Case studies & non-highway applications; Success and failure from real practice

Development of high performance asphalt mixtures for port pavements

M. Sol-Sánchez[1], F. Moreno-Navarro[1], M. C. Rubio-Gámez[1], M. E. Hidalgo-Pérez[2], J. Torres-Pérez[2], V. Pérez-Mena[3], A. García-Siller[3]

[1]Laboratory of Construction Engineering of the University of Granada, LabIC.UGR (Spain), [2]Eiffage Infraestructuras, [3]Cepsa

Abstract

Due to the advances produced in modified asphalt binders, bituminous mixtures are being used in infrastructures where cement concrete has been traditionally conceived as a more competitive solution. In this respect, the use of bituminous mixtures is becoming more popular in the construction and maintenance of port pavements. However, in spite of these advances, the design of bituminous mixture is carried out under similar criteria to those used for road pavements, and their mechanical performance do not offer the expected durability. Because of this fact, during the research study, a new design procedure has been developed in order to define more durable asphalt materials to be used in port pavements. For this purpose, the mechanical response of high-performance bituminous mixtures is evaluated under similar load and environmental conditions to those occurred during their service life (static and dynamic punching, the effect of heavy vehicles at low speed and the presence of fuel). Results demonstrate that using the procedure presented it is possible to optimize the design of bituminous mixtures in order to improve their resistance, especially under adverse service conditions.

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1. INTRODUCTION

The globalization of markets has led to a significant increase in freight transportation, particularly maritime transportation, with the transport of containers increasing annually by approximately 10% [1]. This has led to a higher number of operations in ports, with an increase in the storage of containers as well as the number of loadings, movements, and unloading of such containers. These demands therefore require an improvement in the quality and resistance of existing port pavements, along with an increased surface area for container operations. This implies the need for pavements that are hard-wearing, cost-efficient, and sustainable (requiring less construction time and maintenance) to improve the efficiency of the containers market [2].

Traditionally, pavements for ports have been constructed with concrete due to its high bearing capacity which need to withstand heavy static and dynamic loads [3-5]. However, the development of hard and high performance bitumens (modified with a high quantity of specific polymers) has contributed to the design and expansion of asphalt mixtures with higher bearing capacity and higher resistance to impacts and permanent loads, offering an appropriate material for application in port pavements whilst reducing the time and costs associated with construction and maintenance. Thus, real experiences have been carried out with asphalt pavements in ports in a number of countries (such as Germany, the Netherlands, France, Australia, and New Zealand, among others) [6-10].

In the majority of cases in which the use of asphalt for port pavements has had positive effects on resistance and durability, High Modulus Asphalt Mixtures (HMAM) have been applied. These mixtures are commonly composed of a continuous mineral skeleton (usually with aggregates with a size up to 22-25 mm) and a hard binder (with penetration values of around 10-30 dmm) with the aim of obtaining a material with high bearing capacity while providing resistance to permanent deformations, impacts, and cracking, among other benefits [11, 12]. Thus, in comparison with concrete, this type of asphalt mixture could provide more versatile and cost-efficient pavements for ports, without loss of resistance or mechanical performance. Nonetheless, in order to reap these benefits the asphalt mixtures must be designed in accord with strict application requirements. In particular, the mechanical performance of these materials must be tested under in-service conditions for port pavements, in which higher loads and stresses are expected in comparison with roads where asphalt mixtures are more widely applied.

In this regard, the aim of the present study was to contribute towards the development of asphalt mixtures for use in ports by analysing the mechanical response of various HMAM designed for this purpose. A range of mixtures were manufactured using different types of high-performance bitumens and various types of aggregates to identify the factors that are most relevant in the design of these materials in comparison with conventional concrete pavements. For this purpose, specific laboratory tests were developed to evaluate the behavior of the different mixtures under more realistic conditions for their use in ports, including full-scale tests to assess the mechanical performance of real sections using the designed high-performance asphalt mixtures.

2. METHODOLOGY

2.1 Materials

For the present study, five HMAM were designed and then compared with concrete samples commonly used in pavements for ports. All of the asphalt mixtures had the same design parameters (similar granulometric curve and bitumen content), but differed in terms of the type of bitumen and aggregates used.

The asphalt mixtures were manufactured using aggregates with a maximum size of 22 mm, using limestone for the fine fraction (0/6 mm) while the coarse aggregates (fractions 6/12, 12/18 and 18/22 mm) were composed of limestone for one of the mixtures, and ophite for the other four HMAM (assessing then the effect of the nature of aggregates). All of the mixtures used a cement filler whilst the properties of the aggregates complied with those set out by the Spanish Standard [13] for these type of mixtures. Also, four different bitumens were employed (with a dosage of 4.75% over mixture weight) to evaluate their impact on mixture performance: a conventional hard bitumen type B 15/25 (penetration: 15-25 dmm EN 1426; softening point: 60-76°C EN 1427); a bitumen modified with SBS and crumb rubber from waste tires (20-30 dmm; 63°C); a SBS polymer modified bitumen (20-55 dmm; 65°C); and a conventional bitumen B 15/25 modified in plant with plastomers (polyolefin and bitumen based additive with a melting point of around 130°C and specific gravity close to 0.95 g/cm^3).

