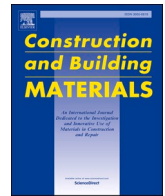




Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Asphalt mix design: Discussion on the bulk specific gravity procedure influence on the results obtained from empirical, volumetric, and performance-based methods

Dinis Gardete^{a,*}, Luís Picado-Santos^b, Silvino Capitão^{b,c}, Rosa Luzia^a^a Instituto Politécnico de Castelo Branco, Portugal, Av. Empresário, 6000-767 Castelo Branco, Portugal^b CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal^c Instituto Politécnico de Coimbra, Instituto Superior de Engenharia de Coimbra, Departamento de Engenharia Civil, Rua Pedro Nunes, 3030-199 Coimbra, Portugal

ARTICLE INFO

Keywords:

Asphalt mixture
Design of composition
Bulk Specific Gravity
Air voids
Pavement performance

ABSTRACT

The purpose of this paper is to shed light on the impact of laboratory procedures for air void content determination on the design and mechanical performance of an asphalt mixture. A dense-graded AC20 and gap-graded SMA12.5 mixtures were designed using empirical and volumetric design methods. Volumetric properties are determined based on several bulk gravity procedures: dry, SSD (saturated surface dry), paraffin coated, vacuum-sealed and dimensions. Relationships between the mixtures designed with bulk specific gravity procedures and their performance made it possible to analyze the impact of these procedures on the properties and performance of the mixtures. Global performance variations were relevant, although the differences were moderate considering the common procedures (less than 10%). Impact on a determined performance property can be considerable, with variations up to 70%. For specific applications, this can have a significant effect on the overall in-service performance.

1. Introduction

Asphalt mix design refers to the process of proportioning its components, generally aggregates and binder, so that the required properties are achieved. These properties can be volumetric, mechanical (e.g. based on empirical tests), or performance properties [1]. The required properties are based on the existing experience with local mixtures, the design method and tests performed, as is the case with performance tests. The performance of bituminous mixtures will depend on factors such as the properties of the materials (e.g. aggregates and binder), design of the mixture (i.e. proportions of the components), structural design, construction methods and equipment used. The “design of the mixture” process seeks to achieve appropriate properties for the mixture, considering the materials used, by defining their quantities in the mix. There is a need for some balance in the design as variations in the mix’s components proportions tend to affect the performance properties of the mixtures in opposite directions [1,2]. As an example, increasing the binder content generally increases fatigue resistance and decreases water sensitivity and reduces rutting resistance [3,4,5,6].

The design methods are generally based on the volumetric or

mechanical properties of the mixtures. The assessment of these properties and the definition of proper procedures is essential for the accuracy of the design methods and in quality control (QC) and quality assurance (QA) analysis. The volume of air voids is essentially the most critical single property for the design and quality control of bituminous mixtures [7,8,9]. The procedures for determining the volume of air voids can vary with the surface texture and the volume and size of connected air voids. These can be affected by the type of mixture (as a function of grading and binder content) or the specimen’s production procedures, such as coring and dimensions [7,10,11,12]. Thus, the procedures to determine air void volume have to adjust to the specimen’s properties (e.g. type of mixture, production methods, coring conditions, size). This adjustment makes it possible to avoid a lack of reliability on air void content values that can lead to difficulties in QA/QC procedures, mixtures’ performance analysis, and pavement design [11]. Compaction method and aggregate gradation influence the size, distribution and interconnectivity of air voids in bituminous mixtures [13,14]. Most air voids in bituminous mixtures are small. Arambula et al. [15] refers average equivalent diameters of 0.65 to 0.97 mm and Hu et al. [16] found that for an SMA11 most voids had equivalent

* Corresponding author at: Escola Superior de Tecnologia de Castelo Branco, Portugal, Av. Empresário, 6000-767, Castelo Branco, Portugal.

E-mail addresses: dgardete@ipcb.pt (D. Gardete), luispicadosantos@tecnico.ulisboa.pt (L. Picado-Santos), capitao@isec.pt (S. Capitão), rluzia@ipcb.pt (R. Luzia).

<https://doi.org/10.1016/j.conbuildmat.2022.127870>

Received 18 December 2021; Received in revised form 2 May 2022; Accepted 13 May 2022

Available online 31 May 2022

0950-0618/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

diameters less than 2.5 mm (5 mm² in area). Enríquez-Léon et al. [14] found that in dense mixtures total air voids show a good correlation with the voids in the fine aggregate matrix. The uniformity of void distribution influences the performance properties of the mixtures, with more uniformity in the distribution leading to less variability in the performance properties [16,17]. Yu et al. [13] found that an increase in the aggregate size increases the void size but lowers the uniformity in their distribution in the mix structure.

The determination of the bulk specific gravity is the most important to accurately determine the volumetric properties of the mixtures, such as void content, VMA (Voids in Mineral Aggregate) and VFB (Voids Filled with Bitumen). The procedures must be suitable for a wide range of specimens with diverse dimensions and production methods. Understanding the soundness of the procedures used and the bias or errors that are present can increase the reliability of the design methods [10,11,18]. Whereas correlations between the several procedures can be drawn, their use is not feasible for practical applications [7,19,20]. However, changes in the procedures will substantially affect mix-design values and QA/QC, mainly for coarse-graded and SMA (Stone Matrix Asphalt) mixtures. Dukatz et al. [21] refers to that the SSD (saturated surface dry) and the vacuum procedures show a shift in the air voids that could be up to 0.5% for coarse-graded mixtures and 0.9% for SMA mixtures causing changes in the design asphalt content of 0.2% and 0.5%, respectively. Differences for in-place air voids, determined on pavement cores, are up to 1.1% for coarse-graded mixtures and up to 1.7% for SMA. The differences between procedures are more significant for coarse graded mixtures and SMA mixtures, with observed differences of up to 10% [22].

In-place air voids are usually higher than design air voids, and during the pavement life, there is a gradual reduction in air voids with traffic loads. Therefore, it can be observed that in most cases, in-place air voids of the mixtures do not match design air voids. However, the determination of air voids in the design stage, and bias derived from the procedure used in air void determination, can affect mixture design and in-service performance even if air voids in the pavement differ from design air voids [8]. Increasing air voids can lead to mixtures with a lower durability, lower stiffness, and lower fatigue resistance. If the air voids content is too low, mixtures have less resistance to rutting and low-temperature cracking [1,16,17,23,24,25].

This work designed mixtures using the Marshall method and a volumetric design method based on SUPERPAVE specifications. In the design process, the bulk specific gravity and volumetric properties were determined for the specimens using different procedures, dry, SSD, paraffin, vacuum-sealed and dimensions. Mixture performance was evaluated through laboratory tests. An analysis was made linking bulk specific gravity procedures results to the expected performance of the mixtures. This approach shed light on the anticipated variations on bituminous mixtures performance throughout a mix-design procedure, considering the different testing methods to measure the volumetric properties.

2. Materials and procedures

2.1. Aggregates and bitumen

Two mixtures were produced, a dense-graded mixture AC20 and a gap graded mixture SMA12.5. These mixtures were selected based on available data [4]. Also, AC20 mixtures are the most common mixtures used in practice. The SMA12.5 was selected for the opposite reason since it is not yet so common for Portuguese technology, and more knowledge in its properties was considered valuable. These mixtures were produced using a 35/50 penetration binder (non-modified), granite aggregates and limestone filler (used in the SMA12.5). The properties of the aggregates are in Table 1. Cellulosic fibres JRS Viatop Premium at 0.3% w/w were used as an additive in the SMA12.5 to prevent binder drainage. The added fibres were provided in pellets composed of 90% cellulosic fibres and 10% bitumen.

2.2. Composition of the blends tested

The SMA12.5 gradation was based on guidelines from the USA and Europe [26,27], whereas the AC20 gradation followed the Portuguese specifications [28]. No procedure was implemented to analyze trial aggregate blends. It was selected aggregate blends for both mixtures that fitted the envelopes defined in the guidelines. Fig. 1 presents the gradation of the mixtures.

For both mixtures, Marshall and Gyrotory compactor specimens were produced. The range of bitumen contents used was chosen to comprise those usually found in the Portuguese practice. For AC20 tests were made with bitumen contents ranging from 3.5 to 5.5%, whereas for SMA12.5, bitumen contents ranged from 5.5 to 7.5%.

2.3. Production of specimens

The target mixing temperature was 165 °C. Aggregate was heated to 170 °C and bitumen to 155 °C before mixing. For the SMA12.5, the fibres were added to the aggregate blend in the mixer and dry mixed for 20 s before bitumen was added, and mixing proceeded until a homogenous mixture was reached (30–40 s).

A laboratory mixer was used to manufacture the blend needed to compact four Marshall specimens and one gyrotory specimen in each batch. A short-term ageing procedure was used to produce gyrotory compacted specimens. The mix was placed in an oven for 2 h at 145 °C (compaction temperature). After this procedure, the mix was placed in the mould and compacted.

