Materiales de Construcción
Vol. 72, Issue 348, October-December 2022, e301
ISSN-L: 0465-2746
https://doi.org/10.3989/mc.2022.03522

Understanding the influence of filler type and asphalt binder content on the moisture and fatigue resistance of asphalt mortars

R. Tauste[a], A.E. Hidalgo[b], G.M. García[a], F. Moreno-Navarro[a], M.C. Rubio-Gámez[a] ✉

a. LabIC.UGR, Universidad de Granada, (Granada, Spain)
b. LANAMME, Universidad de Granada, (Granada, Spain)
✉:mcrubio@ugr.es

Received 1 April 2022
Accepted 1 August 2022
Available on line 19 October 2022

ABSTRACT: An adequate moisture resistance is a key element to guarantee the durability of asphalt materials. This paper identifies the influence of filler typology and bitumen content on the mechanical response of asphalt mortars before and after water action. Two fillers were evaluated: Portland cement and Calcium carbonate, along with different contents of a penetration bitumen (B35/50). Stiffness, ductility, and fatigue were evaluated through a new protocol for asphalt mortar samples using a 3-point-bending test on DMA (Dynamic Mechanical Analyzer). The use of Portland cement presents higher stiffness, lower ductility, and improved fatigue and water resistance compared to Calcium carbonate. It is also possible to optimize bitumen content based on fatigue results. Content beyond the optimal reduce variations after water action but compromise fatigue resistance. Lower content leads to a poorer performance in both terms. This methodology enables asphalt mortar characterisation as a tool to optimise the design of asphalt materials.

KEY WORDS: Fine aggregate matrix; Filler; Bitumen; Asphalt mortar; Fatigue performance; Water performance.

Citation/Citar como: Tauste, R.; Hidalgo, A.E.; García, G.M.; Moreno-Navarro, F.M.; Rubio-Gámez, M.C. (2022) Understanding the influence of filler type and asphalt binder content on the moisture and fatigue resistance of asphalt mortars. Mater. Construcc. 72 [348], e301. https://doi.org/10.3989/mc.2022.03522.

RESUMEN: *La influencia del tipo de polvo mineral y contenido de ligante bituminoso en la resistencia a la humedad y fatiga de morteros bituminosos.* La resistencia al agua es clave para garantizar la durabilidad de los materiales asfálticos. Este estudio identifica la influencia del polvo mineral y contenido de betún en la respuesta mecánica de morteros bituminosos antes y después de la humedad. Se evaluaron dos tipos de filler: cemento Portland y carbonato cálcico (filler calizo), junto con distintos contenidos de betún (B35/50). Rigidez, ductilidad y fatiga fueron evaluados mediante un nuevo ensayo de fatiga a tres puntos para morteros empleando DMA (Dynamic Mechanical Analyzer). El cemento presenta más rigidez, menos ductilidad y mayor resistencia al agua y fatiga que el filler calizo. Los resultados de fatiga permiten además optimizar el contenido de betún. Contenidos por encima del óptimo reducen variaciones tras la humedad pero comprometen la resistencia a fatiga. Contenidos menores conllevan un peor comportamiento en ambos términos. Esta metodología permite usar la caracterización de morteros bituminosos para optimizar el diseño de materiales asfálticos.

PALABRAS CLAVE: Matriz de áridos finos; Polvo mineral; Betún; Mortero bituminoso; Comportamiento a fatiga; Susceptibilidad al agua.

1. INTRODUCTION

The materials used in road construction and the design of asphalt mixtures play a fundamental role in the structural performance, durability, and functionality of the transportation infrastructure. This carries even greater importance nowadays since the demands linked to higher levels of traffic (1) and the effects derived from climate change are increasing (2). This latter phenomenon gives rise to rainfall events of a more extreme nature (3) that lead to the need for new design tools for asphalt materials that provide agile and precise knowledge of their response to the action of water.

Environmental factors, such as thermal gradients, solar radiation, and water derived from precipitations, can incur a profound effect on the durability of asphalt mixtures (4). In mild climatic conditions, the greatest contribution to the deterioration of roads may be that of traffic loading, and the resultant distresses that manifest, such as fatigue cracking, rutting (permanent deformation), and ravelling (5, 6). However, when severe climate comes into play, as is becoming more and more common due to the effects of climate change, these distresses escalate as do the effects linked to the action of water, since these constitute key elements in the degradation of asphalt pavements (7). The presence of moisture destroys the chemical bonds between the asphalt binder and the aggregates thereby reducing the adhesion between them significantly (8). Due to this premature failure of adhesion, the cohesion of the asphalt mixture is compromised, and it ceases to act as a coherent structural unit (9). This affects its bearing capacity and induces other pathologies, such as ravelling and stripping (10). In addition, when combined with other factors (traffic load, temperature gradients, ice formation, ageing, etc.), it could lead to the medium- or long-term failure of the road layer affected. Hence, control of the moisture susceptibility of asphalt materials is essential for the prolongation of the useful life of the pavement and for the enhancement of its durability.

Many variables affect the amount of moisture damage that occurs in asphalt mixtures. Some are related to mixture design and construction (such as air void content, binder film thickness, permeability, and drainage), environmental factors (temperature, pavement age, freeze–thaw cycles, and presence of ions in the water), traffic conditions, bitumen type, and properties of any additives employed (11). Beyond that, it is clear that the materials that condition the resistance of the asphalt mixture to moisture to a greater degree would be those responsible for bitumen/aggregate adhesion. In this respect, the physical and chemical properties of aggregates (12), of the bituminous binder (13), and of the filler typology (14) employed exert a substantial effect on the performance of asphalt mixtures.

