.

References

Al-Qadi, I. L., Abauwad, I. M., Dhasmana, H., Coenen, A. R., & Trepanier, J. S. (2014). *Effects of various asphalt binder additives/modifiers on moisture susceptible asphaltic mixtures.* Champaign, IL: Illinois Center for Transportation.

American Association of State Highway and Transportation Officials [AASHTO]. (2013). *AASHTO M 323. Standard specification for Superpave volumetric mix design*. Washington, DC: AASHTO.

American Society for Testing and Materials [ASTM]. (2016). *ASTM D 6373. Standard specification for performance graded asphalt binder*. West Conshohocken, PA: ASTM.

Anwar, S. W. (2014). Studies on marshall and modified marshall specimens by using CRMB. *International Journal of Structural and Civil Engineering Research, 3*(4), 85-95.

Asphalt Institute. (2001). *Superpave mix design: superpave series No. 2*. Lexington, KY: Asphalt Institute Research Center.

Badeli, S., Carter, A., & Doré, G. (2018). Effect of laboratory compaction on the viscoelastic characteristics of an asphalt mix before and after rapid freeze-thaw cycles. *Cold Regions Science and Technology, 146*, 98-109. DOI: https://doi.org/10.1016/j.coldregions.2017.12.001

Bernucci, L. B., Motta, L. M. G., Ceratti, J. A. P., & Soares, J. B. (2010). *Pavimentação asfáltica: formação básica para engenheiros* (3 reimp.). Rio de Janeiro, RJ: Petrobras/Abeda.

Buchanan, M. S., & Brown, E. R. (2001). Effect of Superpave gyratory compactor type on compacted hot-mix asphalt density. *Transportation Research Record: Journal of the Transportation Research Board, 1761*(1), 50-60. DOI: https://doi.org/10.3141/1761-07

Cao, W. D., Yao, Z. Y., Shang, Q. S., Li, Y. Y., & Yang, Y. S. (2011). Performance evaluation of large stone porous asphalt-rubber mixture. *Advanced Materials Research, 150-151*, 1184-1190. DOI: https://doi.org/10.4028/www.scientific.net/AMR.150-151.1184

Carswell, J., & Gershkoff, D. R. (1993). *The performance of modified dense bitumen macadam roadbases*. Crowthorne, GB: Transport Research Laboratory.

Chen, J., Yao, C., Wang, H., Ding, Y., & Xu, T. (2018). Expansion and contraction of clogged open graded friction course exposed to freeze-thaw cycles and degradation of mechanical performance. *Construction and Building Materials, 182*, 167-177. DOI: https://doi.org/10.1016/j.conbuildmat.2018.06.095

Chun, S., & Kim, K. (2016). Effectiveness of dominant aggregate size range – interstitial component criteria for consistently enhanced cracking performance of asphalt mixtures in the field. *Canadian Journal of Civil Engineering, 43*(6), 523-531.DOI: https://doi.org/10.1139/cjce-2015-0517

Cominsky, R., Leahy, R. B., & Harrigan, E. T. (1994). *Level one mix design: materials selection, compaction, and conditioning*. Washington, DC: National Research Council.

Comité Européen de Normalisation [CEN]. (2003). *BS EN 12697-33: Mélanges bitumineux - Méthodes d'essai - Partie 33 : préparation de corps d'épreuve au compacteur de plaque*. Bruxelles, BE: CEN.

Comité Européen de Normalisation [CEN]. (2004). *NF EN 12697-22*: *Mélanges bitumineux - Méthodes d'essai - Partie 22 : essai d'orniérage.* Bruxelles, BE: CEN.

Consuegra, A., Little, D. N., Von Quintus, H., & Burati Jr., J. L. (1989). Comparative evaluation of laboratory compaction devices based on their ability to produce mixtures with engineering properties similar to those produced in the field. *Transportation Research Record, 1228*(1), 80-87.

Departamento de Estradas de Rodagem do Estado de São Paulo [DER/SP]. (2006). *Especificação técnica: ET-DE-POO/026. Pré-misturado a quente*. São Paulo, SP: DER/SP.

Departamento Nacional de Estradas de Rodagem [DNER]. (1995). *Norma técnica: DNER-ME 043/95. Misturas betuminosas a quente – Ensaio Marshall*. Rio de Janeiro, RJ: DNER.

Emery, S. J. (1996). *Large aggregate mixes in bases*. Isando, ZA: Group Technical Director/Colas Southern Africa Pty Ltd.

Ferreira, J. L. S., Soares, J. B., & Bastos, J. B. S. (2016). Métodos de seleção granulométrica com foco na resistência à deformação permanente. *Transportes*, *24*(2), 46-52. DOI: https://doi.org/10.14295/transportes.v24i2.1129

Georgiou, P., Sideris, L., & Loizos, A. (2016). Evaluation of the effects of gyratory and field compaction on asphalt mix internal structure. *Materials and Structures*, *49*(1), 665-676. DOI: https://doi.org/10.1617/s11527-015-0528-3

Greene, J., Chun, S., & Choubane, B. (2014). Enhanced gradation guidelines to improve asphalt mixture performance. *Transportation Research Record: Journal of the Transportation Research Board, 2456*(1), 3-10. DOI: https://doi.org/10.3141/2456-01

Guarin, A., Roque, R., Kim, S., & Sirin, O. (2013). Disruption factor of asphalt mixtures. *International Journal of Pavement Engineering, 14*(5), 472-485. DOI: https://doi.org/10.1080/10298436.2012.727992

Gudimettla, J. M., Cooley Jr., L. A., & Brown, E. R. (2003). *NCAT: Report 03-03. Workability of hot mix asphalt*. Auburn, AL: National Center for Asphalt Technology/Auburn University.