For Marshall compaction, an automatic compactor was used (EN 12697–30). Marshall specimens of SMA12.5 were compacted with 50 and 75 blows/face. AC20 Marshall specimens were compacted with 75 blows/face. A Controls 76-B0252 gyrotory compactor was used to produce gyrotory compacted specimens. Vertical pressure was 600 kPa, internal gyration angle 1.16°, rotational speed 30 rpm, specimen height was 115 mm and specimen diameter was 150 mm. AC20 specimens were compacted to 125 gyrations, and SMA12.5 specimens were compacted to 50, 75 and 100 gyrations.

Table 1
Properties of the aggregates.

Sieve aperture (mm)	31.5	20	14	10	4	2	0.063	Bulk Gravity Mg/m ³	Flakiness Index EN 933–3 (%)	Shape Index EN 933–4 (%)	Methylene blue value - MB _f EN 933–9 (g/kg)
	Percentage of material passing										
Aggregate 11.2/22.4	100	90.5	20.8	0.8	0.3	0.3	0.2	2.60	14	17	—
Aggregate 4/16	100	100	100	76.3	0.9	0.8	0.5	2.60	15	20	—
Aggregate 0/4	100	100	100	100	100	86.7	15.0	2.67	—	—	1.7
Filler	100	100	100	100	100	100	72.1	2.68	—	—	1.0

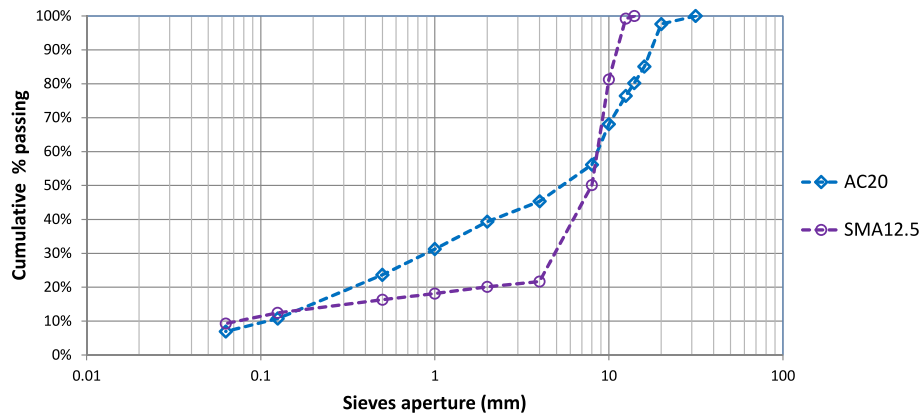


Fig. 1. Gradation curves of the mixtures.

2.4. Bulk gravity procedures

The following procedures measured the bulk specific gravity (G_{mb}): dry, saturated surface dry (SSD), sealed specimen by paraffin, sealed specimen with vacuum and by dimensions. The procedures followed standard EN 12697-6. The vacuum-sealed procedures largely followed EN 12697-6, though they were adapted to the materials and equipment used. The vacuum-sealed procedure was not applied to all produced specimens because of equipment unavailability. In dry, SSD, paraffin coated and vacuum-sealed procedures, specimen volume was determined, through Archimedes' principle using submerged masses. In the dimension's procedure volume was determined by measuring the specimen. The bulk specific gravity, G_{mb} , was obtained by dividing specimen mass by volume.

2.5. Performance test procedures

Laboratory tests were used to characterize the performance of the two mixtures. Three binder contents were used for each mixture: 4.5%, 5.0% and 5.5% for the AC20 mixture and 6.0%, 6.5% and 7.0% for the SMA12.5 mixture. The characterization included compactability, water sensitivity (EN 12697-12), rutting resistance (EN 12697-22), stiffness (EN 12697-26) and fatigue resistance (EN 12697-24). Simple correlations were used to interpolate values for diverse compaction efforts using the bitumen content to link the design compaction energy, N_{des} , and performance results.

2.5.1. Workability

The Compaction Energy Index (CEI) was selected for compactability characterization of the mixtures [29]. The CEI was defined as the area from the 8th gyration to 92% of the theoretical maximum specific gravity [30,31,32]. The CEI was determined from the compaction curves from the gyratory compactor for specimens compacted at 125 gyrations for the AC20 and 100 gyrations for the SMA 12.5. In the result analysis, compactability will be referred to as workability. The results achieved for each bitumen content and compaction energy are the average of two specimens.

2.5.2. Water sensitivity

Water sensitivity was characterized using the Indirect Tensile Strength Ratio (ITSR) value. Specimens were produced with 35 blows/side for both mixtures (EN 12607-23). ITSR values were determined according to EN 12697-12 with a test temperature of 25 °C. The Indirect Tensile Strength Test results showed that AC20 specimens were broken along a diametrical line whereas SMA12.5 specimens did not show a fracture line, or was very limited, and displayed significant deformation (EN 12697-23). The results for each bitumen content were determined by testing 6 specimens (3 tested dry and 3 after immersion).

2.5.3. Permanent deformation resistance

The test was made in a small-size device, model A in air, procedure B (EN 12697-22). The size of the specimens was 300x340 mm²; height was 60 mm for the AC20 specimens and 40 mm for SMA12.5 specimens. Tests were performed in air at 60 °C. A load of 700 N was applied through a rubber wheel to the specimen. The wheel travels 230 mm with a frequency of 26.5 cycles/minute. During the test, 10,000 load cycles are applied to the specimens. The wheel-tracking rate (WTS_{AIR}) was used as a parameter to characterize rutting resistance. The results for each bitumen content are the average of two specimens tested.

2.5.4. Stiffness

Stiffness was determined in four-point bending tests on prismatic shaped specimens according to standard EN 12697-26. Specimens were prismatic with 400x60x60 mm³ for the AC20 and 400x50x50 mm³ for the SMA12.5. The load is applied in the two inner load points placed at 1/3 and 2/3 of the distance between the two fixed outer points. For stiffness modulus, a sinusoidal load with 50 microstrain was applied. Although several testing conditions were applied, the results attained for a temperature of 20 °C, and a frequency of 10 Hz were used for performance analysis. For each bitumen content 3 specimens were tested.

2.5.5. Fatigue resistance

Fatigue resistance tests were performed following standard EN 12697-24. Specimens and test conditions were similar to those used on the stiffness tests. Tests were performed at a temperature of 20 °C and a loading frequency of 10 Hz. For each bitumen content, a fatigue law was determined using 3 strain levels; for each strain level 6 specimens were tested. The value of ϵ_6 , the strain which induces specimen decay after 1 million load cycles, was calculated from the fatigue law equations and used for performance analysis.

3. Mix design

Mixtures were designed using a traditional empirical design (the Marshall method) and a volumetric design on gyratory compacted specimens. An analysis was made to the results of the design and volumetric properties. The design procedures for dense-graded mixtures followed Portuguese guidelines [28]. For SMA mixes, an analysis was made using guidelines from Europe and the USA [26,33] where there is more experience with this type of mixtures.

3.1. Empirical design

The Marshall design method was used for the dense-graded mixture to achieve reference values for the mixture properties. This method is the standard method in Portuguese practice. Therefore, the results represent the optimum binder contents (OBC) used in practice [28].

Binder contents used ranged from 3.5% to 5.5%, with 0.5% increments, and compaction of 75 blows/face was used. An OBC of 5.0% was determined. This binder content led to a VMA of 15% and a VFB of 75.3%.

For SMA12.5, the OBC was attained by analyzing air voids in Marshall specimens compacted with 50 blows/face [26,27,34,35]. Binder content ranged from 5.5% to 7.5%, with 0.5% increments. Target air void for design was set to 4.0% and an OBC of 6.5% was determined based on the paraffin coated procedure results. This binder content led to a VMA of 18.3% and a VFB of 78.3%.

3.2. Volumetric design

Gyratory compacted specimens were used for the volumetric design. AC20 specimens were compacted up to 125 gyrations. Binder contents ranged from 4.0% to 5.5% with 0.5% increments. SMA12.5 specimens were compared to 50, 75 and 100 gyrations. Binder content ranged from 5.0 to 7.5% with 0.5% increments. In both mixtures, OBC was determined for target air voids of 4%. Air voids in the specimens were determined using the procedures defined in EN 12697-6 to analyze volumetric parameters [10]. Bulk gravity dry, bulk gravity SSD, and bulk gravity by dimensions were determined in both mixtures. For the SMA, bulk gravity in paraffin sealed specimens and bulk gravity in vacuum-sealed specimens were also determined. As an example, Fig. 2 presents the OBC results for gyratory compacted specimens estimated from the evolution of specimen height during compaction. There is a difference in the estimated curves for SMA12.5 with 100, 75 and 50 gyrations. This result can be explained by the inaccuracy of the G_{mb} estimation process using height measurement, which is more obvious on gap-graded mixtures such as SMA. The impact of the procedures for bulk density determination is more relevant on gap-graded mixtures and mixtures with significant surface texture [10]. This situation occurs in SMA mixtures in which the surface texture of moulded specimens can impact the determination of the air voids. Therefore, bulk specific gravity was determined with vacuum sealing and paraffin coating. In Fig. 2, SMA12.5 values are based on the bulk specific gravity of paraffin sealed specimens, whereas AC20 values are for the SSD procedure.