The bituminous binder is not only responsible for the visco-elastic behaviour of an asphalt mixture but also for providing its cohesion and stability and its resistance to tensile and shear stresses (15). A proper choice of its dosage constitutes a fundamental factor in preserving the asphalt material from moisture damage without compromising its remaining mechanical properties (such as fatigue resistance, bearing capacity, and permanent deformation performance) (16). This is especially important in course layers, which commonly employ asphalt mixtures with higher binder contents and are more exposed to precipitation events. Furthermore, several studies have shown that the properties of mineral fillers (particles passing through a 0.063 mm sieve) exert a significant effect on the performance of asphalt materials (17, 18). It is common to improve the moisture susceptibility of asphalt mixtures by changing the filler fraction of aggregates, increasing the binder content, or by introducing anti-stripping modifiers (19-23).

Due to the importance of these elements, the availability of design tools focused on the performance of these materials becomes a key factor in the mitigation of the potential moisture damage occurring during the service life of the pavement (24). In particular, in recent years there has been an increase in the study of Fine Matrix Asphalt (FAM), also known as asphalt mortars. The analysis at this scale is focused on the interaction between asphalt binder, filler, and the finest part of the aggregates (commonly less than 2 mm in diameter) (25), which are, indeed, the main components of asphalt mixtures that condition, among other phenomenon, moisture resistance. Several authors have employed this type of analysis to characterise the water susceptibility and fatigue performance of asphalt materials (26-28). The study of the mortar scale enables the influence of bitumen on the adhesiveness of the asphalt materials to be better characterised, not only in relation to the filler (as in the case of mastic), but also to the finest aggregate fraction, thereby testing the maximum specific surface of asphalt mixtures (29, 30).

This study employs a test protocol based on a 3-point bending DMA (Dynamic Mechanical Analyzer) configuration to assess the influence of the type of filler and the bitumen content on the moisture susceptibility and fatigue life of asphalt mortars (FAM).

2. MATERIALS AND METHODS

2.1 Materials

The materials employed in the manufacture of the mortars were B 35/50 penetration bitumen, limestone sand (with a maximum aggregate size of 2 mm and washed to remove filler particles contained thereon), and two different typologies of active filler: Portland cement and Calcium carbonate (Figure 1). The main characteristics of these materials are summarised in Tables 1 and 2.

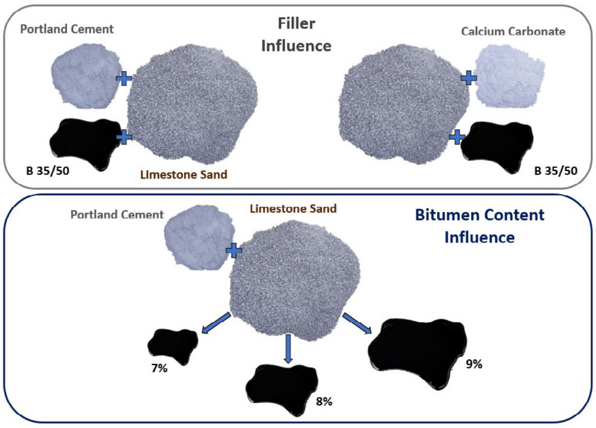

Figure 1. Materials used for the manufacture of the mortars studied.

Table 1. Properties of the limestone sand employed in the study.

Parameter	Sieve (mm)	Percentage of material passing (%)
Granulometry (EN 933-1) (31)	*2*	100.0
	0.5	18.0
	0.063	0.0
Sand equivalent (EN 933-8) (32)		77.0
Density (kg/m³) (EN 1097-6) (33)		2,770.0
Water absorption (%) (EN 1097-6) (33)		0.9

In order to assess the influence of both the typology of filler and the bitumen content on the moisture resistance of asphalt mortars and their implication with the mechanical performance of this kind of material, four mortars were manufactured. Previously, a bitumen content of reference was established by following the methodology proposed in other studies (27, 30, 35). This consisted of manufacturing the complete mixture intended for reproduction (in this case, a BBTM 11 B mixture (UNE 13108-2) (36) with a bitumen content of 5.3% over the total weight of the mixture), which was then disaggregated after it had cooled down (Figure 2). The material was then sifted with the aid of metal balls, to separate it into four groups:

- Group 1: Material retained in the 8 mm sieve.
- Group 2: Material that passes through the 8 mm sieve and is retained in the 4 mm sieve.
- Group 3: Material that passes through the 4 mm sieve and is retained in the 2 mm sieve.
- Group 4: Material that passes through the 2 mm sieve.

Table 2. Properties of the fillers employed in the study.

Parameter	Sieve (mm)	Percentage of material passing (%)	
		Calcium Carbonate	*Portland Cement*
Granulometry (EN 933-1) (31)	*2*	100.0	100.0
	0.5	100.0	100.0
	0.125	100.0	100.0
	0.063	94.0	96.0
Density (kg/m³) (EN 1097-3, Annex A) (34)		2,770.0	2,941.0

Bitumen extraction was performed by employing an ignition oven to determine the binder content in each group. The binder content to be used in the manufacture of the mortar was set using that obtained in Group 4, and was weighted with the values obtained in Group 3. Subsequent to this process, the binder content of reference to manufacture the mortars was set at 8% on the total weight of the asphalt mortar. This content was employed to establish the differences derived from the use of various kinds of filler.

Once the filler that led to the best performance was determined, two new mortars were manufactured to ascertain the influence of using a bitumen content higher and lower than that of reference. The composition and density of the various asphalt mortars studied herein can be consulted in Table 3.