Using these materials, five different high modulus asphalt mixtures were analyzed: HMAM-C-L, HMAM-C-O, HMAM-R-O, HMAM-P-O, and HMAM-Pl-O. Table 1 summarizes the main physical and mechanical properties of the different mixtures analyzed.

Table 1. Properties of the HMAM studied.

Property	HMAM-C-L	HMAM-C-O	HMAM-R-O	HMAM-P-O	HMAM-Pl-O

Type of bitumen	B 15/25	B 15/25	Rubber+SBS modified	SBS polymer modified	B 15/25 + Plastomers
Type of coarse aggregates	Limestone	Ophite	Ophite	Ophite	Ophite
Type of fine particles	Limestone	Limestone	Limestone	Limestone	Limestone
Bulk density (Mg/m^3) EN 12697-6	2.394	2.527	2.522	2.487	2.447
Air void content (%) EN 12697-8	4.0	5.1	5.4	6.6	6.4
Marshall stability (kN) EN 12697-34	22.3	22.9	26.3	21.1	26.9
Marshall deformation (mm) EN 12697-34	3.1	4.5	4.2	5.4	3.2
Indirect Tensile Stiffness at 20°C (MPa) EN 12697-26	11836.3	11086.7	13420.5	9690.6	12863.9

To evaluate the feasibility of using the designed HMAM in port pavements, concrete was used as a reference. This material was composed of limestone-dolomite crushed aggregates with a maximum particle size of 16 mm, divided into three fractions: 50% sand - 0/4; 25% gravel 1 - 2/8; and 25% gravel 2 - 4/16. The sand fraction presented a density of 2.84 Mg/m^3, water absorption of 0.011%, a value of sand equivalent to 73% and a methylene blue value of 0.24 g/100g of fine grains, while the coarse fraction (gravel 2/16) had a density of 2.80 Mg/m^3 and 0.26% of water absorption. The water/cement ratio was 0.6, with a cement type CEM II/A-V 42.5R. The compressive strength was around 35 MPa (EN 12390-3).

2.2 Methods

Three laboratory tests were conducted to evaluate the mechanical performance and resistance of the different materials under the loading conditions expected in port pavements. The tests used in this study were designed to specifically focus on analysing the following main failure modes of port pavements during container operations: (i) resistance to static punching stress due to container storage; (ii) punching impact due to unloading of containers; and (iii) resistance to rutting resulting from a combination of fuel leaks and heavy traffic action. Additionally, (iv) full-scale tests were carried out over the whole pavement section for ports, incorporating the most appropriate mixtures. The testing plan also evaluated the effect of different loading levels and climate conditions that can accelerate the degradation of asphalt mixtures [14].

The first test, referred to as UGR-PASPT (University of Granada – Port Asphalt Static Punching Test), aimed to evaluate the resistance of the various materials to plastic deformation resulting from heavy punching loads, simulating the storage of containers. For this purpose, two specimens (with a horizontal surface of 300 mm x 300 mm and a height of 60 mm) were tested for each material through simulating the contact between the pavement and the container support (Figure 1a and 1d). The tests consisted of applying a constant load for 40,000 seconds, which in this study simulated two levels of stress: 2.6 MPa and 5.2 MPa. To evaluate the effect of climate actions, the asphalt mixtures were analyzed under 25°C and 40°C (for the stress of 2.6 MPa), whilst the impact of water was evaluated by conditioning the specimens in water at 40°C for 72h (later, the load process was carried out at 25°C as in the rest of tests). As results, the deformation-time curve was measured along the test.

The second test used in this study is referred to as UGR-PADPT (University of Granada – Port Asphalts Dynamic Punching Test), which aims to determine the extent to which port pavement materials are susceptible to deformation and damage under impact loads primarily resulting from the unloading of containers. The specimens were prepared in a similar way to those for the static test. A series of dynamic impacts were reproduced by dropping a weight (around 25 kg), which followed a circular movement through a jib (length of 1.5 m) attached to a ball joint (Figure 1b). This process reproduces the impact of containers when dropped from a crane (where the containers show a pendular movement due to the displacement of the crane supporting the container). Two testing methods were carried out: one reproducing a constant fall height (10 cm from the floor) for 30 impacts; and a fatigue test consisting of three height levels (5 cm, 20 cm, and 35 cm) with 10 impacts for each position. After each impact, the punching depth into the specimen was measured to determine the deformation/indentation. The first testing method was carried out at 25°C while the fatigue process was applied at 25°C and 40°C to evaluate the effect of the test temperature along with the effect of dry and wet conditions (similar to those used for the static punching test) to analyse the influence of water on the resistance of the specimens.