3.3. Volumetric properties of the specimens

Fig. 3 represents the relative variation of the OBC and the volumetric properties, VMA and VFB, for both mixtures, bulk specific gravity procedures and compaction energies. It should be noted that these values were determined for a design air void of 4%. The values are in relative

scale; 100% represent the highest value observed for each shown property. It was observed a significant range for the volumetric properties. Comparing the results for the procedures used there is an OBC variation above 30% for SMA12.5 specimens compacted with 50 and 100 gyrations. In VMA and VFB, relative variations are lower but still significant. The SMA12.5 specimens compacted with 75 gyrations showed lesser variation of the properties for the different bulk specific gravity determination procedures. This observation may be linked with laboratory test variability.

For example, Fig. 4 presents the values for air voids, VMA and VFB for SMA12.5 Marshall specimens compacted with 75 blows/face for the bulk specific gravity procedures used. Fig. 5 presents the same properties but for gyratory compacted SMA12.5 specimens at 100 gyrations. The vacuum-sealed specimens and the dimension procedure led to higher binder contents, whereas dry, SSD, and paraffin coated air voids were comparable. The high surface texture can explain these results for the SMA12.5. SMA mixtures have a high surface texture but low inner voids because of the high binder content. This leads to a low interconnection between surface voids and internal voids. In addition, the SMA specimens surface texture is covered by the sealing paraffin, whereas for the vacuum procedure, the plastic film did not adjust to all surface irregularities. These differences between paraffin and vacuum-sealed specimens led to higher air voids for the latter. As expected, dry procedure led to lower air voids and VMA, and higher VFB, whereas the opposite was observed using the dimensions procedure. The differences between procedures tend to be lower with the increase in binder content and the increase in compaction energy, i.e., for lower air voids and lower surface textures.

4. Test results and analysis

4.1. Relationship between bulk specific gravity procedures results

Fig. 6 presents the values for the specific gravity procedures in SMA12.5 specimens compared to the values determined for the SSD procedure. The results include specimens produced for the design procedures and some performance tests, e.g. the specimens used for ITSR tests. Good correlations were observed amongst the bulk specific gravity procedures used. There is no apparent trend in the correlation's coefficients. As the specimen's volume considered by the bulk specific gravity method increases, there is a more significant difference between the values of the gyratory and Marshall specimens. This difference is more perceptible for the SMA12.5 specimens using the vacuum-sealed and dimensions procedure. This can be explained by different relation

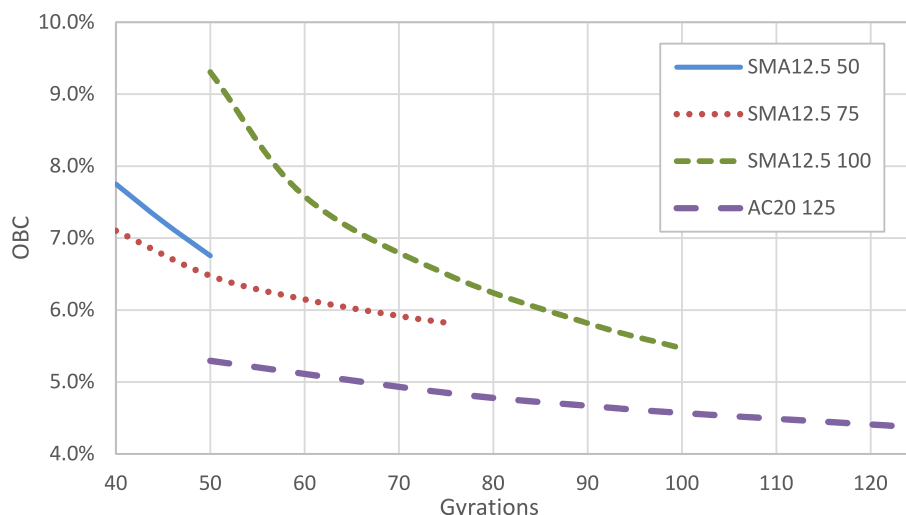


Fig. 2. Optimum binder content (OBC) vs gyrations for AC20 and SMA12.5 mixtures.

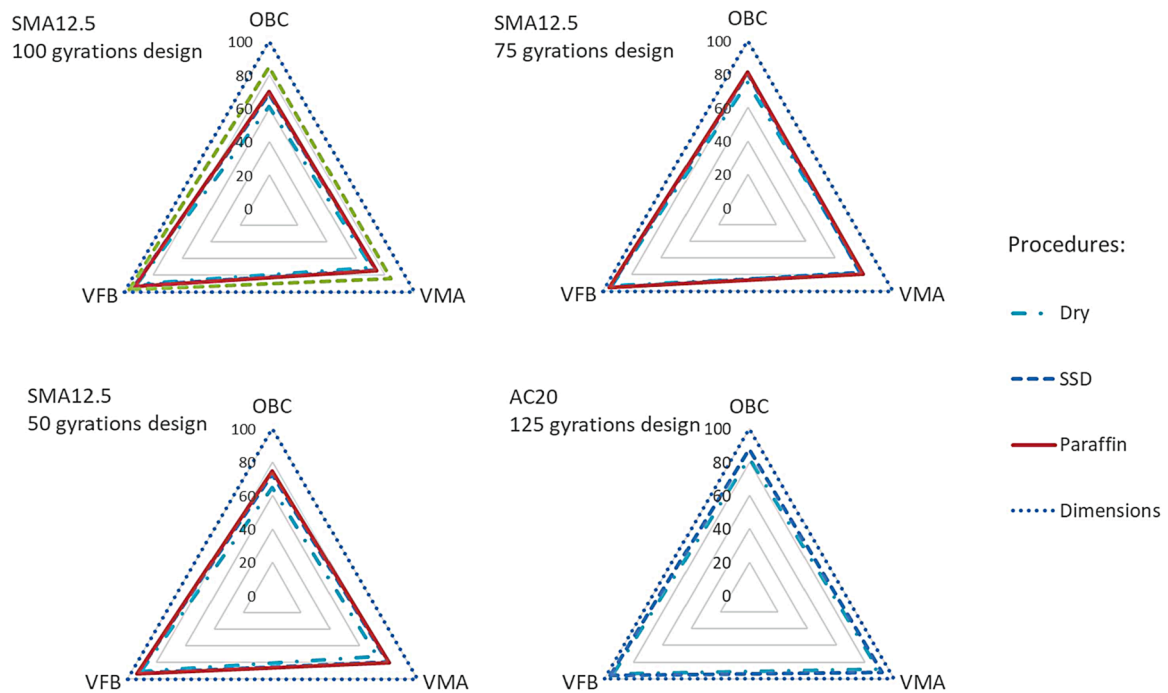


Fig. 3. OBC, VMA and VFB relative variation for SMA designed at 100, 75 and 50 gyrations and AC20 at 125 gyrations.

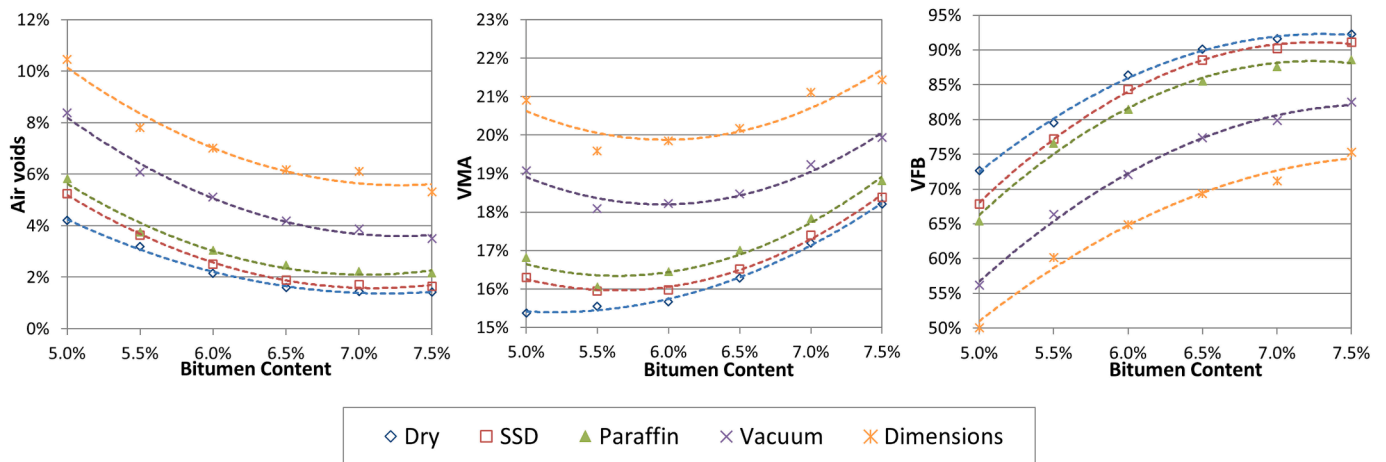


Fig. 4. Air voids, VMA and VFB evolution with binder content for SMA12.5 Marshall specimens compacted with 75 blows/face.

between the surface and volume of the specimens [10].