Hingley, C. E., Peattie, K. R., & Powell, W. D. (1976). *Supplementary Report 242. French experience with Grave-bitume a dense bituminous road base*. Crowthorne, GB: Transport and Road Research Laboratory.

Kandhal, P. S. (1989). *NCAT Report 89-04. Testing and evaluation of large stone mixes using Marshall mix design procedures*. Auburn, AL: National Center for Asphalt Technology/Auburn University.

Kandhal, P. S. (1990). *NCAT Report No. 90-4. Large stone asphalt mixes: design and construction*. Auburn, AL: National Center for Asphalt Technology/Auburn University.

Kim, S., Roque, R., Birgisson, B., & Guarin, A. (2009). Porosity of the dominant aggregate size range to evaluate coarse aggregate structure of asphalt mixtures. *Journal of Materials in Civil Engineering, 21*(1), 32-39. DOI: https://doi.org/10.1061/(ASCE)0899-1561(2009)21:1(32)

Laboratoire Central des Ponts et Chaussées [LPC]. (2007). *Manuel LPC d'aide à la formulation des enrobés Groupe de travail*. Paris, FR: LPC.

Little, D. N., & Epps, J. A. (2001). *The benefits of hydrated lime in hot mix asphalt.* Arlington, VA: National Lime Association.

Mahboub, K. (1990). *KTC-90-12. Large-stone mixes for reducing rutting.* Lexington, KY: University of Kentucky.

Mascarenhas, Z. M. G., Gaspar, M. S., Vasconcelos, K. L., Bernucci, L. L. B., & Bhasin, A. (2020). Case study of a composite layer with large-stone asphalt mixture for heavy-traffic highways. *Journal of Transportation Engineering, Part B: Pavements*, *146*(1), 04019040. DOI: https://doi.org/10.1061/JPEODX.0000143

National Asphalt Pavement Association [Napa]. (2002). *Design, construction, and performance of heavy-duty mixes*. Lanham, MD: National Asphalt Pavement Association.

National Cooperative Highway Research Program [NCHRP]. (1997). *Report 386. Design and evaluation of large stone asphalt mixtures*. Washington, DC: National Research Council.

National Cooperative Highway Research Program [NCHRP]. (2007). *Report 573. Superpave mix design: verifying gyration levels in the Ndesign table*. Washington, DC: National Research Council.

Newcomb, D., Wei, Z., & Stroup-Gardiner, M. (1993). *Investigation of large-stone mixtures*. St. Paul, MN: Minnesota Department of Transportation.

Price, D. A., & Aschenbrener, T. (1994). *Large-stone hot mix asphalt pavements*. Washington, DC: Federal Highway Administration.

Recursos para Desenvolvimento Tecnológico [RDT]. (2014). *Desenvolvimento de equipamento simulador de tráfego de laboratório para previsão de desempenho de misturas asfálticas*. Brasília, DF: Agência Nacional de Transportes Terrestres.

Roque, R., Birgisson, B., Kim, S., & Guarin, A. (2006). *Development of mix design guidelines for improved performance of asphalt mixtures*. Tallahassee, FL: Florida Department of Transportation.

Swiertz, D., Mahmoud, E., & Bahia, H. (2010). *Asphalt mixture compaction and aggregate structure analysis techniques: state of the art report*. Washington, DC: RILEM Technical Committee 206-ATB.

United States Army Corps of Engineers [Usace]. (2000). *Hot-mix asphalt paving handbook. AC 150/5370-14A*. Washington, DC: US Army Corps of Engineers.

Vavrik, W. R., & Carpenter, S. H. (1998). Calculating air voids at specified number of gyrations in Superpave Gyratory Compactor. *Transportation Research Record, 1630*(1), 117-125. DOI: https://doi.org/10.3141/1630-14

Von Quintus, H. L., Scherocman, J. A., Hughes, C. S., & Kennedy, T. W. (1991). *Asphalt-aggregate mixture analysis system, AAMAS*. Washington, DC: Transportation Research Board.

Warren Brothers Company. (1912). *The bitulithic pavement. The best by every test built from experience*. Boston, MA: 59 Temple Place.

Watson, D. E., Moore, J., Heartsill, J., Jared, D., & Wu, P. (2008). Verification of Superpave number of design gyration compaction levels for Georgia. *Transportation Research Record, 2057*(1), 75-82. DOI: https://doi.org/10.3141/2057-09

Yue, Z. Q., & Morin, I. (1996). Digital image processing for aggregate orientation in asphalt concrete mixtures. *Canadian Journal of Civil Engineering, 23*(2), 480-489. DOI: https://doi.org/10.1139/l96-052

Zhao, Y., & Huang, X. (2010). Design method and performance for large stone porous asphalt mixtures. *Journal of Wuhan University of Technology-Materials Science Edition, 25*(5), 871-876. DOI: https://doi.org/10.1007/s11595-010-0111-2