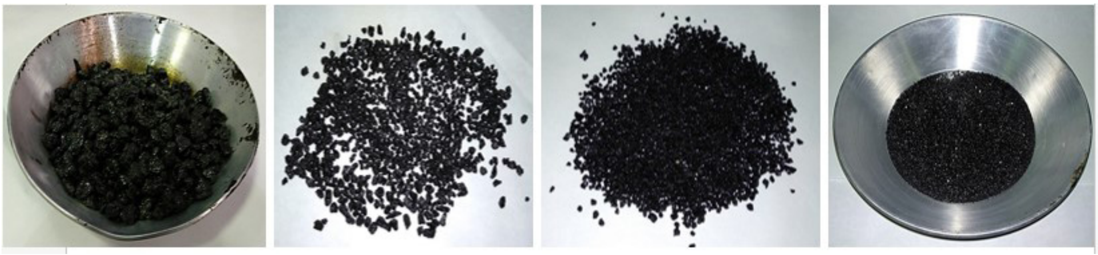

Figure 2. Disaggregation of asphalt mixture into groups to define the bitumen content employed in asphalt mortars.

TABLE 3. Composition and density of the mortars evaluated during this study.

Components	Mortar with $CaCO_3$ + 8% bitumen (CC8)	Mortar with Cement + 8% bitumen (CEM8)	Mortar with Cement + 7% bitumen (CEM7)	Mortar with Cement + 9% bitumen (CEM9)
Asphalt binder B35/50 (% over the total weight of the mortar)	8.0	8.0	7.0	9.0
Limestone Sand (% over the total weight of the mortar)	64.4	64.4	65.1	63.7
Filler: Portland Cement (% over the total weight of the mortar)	-	27.6	27.9	27.3
Filler: Calcium carbonate ($CaCO_3$) (% over the total weight of the mortar)	27.6	-	-	-
Apparent Density (kg/m³) (EN 12697-6) (37)	2338.0	2453.0	2419.0	2383.0

The materials that compose the asphalt mortars (aggregates, filler, and bitumen) were heated up to a temperature of 165°C prior to the mixing process. During the mixing, the temperature was also monitored by using a thermal imaging camera. Cylindrical specimens with a size of 150 mm in diameter were then compacted with the aid of a gyratory compactor (EN 12697-31) (38) at a temperature of 155 °C.

In order to minimise the air void influence on the study of the aggregate/binder adhesiveness and its evolution subsequent to water action, the compaction process targets a void content close to 0% as pointed out in other studies (27, 39). Once compacted, the specimens were cut in order to obtain the prismatic specimens of 8.5 x 8.5 x 50 mm that would subsequently be used in the DMA (Dynamic Mechanical Analyzer) characterisation.

2.2. Testing plan

The study has the main objective of assessing the influence of the type of filler and bitumen content (key elements in the formulation of both mortars and asphalt mixtures) on the behaviour of asphalt mortars in relation to the action of water by analysing their response to fatigue. To this end, a three-point bending test was employed with the aid of DMA equipment. This test enables bearing capacity, ductility, and fatigue resistance of the material to be characterised (30, 40), thereby providing useful information regarding the influence of the components of the mortars on their mechanical performance and the changes thereof induced by moisture action.

In order to assess the susceptibility to water of bituminous mortars, this test procedure was carried out on two groups of samples of each type of mortar (following a methodology similar to that established in the water sensitivity test of bituminous mixtures (EN 12697-12)). Thus, the specimens manufactured were separated into two groups: a dry group of samples maintained at room temperature (20 ± 5 °C), and a wet group that was conditioned for 72 hours in water at 40 °C after applying a vacuum at a pressure of 6.7 ± 0.3 kPa for 30 ± 5 minutes (Figure 3).

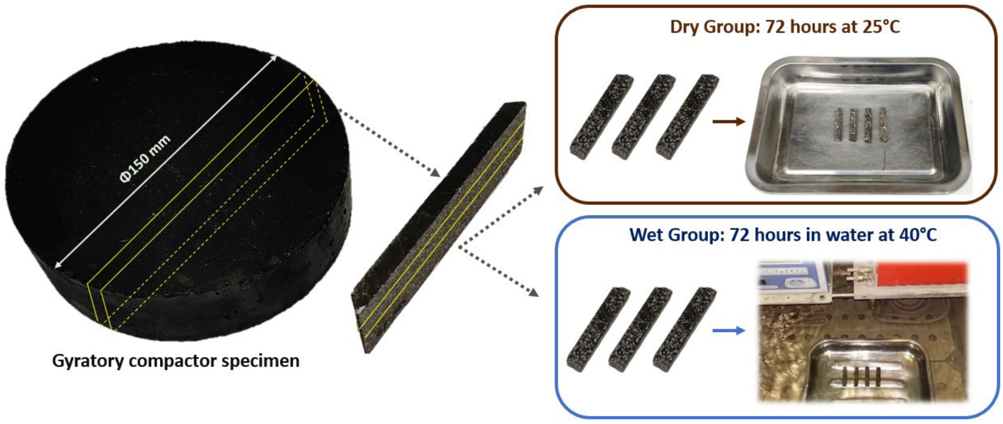

FIGURE 3. Preparation of the samples used in the study and separation into groups.