The third test was the UGR-PARFT (University of Granada – Port Asphalt Resistant to Fuel Test) which determines the resistance of the port pavement to the effects of fuel (resulting from the equipment and vehicles employed in the container operations and from the actual containers) in combination with the action of heavy vehicles circulating at low speed (which increases rutting formation in the pavement). For this purpose, four specimens of each material were tested in a wheel tracker machine using a process adapted from the method described in the Standard EN 12697-22, with two specimens tested under dry conditions and the other two conditioned in contact with fuel (Figure 1c and 1f). The test applied 10,000 cycles at a temperature of 60°C under a stress of 900 KPa. In order to simulate the effect of fuel, 100 ml of this substance was poured directly over the surface of the specimens, and then stored at 25°C for 48h. Before applying the test, the surface of the specimen was washed with water until reaching a neutral and constant pH. Their resistance to plastic deformation was then compared with specimens conditioned under dry conditions.

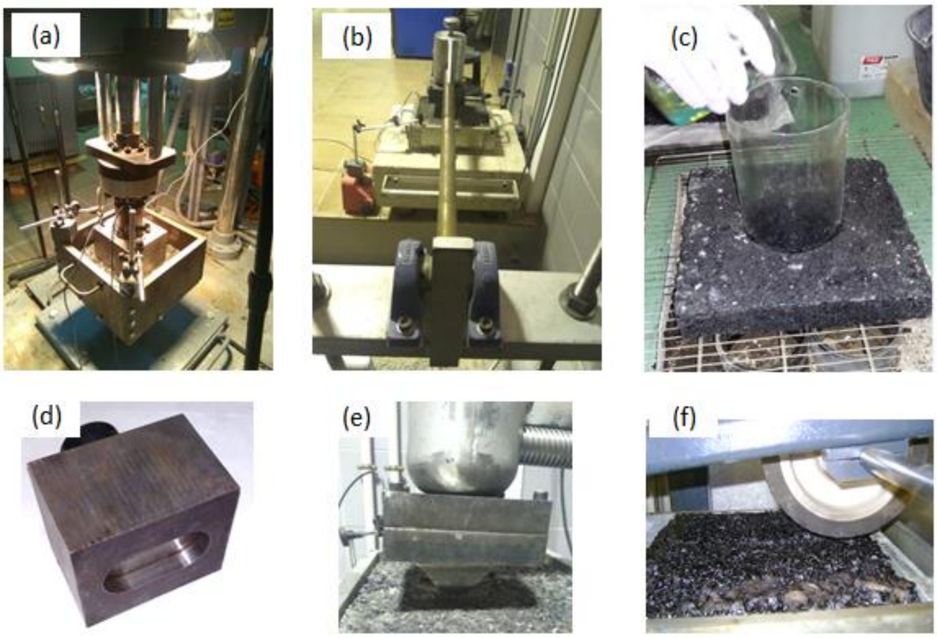

Figure 1. Configurations of the tests carried out in laboratory.

Finally, a series of tests (based on the previously described UGR-PASPT and UGR-PADPT) were carried out over a full-scale section reproduced in a laboratory box to assess the feasibility of applying the designed bituminous mixtures in a real pavement configuration. For this purpose, the built section had horizontal dimensions of 1 m x 1 m and consisted of 18 cm of granular base followed by an asphalt layer of 6 cm of thickness using the most appropriate bituminous materials, as defined by the previous tests.

3. ANALISYS OF RESULTS

3.1 Resistance to static punching from container storage

Figure 2 displays the curves of deformation-time during the last 20,000 seconds of test under 2.6 MPa (Figure 2a) and 5.2 MPa (Figure 2b), at a testing temperature of 25°C. The results reveal that in all the materials there was a small difference when the load was 2.6 MPa. Nonetheless, it is important to note that, in comparison with concrete, the asphalt mixtures showed higher fluidity of deformation since the slope of the trend to deformation was higher than in the case of concrete.

On the other hand, when increasing the level of stress (Figure 2b), the results indicate that mixtures with conventional bitumen presented higher susceptibility to the effects of increasing stress levels, regardless of the type of aggregates (increasing the final deformation values by up to 36-37% in comparison with concrete). However, the HMAM with high performance modified binders (as those with Rubber, Polymers, and Plastomers) showed susceptibility to stress levels, particularly in the case of the mixture with rubber, whose deformation value under heavy loads was only 8% higher than concrete, followed by the bitumen with plastomers and SBS polymers (13% and 18% higher than concrete, respectively).