4.2. Impact of bulk specific gravity procedure in the mix-design

The differences in the volumetric properties determined by different procedures impact the design process by affecting air voids and, consequently, OBC. Fig. 7 shows the variation of OBC with the bulk specific gravity procedure for SMA12.5 gyratory compacted specimens at 50, 75 and 100 gyrations, and AC20 gyratory compacted specimens at 125 gyrations. It was observed that the differences tend to decrease with the increase in the compaction energy. This tendency can be explained by a reduction in the surface texture of the specimens. Nevertheless, this reduction was mild. In the SMA12.5 differences in the optimum binder content can be as high as 3.2% amongst procedures. However, for the most common procedures, SSD and paraffin sealed, the results are close. The vacuum procedure was only used in 100 gyrations compacted specimens. Therefore, there is only one point in Fig. 7 for this set of specimens. For the AC20, the differences between procedures are

smaller, showing a difference of 0.9% in OBC between the dry and the dimensions procedure. This result can be explained by the lower surface texture of the specimens for this mixture compared to the SMA mixture. It should be noted that a value for N_{des} of 125 gyrations used AC20 is relatively high, leading to low air void content and smooth surface specimens.

4.3. Performance analysis

The performance tests results were used to analyze the impacts of the bulk specific gravity procedures in the design. The binder content was used to relate the bulk specific gravity procedure with the mixtures' performance in the tests. Table 2 presents the results for the parameters determined in the performance tests. It should be underlined that the binder content range in the volumetric design was broader than that used in the performance tests. Therefore, some results were derived from experimental results by extrapolation. The same also happened to estimate OBC values for a particular N_{des} . The possible bias of the

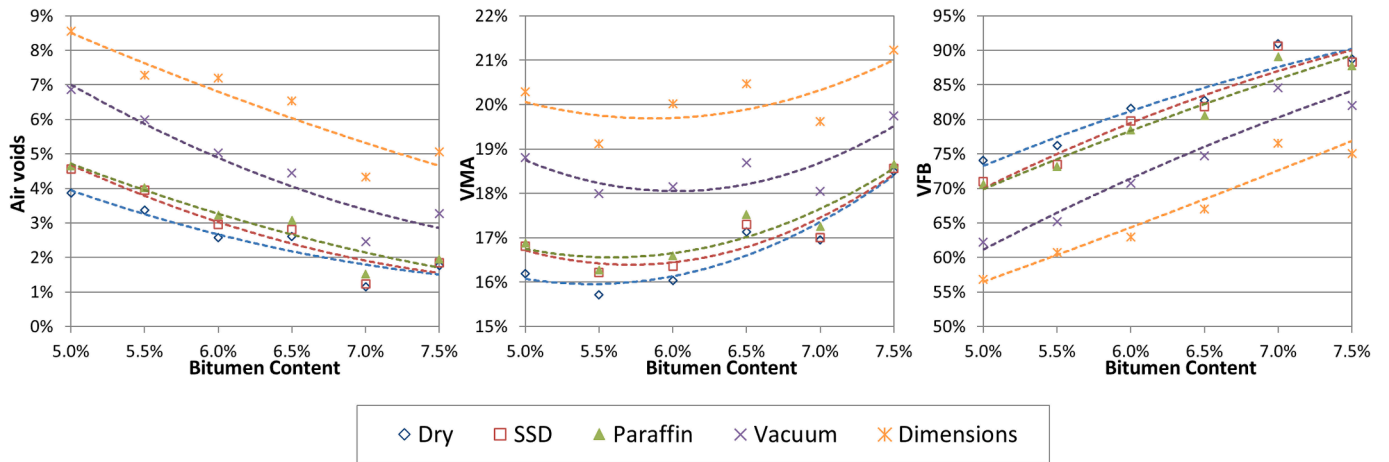


Fig. 5. Air voids, VMA and VFB evolution with binder content for SMA12.5 gyratory compacted specimens with 100 gyrations.

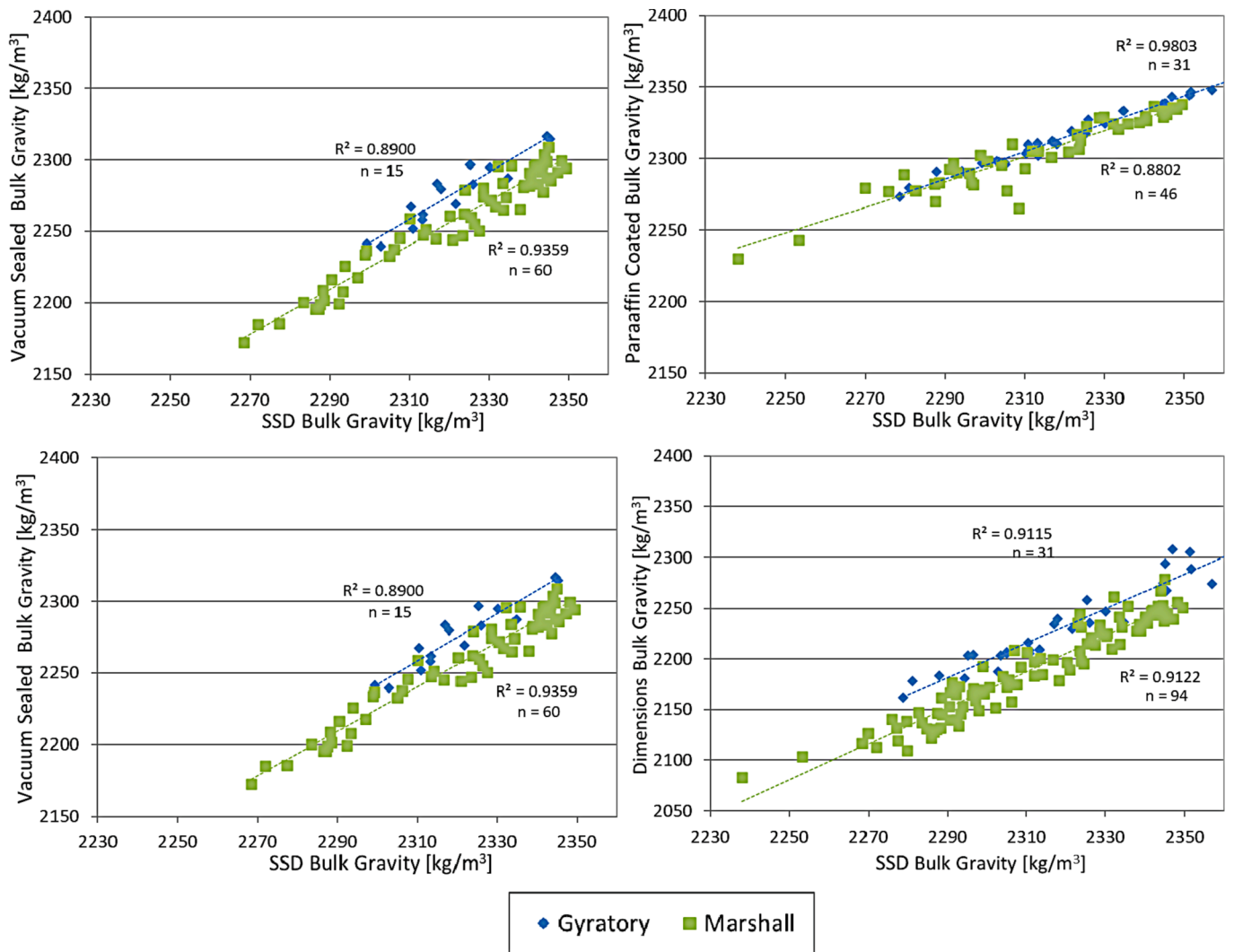


Fig. 6. Relationship between SSD air voids and dry, paraffin coated, vacuum-sealed and dimensions air voids for the SMA12.5 specimens.

extrapolation estimates was reduced in the SMA12.5 using sets of specimens compacted at 50, 75 and 100 gyrations and estimating one value in each set (40, 65 and 90, respectively). For the AC20, bias should be more negligible due to the reduced surface texture. For this mixture, all values were estimated from the specimens compacted at 125

gyrations. The results follow the expected trends, so they can be taken as indicative [1].