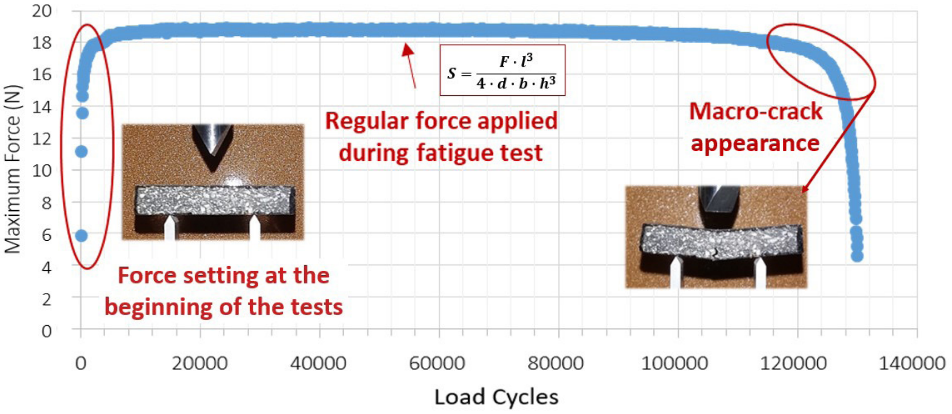

FIGURE 4. Example of the graph of maximum force vs. load cycles obtained for an specimen in the 3-point bending fatigue test.

For each group, nine specimens were considered, three for each level of strain studied (40, 60 and 80 µm, tested in strain-controlled mode). These present levels of load sufficient to reach the range of linear visco-elastic behaviour and to maintain it sufficiently for the evaluation of changes in stiffness and ductility before the fatigue failure occurs. Each sample was tested at a temperature of 35 °C (a demanding temperature to induce fatigue response, which enables a suitable characterisation and test durations to be attained) and 5 Hz until fatigue failure is reached (Figure 4).

The effect of moisture on the mortars was evaluated by comparing, for both groups, the various parameters obtained from the test (27):

- Stiffness (S). This parameter enables the bearing capacity of the material to be assessed, and with it, the resistance to permanent deformations. It is a measure of the visco-elastic behaviour of the material (as it becomes higher, the mortar becomes more elastic). It is calculated on Young's Modulus obtained from Equation [1] (41) as a relationship between the force applied and the deflection produced in the mortar specimen after 1000 load cycles (Figure 4),

$$S = \frac{F \cdot l^3}{4 \cdot d \cdot b \cdot h^3} \qquad [1]$$

where:
F: maximum force applied in the load cycle 1000 (when the specimen is considered undamaged (Figure 4))
l: length between supports
d: deflection displacement measured in the cycle 1000
b: width of the specimen
h: height of the specimen

- Maximum deflection (d_{max}). This parameter makes it possible to evaluate the ductility of the material tested: the more this parameter increases, the higher the ductility. It is measured as the accumulated deflection in the specimen before the appearance of significant damage in the form of macro-cracks (Figure 5).
- Cycles to failure (N_f). This last parameter is that employed when assessing the fatigue resistance

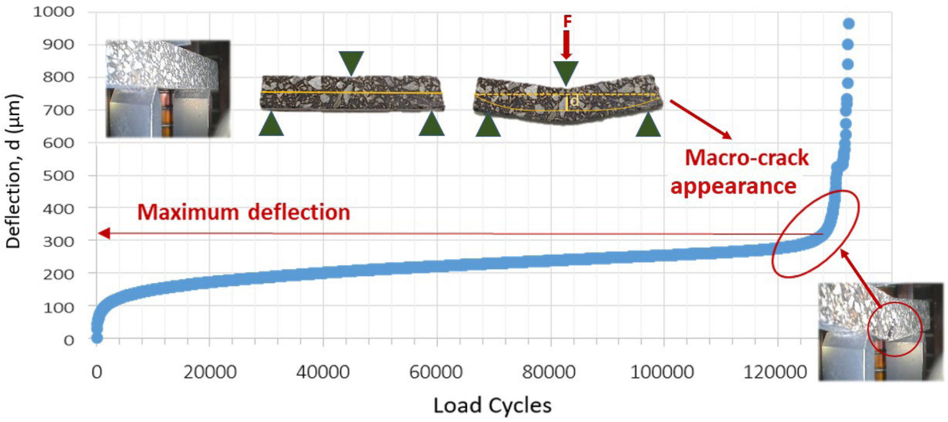

FIGURE 5. Deflection (d) evolution and specimen images registered during the 3-point bending fatigue tests on a DMA.

of the mortars tested and, therefore, constitutes a key element in the evaluation of their mechanical performance. It is defined as the total number of load cycles applied in the specimen until the appearance of a macro-crack. This is controlled by making use of a real-time camera installed in the DMA device (Figure 5) and comparing the images recorded with the maximum force measured by the machine in each load cycle (a sharp drop in the values is indicative of the macro-crack apparition, Figure 4). Alternatively, if no macro-crack appears after 250,000 load cycles, then this would be the value established as the failure of the specimen.

3. RESULTS AND DISCUSSION

The aforementioned parameters were employed to assess the influence of the type of filler and bitumen content on the fatigue performance and moisture resistance of asphalt mortars.

3.1 Influence of the type of filler

As can be observed in Figure 6, the use of cement (CEM 8) leads to a greater degree of rigidity and less deflection than does the use of calcium carbonate (CC8), regardless of whether the material has been subjected to water action. This means greater bearing capacity, and therefore higher resistance to permanent deformations.

In relation to the mortar manufactured with calcium carbonate (CC8), once the material is subjected to the action of the water, its stiffness does not vary significantly. However, it does increase the degree of deflection accumulated before failure, thereby proving this parameter to be more sensitive to moisture effect. As for Portland cement, its use presents smaller differences not only in terms of stiffness (as was the case with carbonate) but also in terms of ductility, thereby indicating a higher resistance to moisture.