Thus, results indicate that the asphalt mixtures with conventional bitumen show a higher propensity for creep deformations than the modified bitumens (which is in accordance with the findings of other studies such as [15-17]), proving that the type of bitumen plays a key role in the resistance to static punching whilst the type of aggregate has relatively little influence.

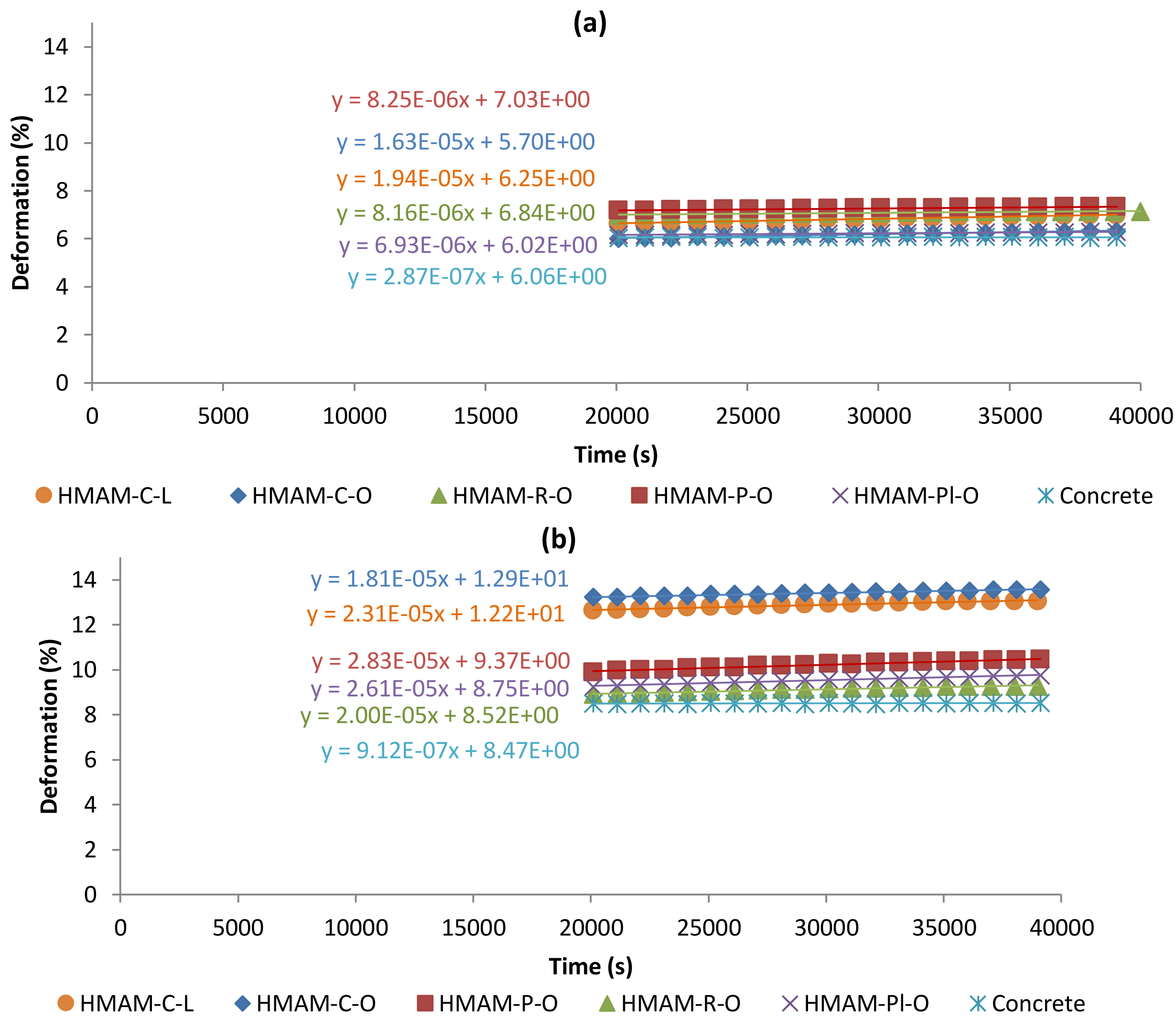

Figure 2. Curves of deformation during the last 20,000 seconds of load under (a) 2.6 MPa and (b) 5.2 MPa.