Results show that the SMA12.5 mixture underperformed in the resistance to permanent deformation compared to what was expected. This can be linked to the gradation of the mix, penetration grade

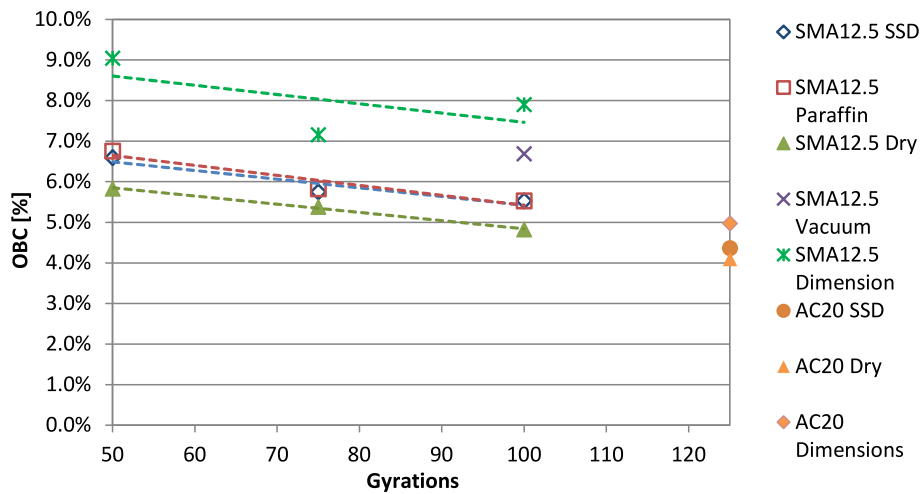


Fig. 7. OBC variation for SMA12.5 specimens compacted with 50, 75 and 100 gyrations and AC20 with 125 gyrations with bulk specific gravity determination procedures.

Table 2 Performance properties of the mixtures.

Gmb Procedure	SMA12.5							AC20						
	N _{des}	OBC [%]	CEI	ITSR [%]	WTS _{AIR} [mm/1000cycles]	Stiffness [MPa]	ε ₆ [μstrain]	N _{des}	OBC [%]	CEI	ITSR [%]	WTS _{AIR} [mm/1000cycles]	Stiffness [MPa]	ε ₆ [μstrain]
Dry	40	7.27	63.6	90.18	0.99	5763	187.3	50	5.13	5.6	81.13	0.25	6539	122.1
	50	5.83	122.0	73.86	0.61	7157	147.7	70	4.72	15.9	61.61	0.17	6899	115.7
	65	5.75	126.6	72.94	0.59	7237	145.4	80	4.57	23.4	54.29	0.14	7035	113.3
	75	5.38	149.7	68.75	0.50	7594	135.3	100	4.33	43.7	42.60	0.09	7251	109.5
	90	5.24	159.8	67.11	0.46	7734	131.3	125	4.10	78.9	31.53	0.04	7455	105.8
SSD	40	4.82	192.9	62.39	0.35	8138	119.8	-	-	-	-	-	-	-
	50	7.46	58.3	92.36	1.04	5577	192.6	50	5.29	3.8	88.59	0.28	6401	124.6
	50	6.59	86.4	82.51	0.81	6419	168.7	70	4.93	9.4	71.33	0.21	6720	118.9
	65	6.03	111.7	76.08	0.66	6968	153.1	80	4.79	13.4	64.80	0.18	6840	116.8
	75	5.75	126.7	72.92	0.59	7238	145.4	100	4.57	23.4	54.30	0.14	7034	113.3
Paraffin	90	5.72	128.2	72.63	0.58	7263	144.7	125	4.36	40.0	44.28	0.09	7220	110.0
	100	5.41	147.9	69.05	0.50	7568	136.0	-	-	-	-	-	-	-
	40	7.75	51.1	95.66	1.11	5294	200.6	-	-	-	-	-	-	-
	50	6.76	80.3	84.34	0.85	6262	173.1	-	-	-	-	-	-	-
	65	6.11	107.6	77.01	0.68	6888	155.3	-	-	-	-	-	-	-
Vacuum	75	5.82	122.7	73.73	0.61	7169	147.4	-	-	-	-	-	-	-
	90	5.85	120.9	74.10	0.62	7137	148.3	-	-	-	-	-	-	-
	100	5.53	140.3	70.38	0.53	7455	139.2	-	-	-	-	-	-	-
	90	6.92	74.6	86.18	0.89	6104	177.6	-	-	-	-	-	-	-
	100	6.69	82.8	83.59	0.83	6326	171.3	-	-	-	-	-	-	-
Dimensions	40	9.61	22.0	116.75	1.59	3492	251.8	50	5.70	1.3	108.65	0.37	6030	131.2
	50	9.04	28.5	110.30	1.45	4043	236.2	70	5.42	2.6	95.20	0.31	6279	126.8
	65	7.41	59.7	91.79	1.02	5625	191.2	80	5.32	3.5	90.04	0.29	6374	125.1
	75	7.16	66.9	88.91	0.96	5871	184.2	100	5.14	5.4	81.66	0.25	6529	122.3
	90	8.14	42.8	100.09	1.21	4916	211.4	125	4.97	8.4	73.55	0.22	6679	119.6
Reference design	100	7.90	47.8	97.35	1.15	5150	204.7	-	-	-	-	-	-	-
Reference design	6.51	89.8	81.56	0.79	6500	166.4	5.00	7.8	74.87	0.22	6654	120.1		

bitumen without modification, and the test temperature. The range of stiffness values was similar for both mixtures. These results can be explained by a higher air voids content in the AC20 specimens (6.4% average) when compared to the SMA 12.5 specimens (4.2% average). It should also be underlined that the surfaces of the SMA specimens were sawed to ensure evenness, thus, removing the surface texture of the specimens. For ITSR, stiffness and ε₆ higher values represent a better performance, whereas for CEI and WTS_{AIR}, better behaviour corresponds to lower values. Since the design was made at 4% air void, the trends observed in the performance parameters were expected to represent the observed variation of the OBC. For SMA12.5, workability shows the most significant variation with CEI differences between procedures as high as 77%. The variation in stiffness modulus reached 43%, whereas in WTS_{AIR}, the difference was 70%, ε₆ 41% and ITSR 36%. For AC20 differences between procedures were as high as 89% in CEI; variation in

stiffness modulus reached 10%, in WTS_{AIR} 82%, in ε₆ 12% and in ITSR 57%. Relative differences in performance were higher in series with higher N_{des}.

5. Discussion on the properties and procedures

Figs. 8 and 9 present relative performance for SMA12.5 specimens compacted at up to 100 gyrations and AC20 specimens compacted at up to 125 gyrations. In these figures 100% represents the best performance for all the parameters indicated in the ordinate axis. The relative performance (RP_p) was calculated by equation (1), when higher parameter values represent better performance, and equation (2) when lower parameter values mean better performance.

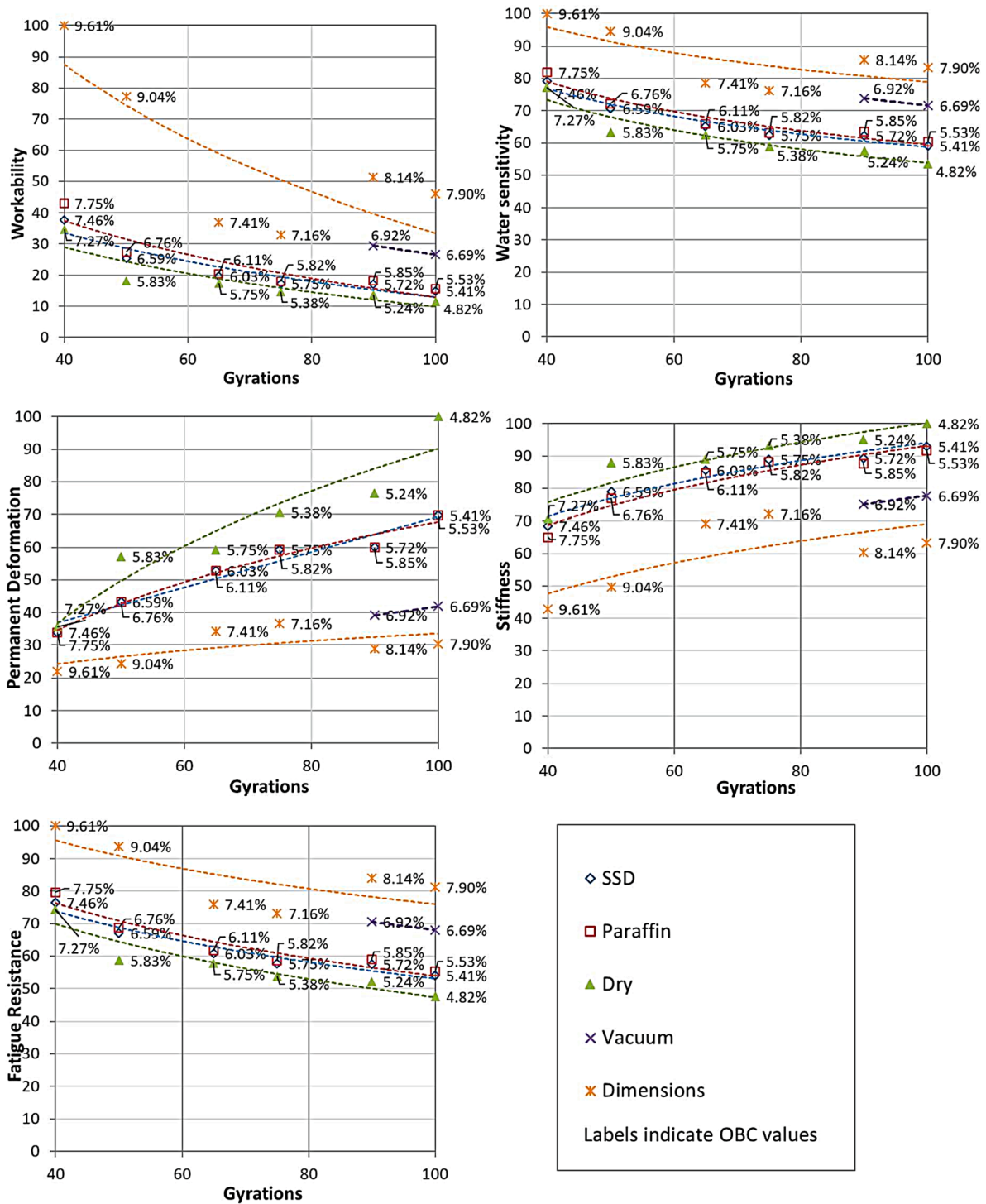


Fig. 8. Relative performance for the SMA12.5 versus N_{des} values.