Figure 7a shows the fatigue laws of both mortars before they are subjected to the effect of moisture. In this way, it can be deduced that, in line with that observed above in Figure 6, the higher rigidity and lower degree of ductility of mortars made with Portland cement (CEM8) also lead to a greater fatigue resistance than its counterpart made of Calcium carbonate (CC8) throughout the entire range of loads. The lower the load applied, the more marked the differences, which indicates a greater durability of mortars that use Portland cement as active a filler (since a higher level of load is required to obtain a similar fatigue life in the two materials, otherwise cement resistance is significantly higher).

Once mortars have been subjected to the action of water (Figure 7b), it can be observed how the difference between the fatigue lives of the two materials becomes more marked across the entire range of loads. This confirms the increased moisture resistance of the mortars that use Portland cement as already pointed out by the results of stiffness and ductility (Figure 6). It can therefore be said that the use of cement as active filler shows better performance than does calcium carbonate in terms of bearing capacity and resistance to both moisture and fatigue. Portland cement was hence chosen as the reference filler for the assessment of the influence of the bitumen content employed.

3.2 Influence of the binder content

Figure 8 shows the effect of the binder content on the stiffness and ductility of the asphalt mor-

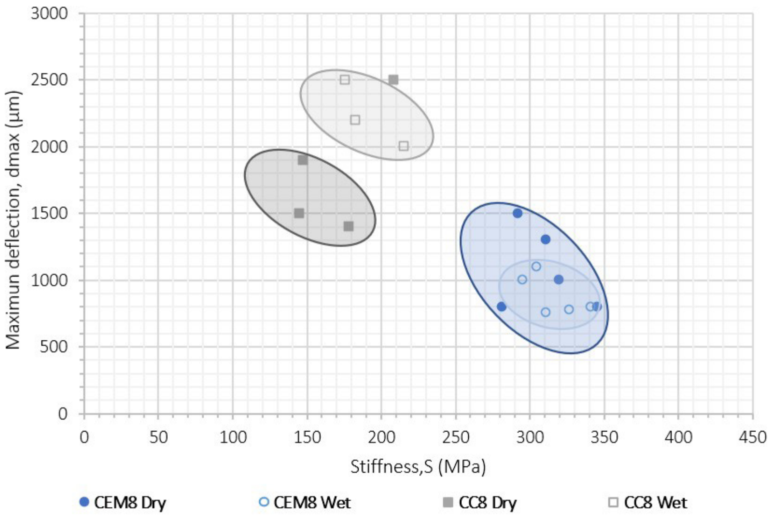

FIGURE 6. Influence of the type of filler on stiffness and maximum deflection of asphalt mortars.

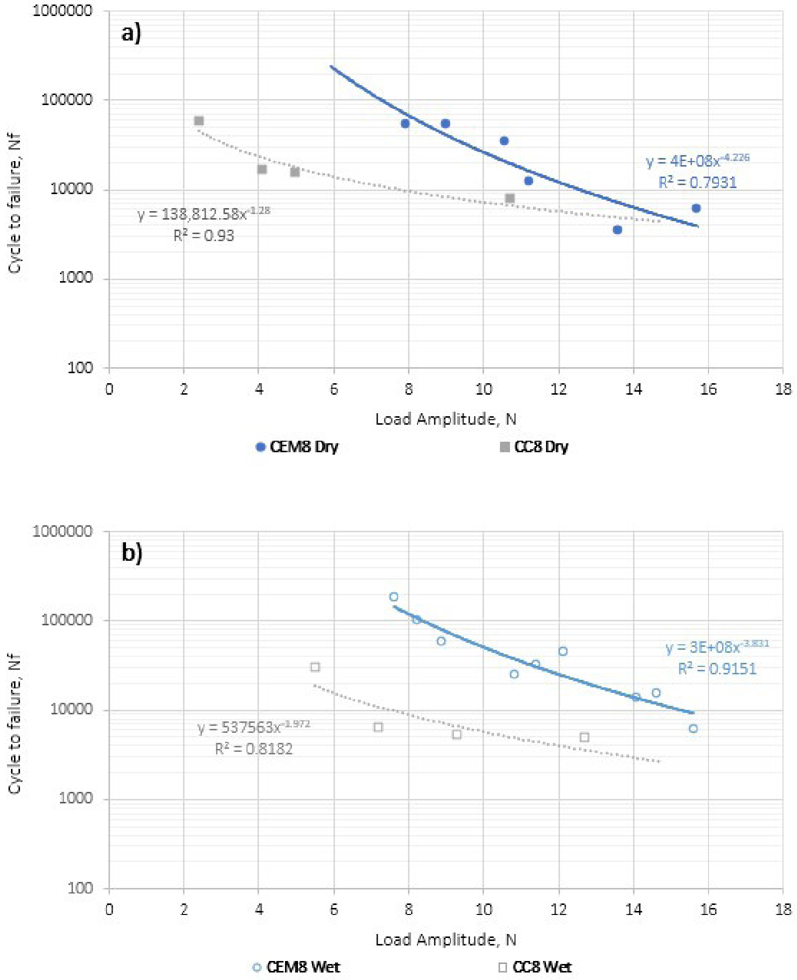

Figure 7. Influence of the type of filler on fatigue resistance of asphalt mortars before (a) and after (b) the action of the water.