Figure 3 represents the final values of deformation for the different mixtures tested at 40°C (and under dry conditions) and under conditions of water action (wet specimens), compared with those values observed under standard dry testing conditions at 25°C. The results indicate that, in the case of the mixtures with conventional bitumen, the increase in testing temperature led to a significant decrease in resistance to plastic deformations while the increase in deformation susceptibility was lower for the mixtures with modified bitumens, particularly in the case of rubber, followed by the mixture with polymers (SBS) and that with plastomers. Moreover, the effect of water generally reduced the resistance of the mixtures to permanent deformations, whilst the type of aggregate and bitumen had no clear impact. The mixture with rubber presented even lower values in the case of wet specimens, which could be related to its low susceptibility to in-service conditions, as reported by other authors [18]. Therefore, generally speaking, these results indicate that the effect of climate conditions (particularly temperature) was lower on the specimens of modified bitumen mixture (particularly those containing rubber from waste tyres) whilst the type of aggregate again had little influence.

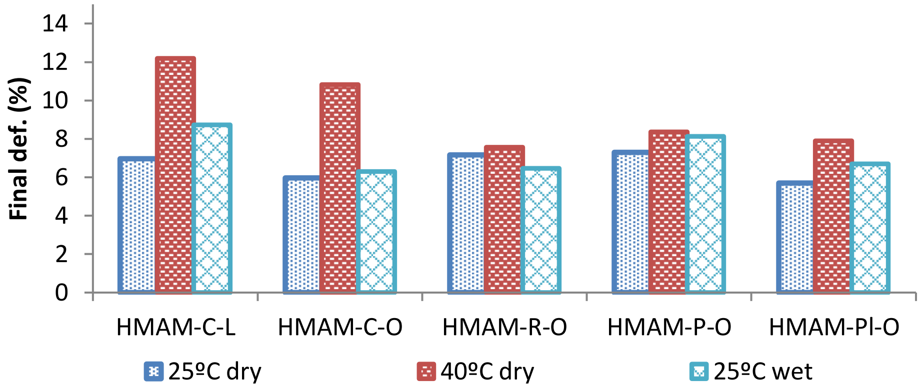

Figure 3. Effect of climate conditions on the resistance to permanent deformations.

3.2 Resistance to dynamic punching from the unloading of containers

Table 2 shows the values of indentation (deformation) due to the dropping of a weight (simulating the unloading of containers) from a constant height (constant impact energy throughout 30 blows) and also from increasing height. It is clear that the concrete specimens had the lowest values of deformation, regardless of the type of test and the step of the process (15 or 30 blows). Regarding the effect of the types of mixtures, the results show that the materials with modified bitumen presented similar resistance to impact punching with the type of modifier exerting little influence, presenting a slight increase in punching depth in comparison with concrete. On the other hand, the use of conventional hard bitumen led to a higher increase in punching depth in comparison with the previous mixtures, offering the lowest resistance to such distress, particularly when limestone aggregates are used as opposed to ophite in manufacturing the mixture, which could be related to the lower resistance of such types of aggregates [19].

Thus. these results again show that the mixtures with modified bitumen have a lower susceptibility to load levels (which could make them more appropriate for application in port pavements than the same mixture using conventional binder) whilst the type of aggregate has a lower impact on the resistance of the mixtures. Nonetheless. the materials with limestone particles show a slightly higher tendency towards deformation under heavy loads.

Table 2. Final deformation after dynamic punching impacts.

Parameter	HMAM -C-L	HMAM- C-O	HMAM- R-O	HMAM- P-O	HMAM -Pl-O	Concrete
Constant height blows						
Indentation (%) 30 blows	7.1	5.9	4.6	4.3	4.4	2.9
Increasing height blows						
Indentation (%) 30 blows	12.2	11.7	9.5	9.7	10.8	7.7

In order to analyse the impact of testing and climate conditions on the behavior of the asphalt mixtures in response to dynamic impacts, Figure 4 displays the effect of increasing the temperature from 25°C to 40°C and the impact of water action on the capacity of the mixtures to resist punching deformation. The results indicate that both climate actions lead to an increase in the depth of punching after 30 impacts (including the three fall heights of 10 blows each), with all the materials presenting broadly similar values when tested at 40°C. This indicates that the increase in temperature reduces the impact of the type of binder on the ability of the mixtures to show resistance to punching. in comparison with the impact of temperature under heavy loads. Further, water action generally had a higher impact on the mixtures with conventional bitumen. obtaining the lowest values of deformation in the cases of SBS polymers and rubber (particularly in the latter case), which is compatible with the results obtained from the previous analysis of the effect of water.