$$RP_p = \frac{V_p}{\max(V_1 \dots V_n)} \times 100 \quad (1)$$

$$RP_p = \frac{\min(V_1 \dots V_n)}{V_p} \times 100 \quad (2)$$

where $V_1 \dots V_n$ represent the range values of the performance parameter for a specific property and V_p the performance individual values for the same parameter.

It should be stressed that variations in the performance are highly dependent on the parameters taken as representative of the tests.

Considering that these relationships were derived from an experimental laboratory program, they should be considered an estimate of the expected variation for the in-service performance.

The variations in the relative performance amongst bulk specific gravity procedures were higher for the SMA12.5. This variation may be linked to the higher surface texture of the mixture, leading to more significant differences in the void content measured by different procedures. Consequently, that led to a more extensive range in the OBC. This trend can be observed in relative performance values for stiffness and fatigue resistance in the SMA12.5 (Fig. 8) compared to the range of relative performance for the same properties in the AC20 (Fig. 9).

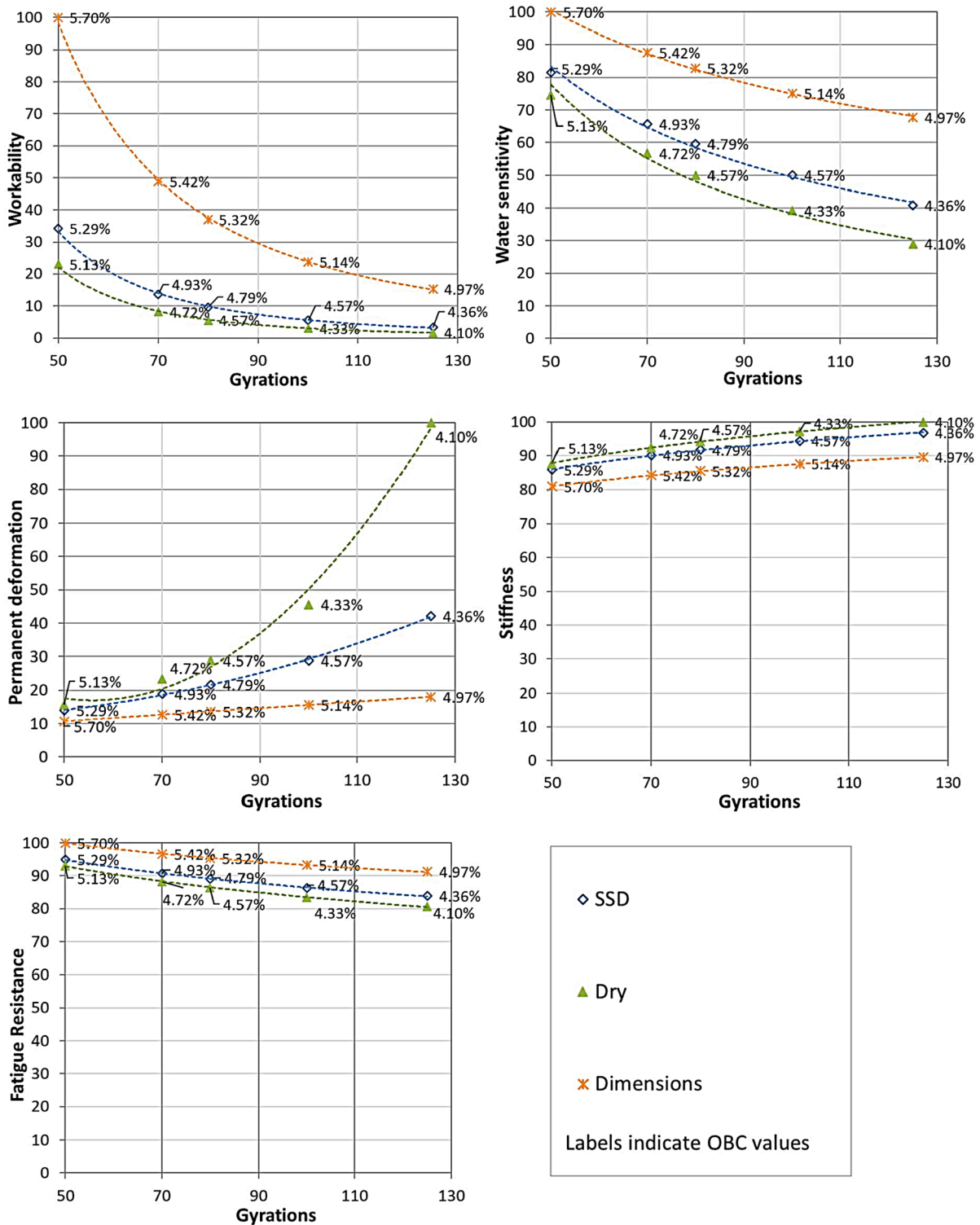


Fig. 9. Relative performance for the AC20 versus N_{des} values.

However, AC20 showed higher variation in relative performance for water sensitivity amongst bulk specific gravity procedures. This result can be explained by the relatively low binder content of the AC20.

Following a methodology proposed by the authors [36], a global score was defined based on the values of performance parameters to illustrate the impact of these results on the global performance of mixtures. The values are based on SMA12.5 specimens compacted at 100 gyrations and AC20 specimens compacted at 125 gyrations. The likely weights considered for calculating the global score are presented in

Table 3. The authors defined the weights based on their experience [4,36] and the potential values to represent a possible balance of properties for average in-service conditions, referred to as likely values. For the SMA12.5, these average conditions may correspond to an application as a surface layer in moderate climate and traffic. Therefore, permanent deformation resistance and water sensitivity had the highest weights. On the other hand, for the AC20, the likely values can represent an application in a base layer for moderate climate and traffic in a medium thickness pavement. Therefore, fatigue resistance had the

Table 3
Range of weights considered in the global score and sensitivity analysis.

Performance property	SMA12.5			AC20		
	Min. (%)	Likely (%)	Max. (%)	Min. (%)	Likely (%)	Max. (%)
Workability	5	10	30	10	15	35
Water sensitivity	20	25	45	5	10	30
Stiffness	5	10	30	10	15	35
Rutting resistance	30	35	55	20	25	45
Fatigue resistance	15	20	40	30	35	55

highest weight.

Fig. 10 presents the values determined for the global score based on the likely weights. In this score, a design with the best performance in all properties achieves a score of 100%. The performance of the reference design, using the empirical design methodologies mentioned in 3.1, was included. However, considering that the specimen size, production procedures and compaction energy used in the empirical design and the volumetric design are diverse, a direct comparison should be carried out with caution. For example, if different compaction energy was used for specimen production, the performance of the gyratory specimens would compare differently with the reference design [4]. Furthermore, the comparison between SMA12.5 and AC20 should not be made since their relative performances were determined independently and with different weights.

Global performance shows that the highest difference resulting from the procedures used is 7.4% (from 70.6 to 78%) for the SMA12.5 and 12.4% (from 71.4 to 83.8%) for the AC20. However, if we consider the most common procedures used for SMA mixtures, SSD, paraffin coated and vacuum-sealed, the difference is 0.6%. For the SMA12.5, in which

significant differences result from the use of different bulk specific gravity procedures, for the most used, SSD, paraffin coated and vacuum-sealed, results showed moderate differences with limited impacts on global performance.

Diverse in-service conditions may require different relative importance of the considered performance parameters. Thus, a sensitivity analysis was performed with more comprehensive ranges of weights to evaluate potential scenarios for the relative performance amongst the compositions resulting from different procedures. For example, a property had its weight increased by 20 %, whereas the other four properties had the weight reduced 5% to perform the sensitivity analysis in each scenario. This procedure was performed for each property, with five scenarios tested. Table 3 summarizes the ranges of weights considered in the analysis. The calculation created an envelope with the maximum and minimum global score values. The range of variation of the weights was chosen to represent a severe range of practical applications in which a particular property could gain more importance. For instance, for a SMA12.5 used in the surface layer on a low traffic road and humid climate, water sensitivity performance is more critical than permanent deformation performance. Fig. 10 presents the results from the sensitivity analysis with the indication of the range observed for the performance score (represented by the variation lines).