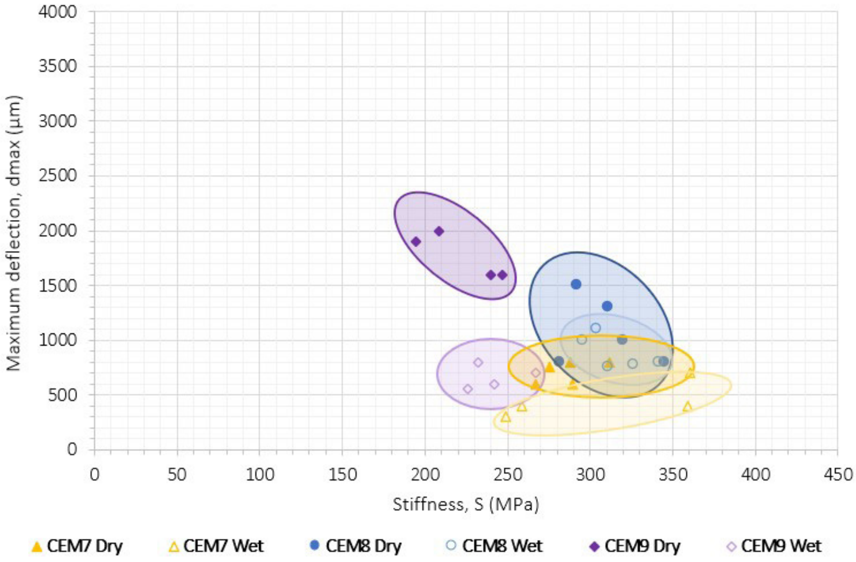

Figure 8. Results of stiffness and maximum deflection for mortars with different binder content.

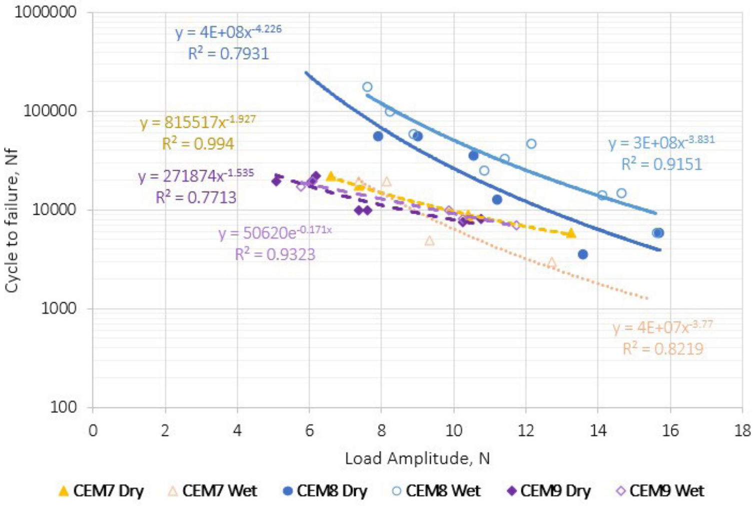

Figure 9. Fatigue laws of the asphalt mortars manufactured with different bitumen content.

tars for both dry and wet groups. Regarding stiffness and by focusing on the mortars before water conditioning, it can be observed how the most rigid mortar is the reference mortar (with an intermediate binder content (CEM 8)) with a stiffness that ranges between 300-350 MPa. When the binder content is decreased (CEM 7), the level of stiffness achieved is similar, however, the deflection experienced is lower. This points towards a lower flexibility of the material when the binder content is reduced. On the other hand, when the bitumen content is increased (CEM9), the changes become more marked, with a significant reduction of stiffness (in a range of 200-250 MPa) and an increase of maximum deflection (approximately 1500 µm compared to the lower bitumen contents that stand at approximately 1000-500 µm for 8 and 7%, respectively). In this way, a higher percentage of asphalt binder in the mixture leads to the mortar becoming more ductile.

As regarding the effect of water on the mechanical behaviour of mortars, it can be observed that, regardless of the bitumen content, similar mechanical behaviour is reached. The maximum deflection of the samples of the wet group decreases although the stiffness of the material does not change significantly subsequent to the water action. Despite this general consideration, different degrees of deflection variations can be observed between the different contents of bitumen. Intermediate content (CEM8) shows a lower rate of change that is more marked when this percentage is reduced (CEM 7) and it becomes even more pronounced after increasing the bitumen content (CEM 9). This points towards a higher degree of sensitivity of this ductility parameter regarding moisture resistance.

Figure 9 shows fatigue life (Nf) in reference to the load applied in the test. According to the results, it can be observed how this methodology has remarkable potential to establish an optimal bitumen content for the binder tested, which considers both fatigue and moisture resistance since the three percentages analysed present different degrees of fatigue resistance and rate of change subsequent to water conditioning. As can be observed, the mortar manufactured with 8% of bitumen (CEM8) presents the highest degree of durability with levels of fatigue resistance superior to those achieved by the other bitumen contents, regardless of whether they have been subjected to the action of water.

In relation to moisture susceptibility, it can be observed that the reduction of deflection experienced after the water action (Figure 8) leads to even greater fatigue lives of the wet group. Nonetheless, this phenomenon changes for the other two contents. When the bitumen content is below the optimum (CEM 7), the fatigue life reached decreases despite the lower degree of ductility of the material. This could be related to a poorer bitumen/aggregate adhesion which is confirmed by the results obtained after the water action. According to these results, the fatigue resistance is reduced to a greater extent as the solicitation load level is higher.

When the bitumen content exceeds the considered optimum (CEM9), the differences between the levels of durability achieved before and after water conditioning are the lowest, which would confirm that a rise in the bitumen content is positive to the performance of asphalt materials against water (5). Nevertheless, the fatigue resistance of this material is significantly lower than the mortar manufactured with 8% of bitumen due to the reduction of stiffness and the increase of ductility (Figure 8) experienced once the optimum content of bitumen is exceeded. This proves the potential of the methodology proposed since, for the materials tested, it enables the effects of moisture on the asphalt mortars to be studied without limiting the assumption of a better performance to the differences found in a specific parameter before and after water conditioning. Instead, the joint consideration of stiffness, ductility, and fatigue evolution enables an optimal bitumen content to be established that considers the permanent deformation, fatigue, and moisture resistance of the material.