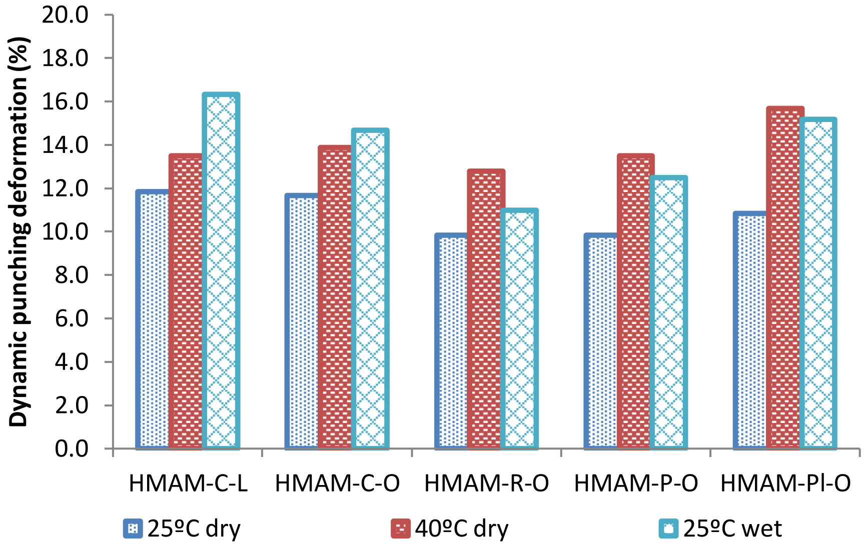

Figure 4. Effect of climate conditions on the resistance of the materials to impact loads.

3.3 Resistance to fuel and rutting under heavy traffic

Figure 5 displays the results recorded for the various materials on the rutting test. simulating in laboratory heavy and low speed vehicles under different in-service conditions (dry or fuel action. combined with high temperature). The results are shown through the parameters WTS (Wheel Tracking Slope) and PRD (percentage of rutting depth), indicating the results under dry conditions and the increase in specimen deformation due to fuel action.

It can be seen that the asphalt specimens presented a higher trend towards deformation than the concrete pavement. regardless of the type of aggregates and bitumen. Nonetheless, despite the fact that all asphalt specimens led to comparable final WTS values under dry conditions, it was shown that the mixtures with high performance bitumens allowed for a lower increase in such parameter under fuel action whilst also presenting a lower rutting depth. This indicates that the use of this type of bitumen leads to lower susceptibility to fuel action, particularly in the case of the rubberized bitumen mixture.

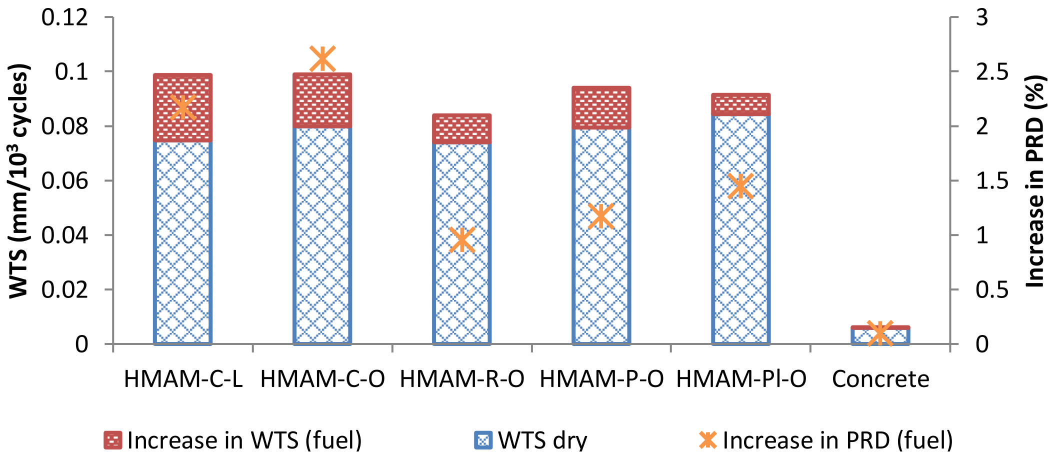

Figure 5. Results of rutting test under heavy traffic and fuel action.

3.4 Performance of full-scale section including the mixtures

To assess the performance of the bituminous solutions in a real section for port pavements, the selected mixtures were HMAM-C-O, HMAM-R-O, and HMAM-Pl-O in order to analyse the influence of high-performance binders (rubberized bitumen and conventional binder modified with plastomers, which showed appropriate results) in comparison with the conventional bitumen commonly used in traditional asphalt mixtures.

Figure 6 displays the results obtained on the static tests (at two different stress levels) for the high performance mixtures in reference to the conventional HMAM under the lowest stress level (2.6 MPa). The results indicate that both high-performance HMAM (with modified binders) recorded lower values of final deformation and trend towards deformation than the conventional HMAM, which confirms the importance of the bitumen used in the manufacturing of these materials for port pavements. In particular, it was observed that the mixture with rubber (HMAM-R-O) presented the lowest values of permanent deformation, which is in agreement with the findings of other studies [20], thus highlighting the benefits of using crumb rubber in terms of reducing plastic deformations.