Regarding SMA12.5, the sensitivity analysis showed that an increase of the permanent deformation resistance weight to 55% would lead to the maximum difference of global score between procedures (22.2%). When the weight of the water sensitivity increased to 45%, the mixture with the best global score would be designed using the dimensions procedure, and the difference of global score between procedures would be reduced to 6.6%, the minimum difference. However, the dry and dimensions procedures are not generally used in design methods for these mixtures. Differences between SSD, paraffin coating and vacuum-sealing were low using the likely weight values, 0.6%. The difference of

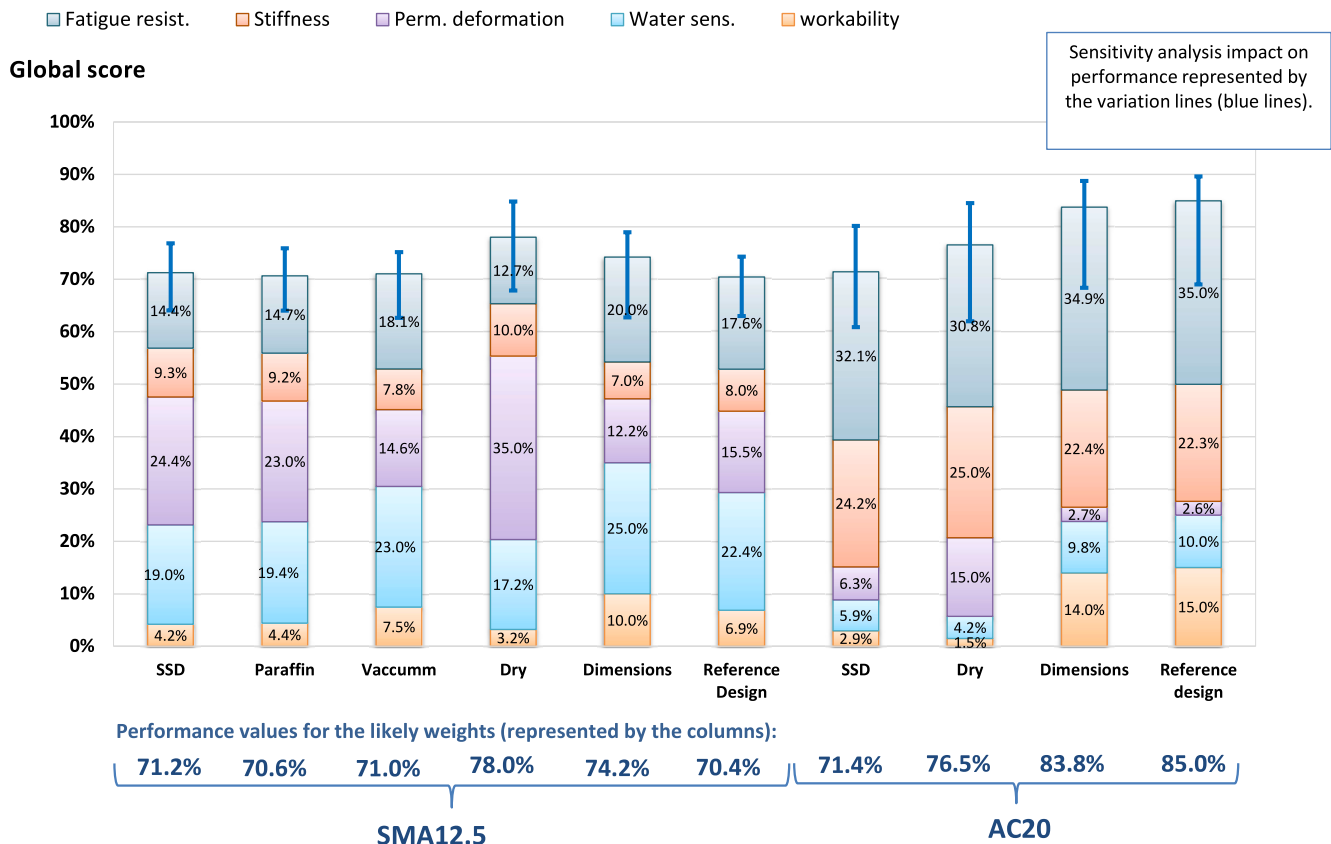


Fig. 10. Global performance score for SMA12.5 and AC20 (performance for the likely weights is presented in columns and the sensitivity analysis results by variation lines).

global score amongst these procedures reached a maximum of 8.4% in the sensitivity analysis.

For the AC20, the maximum variation obtained was 26.3% when the workability weight was increased to 35%, and the minimum was 6.1% when the stiffness weight was increased to 35%. In the AC20, the dimensions procedure achieved a better global score (83.8%); a higher fatigue resistance and improved workability can explain a better score since this procedure led to higher OBC. The sensitivity analysis for the AC20 also showed that increasing the workability weight to 35% would lead to a global score variation of 26.3%. When the weight of the stiffness was increased to 35%, the difference in the global score was reduced to 6.1%. For the SMA12.5, changes in the global score ranking for the bulk specific procedures were observed. The dry procure or the dimensions procedure achieved the highest global score, depending on whether the weight maximised performance property benefited from low or high bitumen content. For the AC20, the dimensions procedure achieved the highest scores in most cases.

Permanent deformation resistance and workability were the properties that most influenced the difference between procedures. This result is linked to the range of variation of the parameters used, WTS_{AIR} and CEI, which impact the relative performance variation (Figs. 8 and 9).

While global scores would not differ much for the bulk gravity procedures in a typical application scenario, it is observed that for applications where one or two properties may gain additional relevance, the performance of the mixtures could have considerable variations. Because the design is carried out for specific air void content, affecting the OBC, the procedures lead to performance changes of the designed mixtures. For applications where some properties are more influential for the performance of the mixtures in the pavement, the influence in the performance may be very significant.

The results from this work are linked to the mixtures and designs used. Therefore, the extrapolation of these results to other mixtures or compositions must be made carefully. In addition, laboratory test precision, repeatability and reproducibility are also important and may affect results. However, test results are in the expected range of values and trends.

6. Conclusions

Based on the results obtained in this study, the following conclusions can be made:

- Bulk gravity determination procedures can considerably impact the volumetric properties values, therefore significantly influencing the design and performance properties of the mixtures. The influence of those procedures was more noticeable on the SMA12.5 than on the AC20. This result can be explained by the higher surface texture of the SMA12.5. For the SMA12.5, the OBC difference resulting from the several bulk gravity procedures was 3.2% (50 gyrations specimens), whilst for AC20, the difference was 0.9% (125 gyrations specimens).
- OBC decreased with increasing compaction energy. Likewise, the VMA and VFB range resulting from the several bulk gravity procedures decreased with increasing design compaction energy. The differences were more remarkable for the SMA12.5 than for the AC20.
- The dimensions procedure contributes significantly to the range of values. For SMA12.5 specimens compacted at 50 gyrations, the range was 3.2% for OBC, 6.4% for VMA and 7.8% for VFB. Excluding the dimensions procedure, the range was 0.9% for OBC, 1.9% for VMA and 2.3% for VFB.
- Performance of the mixtures was affected by OBC changes resulting from the bulk specific gravity procedure used in the design. Workability variation derived by the bulk gravity procedure reached 75% (SMA12.5 specimens compacted at 100 gyrations). The variation was

much more limited for stiffness, e.g. maximum variation for AC20 specimens was 10% (specimens compacted at 125 gyrations). However, it should be stressed that relative performance variation is strongly affected by the indexes chosen to characterize the performance.

- A global score based on weighting performance properties was used to evaluate mixtures' performance. Maximum variation in the global score was approximately 10% between bulk specific gravity procedures. Global score variation was moderate for commonly used procedures (SSD, paraffin coated, vacuum-sealed). For the SMA12.5 specimens compacted at 100 gyrations, the global score variation was below 1% when considering those procedures. However, the global score variation increases considerably for in-service conditions where one performance property assumes critical importance. A sensitive analysis showed an increase in the global score range from 1% to 8% for the case aforementioned.

Future work will focus on validating the expected in-service performance based on data collected on-site data. In addition, this approach will better understand of how laboratory procedures performed within the mix-design methods may impact in-service performance.