4. CONCLUSIONS

This paper studies the influence of the filler typology and binder content on the water and fatigue resistance of asphalt mortars. For this purpose, a methodology based on the 3-point bending fatigue test using the DMA has been applied. On the basis of the results obtained for the materials tested, the following conclusions can be drawn:

- The type of filler employed affects the performance of the mortar. The use of Portland cement leads to a greater degree of rigidity and less ductility. Both parameters change after water action, whereby the variations are less marked after the use of cement instead of Calcium carbonate, which indicates a higher resistance of Portland cement.
- The use of Portland cement leads to higher fatigue resistance than does Calcium carbonate. The differences become greater after the action of water, thereby confirming its better performance against moisture and higher durability of the cement mortar.
- Regarding bitumen content, that below the optimum leads to lower values of deflection but similar levels of stiffness. However, when the content is higher, the variations are more pronounced for both reduction of stiffness and increase of ductility.
- Regardless of the binder content, the action of water leads to changes in the maximum deflection experienced by mortars while the stiffness remains of the same order. Maximum deflection is a more sensitive parameter than is stiffness in the assessment of the changes induced by moisture in asphalt mortars.
- An optimal bitumen dosage can be clearly found based on the fatigue resistance of asphalt mortars by using the methodology proposed.
- Bitumen contents below the optimal present lower variations after the action of water but the fatigue resistance is then compromised. When the content is below the optimal, the wet group displays a decreasingly lower fatigue life than that of the dry group as the level of load increases.

The methodology proposed enables the effects of moisture on the asphalt mortars to be assessed without limiting the assumption of a better performance to the differences found in a specific parameter before and after water conditioning. Instead, their implications in bearing capacity, ductility, and fatigue are considered. Hence, the mechanical performance of asphalt materials can be established to confront the effects of climate change, as a way to optimise the mixing design. Future work will be carried out on the validation of the potential of the methodology proposed in mortars manufactured with bitumen of different penetration grades, polymer-modified binders, and aggregates of a diverse nature.

AUTHOR CONTRIBUTIONS:

Conceptualization: F. Moreno-Navarro, A.E. Hidalgo. Data curation: R. Tauste, A.E. Hidalgo, F. Moreno-Navarro. Formal analysis: R. Tauste, A.E. Hidalgo. Investigation: R. Tauste, A.E. Hidalgo, G.M. García. Methodology: F. Moreno-Navarro, A.E. Hidalgo. Project administration: M.C. Rubio-Gámez. Resources: F. Moreno-Navarro, M.C. Rubio-Gámez. Software: F. Moreno-Navarro, A.E. Hidalgo, R. Tauste. Supervision: F. Moreno-Navarro, M.C. Rubio-Gámez. Validation: F. Moreno-Navarro, M.C. Rubio-Gámez, R. Tauste. Visualization: G.M. García-Travé, M.C. Rubio-Gámez. Writing - original draft: F. Moreno-Navarro, R. Tauste, A.E. Hidalgo. Writing - review & editing: R. Tauste, M.C. Rubio-Gámez.

REFERENCES

1. Nicodème, C.; Diamandouros, K.; Diez, J.; Durso, C.; Arampidou, K.; Nuri, A. K. (2017) Road statistics yearbook 2017. European Union Road Federation
2. Barnes, P.W.; Williamson, C.E.; Lucas, R.M.; Robinson, S.A.; Madronich, S.; et al. (2019) Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future. *Nat. Sustain.* 2, 569-579. https://doi.org/10.1038/s41893-019-0314-2.
3. Trenberth, K.E. (2011) Changes in precipitation with climate change. *Clim. Res.* 47(1-2), 123-138. https://doi.org/10.3354/cr00953.
4. Tauste, R.; Moreno-Navarro, F.; Sol-Sánchez, M.; Rubio-Gámez, M.C. (2018) Understanding the bitumen ageing phenomenon: A review. *Construc. Build. Mat.* 192, 593-609. https://doi.org/10.1016/j.conbuildmat.2018.10.169.
5. Hunter, R. N.; Self, A.; Read, J.; Hobson, E. (2015) The shell bitumen handbook (p. 789) London, UK: Ice Publishing.
6. Moreno-Navarro, F.; Sol-Sánchez, M.; García-Travé, G.; Rubio-Gámez, M.C. (2018) Fatigue cracking in asphalt mixtures: the effects of ageing and temperature. *Road Mater. Pavem. Des.* 19 [3], 561-570. https://doi.org/10.1080/14680629.2018.1418717.
7. Thom, N. (2008) Principles of pavement engineering (p. 470) London: Thomas Telford.
8. Moreno-Navarro, F.; García-Travé, G.; Rubio-Gámez, M. D. C.; Martinez-Echevarria, M. J. (2014) Analysis of the moisture susceptibility of hot bituminous mixes based on the comparison of two laboratory test methods. *Dyna* 81 [183], 49-59. https://doi.org/10.15446/dyna.v81n183.30893.
9. Gorkem, C.; Sengoz, B. (2009) Predicting stripping and moisture induced damage of asphalt concrete prepared with polymer modified bitumen and hydrated lime. *Construc. Build. Mat.* 23 [6], 2227-2236. https://doi.org/10.1016/j.conbuildmat.2008.12.001.
10. Moreno-Navarro, F.; Sol-Sánchez, M.; Tomás-Fortún, E.; Rubio-Gámez, M.C. (2016) High-modulus asphalt mixtures modified with acrylic fibers for their use in pavements under severe climate conditions. *J. Cold Reg. Eng. 30 [4]*, 04016003. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000108.
11. Behiry, A.E.A.E-M. (2013) Laboratory evaluation of resistance to moisture damage in asphalt mixtures. *Ain*

Shams Eng. J. 4 [3], 351-363. https://doi.org/10.1016/j.asej.2012.10.009.