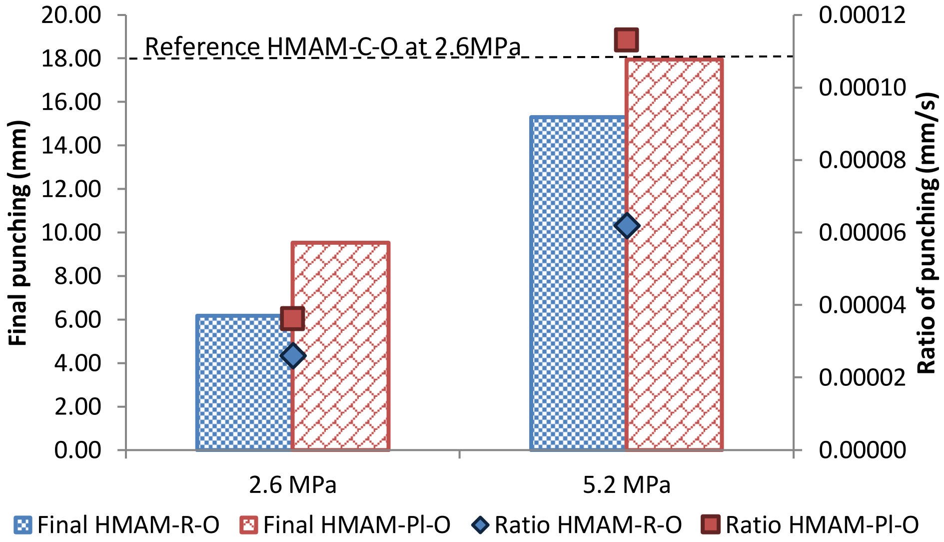

Figure 6. Results of static tests over a full-scale pavement section.

Figure 7 displays the results (trend towards deformation and final deformation) of the dynamic tests under 30 constant impacts (both vertical and inclined). The results show that the inclined loads generally lead to higher values of deformation regardless of the material, with the highest values of material degradation being recorded in the case of the mixtures with conventional binder. In particular, the HMAM with rubber recorded the lowest values of deformation. even showing comparable results under inclined loads (the most unfavourable condition) to those obtained when subjecting the conventional binder to vertical impacts.

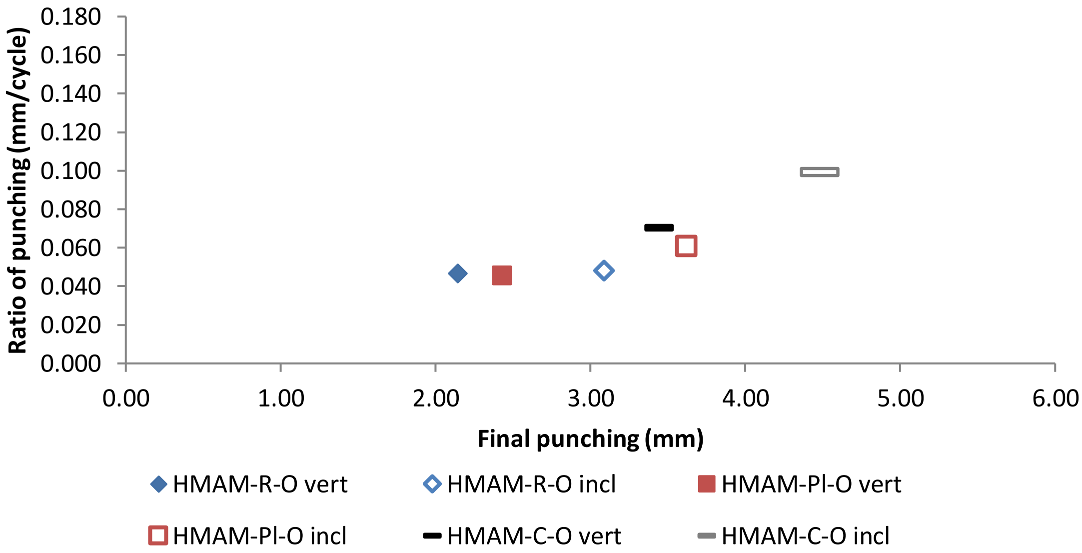

Figure 7. Results of dynamic impacts on bituminous full-scale port pavements.

4. CONCLUSIONS

The present paper examined the mechanical performance of various HMAM through the use of specific laboratory tests (including full-scale sections of port pavements) simulating the expected in-service conditions of port pavements (storage of containers. impacts due to unloading containers, and heavy traffic). The tests aimed to determine the effect of the type of aggregates and bitumen on the resistance of the mixtures to different failure modes when compared with a concrete pavement that is traditionally used in ports. On the basis of the results obtained in this study, the following conclusions can be drawn:

- The type of bitumen (conventional or modified with polymers) plays an essential role in the resistance of HMAM to loads and climate conditions expected in port pavements, while the type of aggregate appears to have little effect in comparison with the characteristics of the bitumen.