CRediT authorship contribution statement

Dinis Gardete: Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Luís Picado-Santos:** Conceptualization, Project administration, Methodology, Supervision. **Silvino Capitão:** Methodology, Writing – original draft, Writing – review & editing. **Rosa Luzia:** Investigation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors want to thanks to the technical personnel working at the Laboratory of Highways and Transportation (LVTC) of the CERIS, Instituto Superior Tecnico, Universidade de Lisboa. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

- [1] M. Zaumanis, L. Poulidakos, M. Partl, Performance-based design of asphalt mixtures and review of key parameters, *Materials & Design*. 141 (2018) 185–201, <https://doi.org/10.1016/j.matdes.2017.12.035>.
- [2] M. Guler, Effects of Mix Design Variables on Mechanical Properties of Hot Mix Asphalt, *Journal of Transportation Engineering* 134 (3) (2008) 128–136, [https://doi.org/10.1061/\(ASCE\)0733-947X\(2008\)134:3\(128\)](https://doi.org/10.1061/(ASCE)0733-947X(2008)134:3(128)).
- [3] E. Hajj, A. Ulloa, P. Sebaaly, G. Bazi, Impact of rich-bottom design in asphalt pavements, *Int. J. Pavement Res. Technol.* 4 (6) (2011) 313–323.
- [4] D. Gardete, L. Picado-Santos, S. Capitão, Improving bituminous mixture performance by optimizing the design compaction energy – A cost effective approach for better pavements, *Construction and Building Materials* 190 (2018) 1173–1181, <https://doi.org/10.1016/j.conbuildmat.2018.09.169>.
- [5] E. Remišová, Effect of film thickness on resistance to permanent deformation in asphalt mixtures, *The Baltic Journal of Road and Bridge Engineering* 10 (4) (2015) 333–339, <https://doi.org/10.3846/bjrbe.2015.42>.
- [6] H. Gong, Y. Sun, W. Hu, P. Polaczyk, B. Huang, Investigating impacts of asphalt mixture properties on pavement performance using LTPP data through random forests, *Construction and Building Materials* 204 (2019) 203–212, <https://doi.org/10.1016/j.conbuildmat.2019.01.198>.
- [7] S. Bhattacharjee, R. Mallick, An Alternative Approach for the Determination of Bulk Specific Gravity and Permeability of Hot Mix Asphalt (HMA), *The International Journal of Pavement Engineering* 3 (3) (2002) 143–152.
- [8] G. Huber, J. Haddock, J. Wielinski, A. Kriech, A. Hekmafter, Adjusting design air void levels in Superpave mixtures to enhance durability, 6th Eurasphalt & Eurobitume Congress, 1-3 June (2016), Prague.

- [9] F. Praticó, A. Casciano, Variability of HMA characteristics and its influence on pay adjustment, *Journal of Civil Engineering and Management* 21 (1) (2015) 119–130, <https://doi.org/10.3846/13923730.2013.802713>.
- [10] F.G. Praticó, R. Vaiana, A. Moro, Dependence of Volumetric Parameters of Hot Mix Asphalts on Testing Methods, *Journal of Materials in Civil Engineering* 26 (1) (2014) 45–53.
- [11] M. Sadique, H. Al-Nageim, F. Stopps, The reliability of asset management regime of the SROH using air void content of asphalt mixtures, *International Journal of Pavement Engineering* 20 (1) (2019) 100–111, <https://doi.org/10.1080/10298436.2016.1260131>.
- [12] J. Anochie-Boateng, J. Komba, D. Ventura, B. Verhaeghe, Effect of sample geometry on bulk relative density of hot-mix asphalt mixes, 10th Conference on Asphalt Pavements for Southern Africa (CAPSA), 11–14 September (2011), KwaZulu-Natal, South Africa, 2011.
- [13] B. Yu, X. Gu, F. Ni, L. Gao, Microstructure characterization of cold in-place recycled asphalt mixtures by X-ray computed tomography, *Construction and Building Materials* 171 (2018) 969–976, <https://doi.org/10.1016/j.conbuildmat.2018.03.203>.
- [14] A.J. Enriquez-León, T.D.d. Souza, F.T.S. Aragão, A.M.B. Pereira, L.P. Nogueira, “Characterization of the air void content of fine aggregate matrices within asphalt concrete mixtures, *Construction and Building Materials* 300 (2021) 124214.
- [15] E. Arambula, E. Masad, A. Martin, Influence of Air Void Distribution on the Moisture Susceptibility of Asphalt Mixes, *Journal of Materials in Civil Engineering* 19 (8) (2007) 655–664, [https://doi.org/10.1061/\(ASCE\)0899-1561\(2007\)19:8\(655\)](https://doi.org/10.1061/(ASCE)0899-1561(2007)19:8(655)).
- [16] J. Hu, P. Liu, D. Wang, M. Oeser, T. Tan, Investigation on fatigue damage of asphalt mixture with different air-voids using microstructural analysis, *Construction and Building Materials* 125 (2016) 936–945, <https://doi.org/10.1016/j.conbuildmat.2016.08.138>.
- [17] E. Kassem, E. Masad, R. Lytton, A. Chowdhury, Influence of Air Voids on Mechanical Properties of Asphalt Mixtures, *Road Materials and Pavement Design* 12 (3) (2011) 493–524, <https://doi.org/10.1080/14680629.2011.9695258>.
- [18] M. Buchanan, T. White, Hot Mix Asphalt Mix Design Evaluation Using the Corelok Vacuum-Sealing Device, *Journal of Materials in Civil Engineering* 17 (2) (2005) 137–142, [https://doi.org/10.1061/\(ASCE\)0899-1561\(2005\)17:2\(137\)](https://doi.org/10.1061/(ASCE)0899-1561(2005)17:2(137)).
- [19] F. Russo, S. Biancardo, A. Formisano, G. Dell’Acqua, Predicting percent air voids content in compacted bituminous hot mixture specimens by varying the energy laboratory compaction and the bulk density assessment method, *Construction and Building Materials* 164 (2018) 508–524, <https://doi.org/10.1016/j.conbuildmat.2017.12.174>.
- [20] F. Praticó, A. Moro, R. Ammendola, Modeling HMA Bulk Specific Gravities: a Theoretical and Experimental Investigation, *International Journal of Pavement Research and Technology* 2 (3) (2009) 115–122.
- [21] E. Dukatz, J. Haddock, K. Hall, J. Kliewer, C. Marek, J. Musselman, A. Regimand, R. West, G. Sholar, N. Tran, A Review of Aggregate and Asphalt Mixture Specific Gravity Measurements and Their Impacts on Asphalt Mix Design Properties and Mix Acceptance, NCAT Report 12-06 (2009), Auburn.
- [22] F. Praticó, A. Moro, Measurement of air void content in hot mix asphalts: Method and core diameter dependence, *Construction and Building Materials* 26 (2012) 344–349, <https://doi.org/10.1016/j.conbuildmat.2011.06.032>.
- [23] M. Wróbel, A. Wozuk, W. Franus, Laboratory Methods for Assessing the Influence of Improper Asphalt Mix Compaction on Its Performance, *Materials*, Vol. 13(11) (2020). <https://doi.org/10.3390/ma13112476>.
- [24] S. Caro, D. Castillo, M. Darabi, E. Masad, Influence of different sources of microstructural heterogeneity on the degradation of asphalt mixtures, *International Journal of Pavement Engineering* 19 (1) (2018) 9–23, <https://doi.org/10.1080/10298436.2016.1149839>.
- [25] M. Ren, L. Cong, H. Gong, Accelerated stochastic damage modeling of the long-term moisture effect on hot-mix asphalt, *Construction and Building Materials* 295 (2021) 123692.
- [26] AASHTO, Standard, Specification for Stone Matrix Asphalt (SMA), AASHTO standard M-325, American Association of State Highway and Transportation Officials, 2012.
- [27] EAPA, Heavy Duty Surfaces – The Arguments for SMA, European Asphalt Pavement Association, Brussels, 1998.
- [28] EP, Caderno de Encargos Tipo Obra. Estradas de Portugal, Almada, 2014.
- [29] D. Gardete, L. Picado Santos, S. Capitão, Avaliação da Trabalhabilidade de Misturas Betuminosas com base nas Curvas de Compactação, 8º Congresso Rodoviário Português, abril 12-14 (2016), Lisbon.
- [30] A. Mahmoud, H. Bahia, Using gyratory compactor to measure mechanical stability of asphalt mixtures, WHRP 05–02, Wisconsin Highway Research Program, Wisconsin Department of Transportation, Madison, 2004.
- [31] R. Anderson, P. Turner, R. Peterson, R. Mallick, Relationship of Superpave Gyratory Compaction Properties to HMA Rutting Behavior, NCHRP Report 478, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2002.
- [32] P. Reza, J. Haddock, A new framework for understanding aggregate structure in asphalt mixtures, *International Journal of Pavement Engineering* 22 (9) (2021) 1090–1106, <https://doi.org/10.1080/10298436.2019.1660340>.
- [33] CEN, EN 13108-5 - Bituminous mixtures. Material specifications. Stone Mastic Asphalt, European Committee for Standardization, Brussels, 2016.
- [34] DER, Concreto Asfáltico Tipo SMA, Departamento de Estradas de Rodagem, São Paulo (2007).
- [35] L. Drüschner, V. Schäfer, Stone Mastic Asphalt, German Asphalt Association, Bonn, 2000.
- [36] F. Martinho, L. Picado-Santos, S. Capitão, Mechanical properties of warm-mix asphalt concrete containing different additives and recycled asphalt as constituents applied in real production conditions, *Constr. Build. Mater.* 131 (2016) 78–89, <https://doi.org/10.1016/j.conbuildmat.2016.11.051>.