- Mixtures manufactured with modified bitumens presented lower susceptibility to creep than conventional ones, offering higher resistance to loads and climate actions, regardless of the type of modified binder analysed, presenting results comparable with those recorded for the concrete specimens.

- It was seen that the benefits of using modified binders were higher when increasing the level of load (energy of impact), particularly in the case of the mixtures with rubberized binder and with SBS polymers.

- Similarly, asphalt mixtures with modified bitumens showed lower susceptibility to fuel action, presenting a lower increase in the tendency to show deformation and a reduced rutting depth when simulating the combined effect of fuel with heavy and low speed traffic.

- Tests over full-scale sections of port pavements confirmed the strong influence of the binder on the performance of the mixtures, with modified bitumen presenting the most satisfactory results.

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5. REFERENCES

[1] Noelting, M.; Arnold, J.; Jones, B. Heavy duty pavements. New asphalt designs meet extreme challenges. AAPA pavements industry conference, Surfers Paradise, Queensland, Australia, 2005.
[2] Meletiou, M. and Knapton, J. Container terminal pavement management. Monograph no. 5, UNCTAD, United Nations Conference on Trade and Development, United Nations, 1996.
[3] ROM 4.1. Recomendaciones para el Proyecto y construcción de pavimentos portuarios. Puertos del Estado, 1994.
[4] Knapton, J. and Smith, D. R. Port and Industrial Pavement Design with Concrete Pavers. 2nd Edition. Interlocking Concrete Pavement Institute, 1997.
[5] Moffatt, J. and Nichol, F. Container Terminal and Intermodal Rail Yard Operational Area Consideration for Pavement Design. Port Pavement Design Guide. The Port of Los Angeles, California, USA, 2009.
[6] Butz, T; Nölting, M.; Arnold, J. Binder and asphalt designs for heavy duty pavements case studies. 11th International Conference on Asphalt Pavements, Nagoya, Japan, 2010.
[7] Fournier, P. Port of Napier debuts highly modified asphalt. Asphalt Review, Roads, 2011.
[8] Schäfer, V. and Rosauer, V. Experience with asphalt pavement on the heavy loaded port area of the Niedersachsenkai. 6th Eurasphalt & Eurobitume Congress, 1-3 June, Prague-Czech Republic, 2016.
[9] Euclid Chemical web-site Last Access, December 2017. http://www.euclidchemical.com/
[10] Boral web-site Last Access, December 2017. http://www.boral.com.au/
[11] Gent, H.; Clopotel, C.S.; Bahia, H.U. Effects of high modulus asphalt binders on performance of typical asphalt pavement structures. Construction and Building Materials, 44 (2013), pp. 207-213.
[12] Wang, C.; Wang, H.; Zhao, L.; Cao, D. Experimental study on rheological characteristics and performance of high modulus asphalt binder with different modifiers. Construction and Building Materials, 155 (2017), pp. 26-36.
[13] PG-3: Spanish Technical Standard for Roads and Bridges Construction. Ministerio de Fomento, Spain.
[14] Sol-Sánchez, M.; García, G.; Moreno-Navarro, F.; Rubio-Gámez, M. C. Laboratory study of the long-term climatic deterioration of asphalt mixtures. Journal of Construction and Building Materials, 88 (2015), pp. 32-40.
[15] Khodaii, A. and Mehrara, A. Evaluation of permanent deformation of unmodified and SBS modified asphalt mixtures using dynamic creep test. Construction and Building Materials, 23 (2009), pp. 2586-2592.
[16] García-Travé, G.; Tauste, R.; Sol-Sánchez, M.; Moreno-Navarro, F. Mechanical performance of SMA mixtures manufactured with reclaimed geomembrane-modified binders. Journal of materials in Civil Engineering, 30 (2018).
[17] Radziszewski, P. Modified asphalt mixtures resistance to permanent deformations. Journal of Civil Engineering and Managemenet, 13:4 (2007), pp. 307-315.
[18] Pszczola, M.; Jaczewski, M.; Szydlowski, C.; Judycki, J.; Dolzycki, B. Evaluation of low temperature properties of rubberized asphalt mixtures. Procedia Engineering, 172 (2017), pp. 897-904.
[19] Moreno-Navarro, F. and Rubio-Gámez, M.C. Effect of aggregate nature on the fatigue cracking behavior of asphalt mixtures. Materials and Design, 47 (2013), pp. 61-67.
[20] Moreno-Navarro, F.; Sol-Sánchez, M.; Martín, J.; Martínez, M.; Rubio-Gámez, MC. The effect of crumb rubber modifier on the resistance of asphalt mixes to plastic deformation. Materials and Design, 47 (2013), pp. 274-280