12. Cala, A.; Caro, S.; Lleras, M.; Rojas-Agramonte, Y. (2019) Impact of the chemical composition of aggregates on the adhesion quality and durability of asphalt-aggregate systems. *Construc. Build. Mat.* 216, 661-672. https://doi.org/10.1016/j.conbuildmat.2019.05.030.
13. Moreno-Navarro, F.; Sol-Sánchez, M.; Jimenez del Barco, A.; Rubio-Gámez, M.C. (2017) Analysis of the influence of binder properties on the mechanical response of bituminous mixtures. *Int. J. Pavem. Eng.* 18 [1], 73-82. https://doi.org/10.1080/10298436.2015.1057138
14. Chen, Y.; Xu, S.; Tebaldi, G.; Romeo, E. (2022) Role of mineral filler in asphalt mixture. *Road Mater. Pavem. Des.* 23 [2], 247-286. https://doi.org/10.1080/14680629.2020.1826351.
15. Moreno-Navarro, F.; Sol-Sánchez, M.; Rubio-Gámez, M.C. (2015) The effect of polymer modified binders on the long-term performance of bituminous mixtures: The influence of temperature. *Mater. Des.* 78, 5-11. https://doi.org/10.1016/j.matdes.2015.04.018.
16. Airey, G.D.; Collop, A.C.; Zoorob, S.E.; Elliott, R.C. (2008) The influence of aggregate, filler and bitumen on asphalt mixture moisture damage. *Construc. Build. Mat.* 22 [9], 2015-2024. https://doi.org/10.1016/j.conbuildmat.2007.07.009.
17. Mogawer, W.S.; Stuart, K.D. (1996) Effects of mineral fillers on properties of stone matrix asphalt mixtures. *Transp. Res. Rec.* 1530 [1], 86-94. https://doi.org/10.1177/0361198196153000111.
18. Movilla-Quesada, D.; Raposeiras, A.C.; Castro-Fresno, D.; Peña-Mansilla, D. (2015) Experimental study on stiffness development of asphalt mixture containing cement and Ca(OH)$_2$ as contribution filler. *Mater. Des.* 74, 157-163. https://doi.org/10.1016/j.matdes.2015.02.026.
19. Huang, S-C.; Robertson, R.E.; Branthaver, J.F.; Claine Petersen, J. (2005) Impact of lime modification of asphalt and freeze–thaw cycling on the asphalt–aggregate interaction and moisture resistance to moisture damage. *J. Mater. Civ. Eng.* 17 [6], 711-718. https://doi.org/10.1061/(ASCE)0899-1561(2005)17:6(711).
20. Arabani, M.; Hamedi, G.H. (2014) Using the surface free energy method to evaluate the effects of liquid antistrip additives on moisture sensitivity in hot mix asphalt. *Int. J. Pavem. Eng.* 15 [1], 66-78. https://doi.org/10.1080/10298436.2013.778410.
21. Nasrekani, A.A.; Nakhaei, M.; Naderi, K.; Fini, E.; Aflaki, S. (2017) Improving moisture sensitivity of asphalt concrete using natural bitumen (Gilsonite) In Proceedings of the Transportation Research Board (TRB 2017), the 96th Annual Meeting, Washington, DC, USA (pp. 8-12).
22. Mirzababaei, P.; Moghadas Nejad, F.; Naderi, K. (2020) Effect of liquid silane-based anti-stripping additives on rheological properties of asphalt binder and hot mix asphalt moisture sensitivity. *Road Mater. Pavem. Des.* 21 [2], 570-585. https://doi.org/10.1080/14680629.2018.1507920.
23. Arbabpour-Bidgoli, M.; Naderi, K.; Moghadas-Nejad, F. (2019) Effect of filler type on moisture susceptibility of asphalt mixtures using mechanical and thermodynamic properties. *J. Mater. Civ. Eng.* 31 [4], 04019024. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002648.
24. Lu, Q. (2005) Investigation of conditions for moisture damage in asphalt concrete and appropriate laboratory test methods. University of California, Berkeley.
25. Underwood, B.S.; Kim, Y.R. (2011) Experimental investigation into the multiscale behaviour of asphalt concrete. *Int. J. Pavem. Eng.* 12 [4], 357–370. https://doi.org/10.1080/10298436.2011.574136.
26. Ding, J.; Jiang, J.; Ni, F.; Dong, Q.; Zhao, Z. (2020) Correlation investigation of fatigue indices of fine aggregate matrix (FAM) and asphalt mixture containing reclaimed asphalt pavement materials. *Construc. Build. Mat.* 262, 120646. https://doi.org/10.1016/j.conbuildmat.2020.120646.
27. Hidalgo, A.E.; Moreno-Navarro, F.; Tauste, R.; Rubio-Gámez, M.C. (2020) The influence of reclaimed asphalt Pavement on the mechanical performance of bituminous mixtures. An analysis at the mortar scale. *Sustainability.* 12 [20], 8343. https://doi.org/10.3390/su12208343.
28. Nabizadeh, H.; Haghshenas, H.F.; Kim, Y.R.; Aragão, F.T.S. (2017) Effects of rejuvenators on high-RAP mixtures based on laboratory tests of asphalt concrete (AC) mixtures and fine aggregate matrix (FAM) mixtures. *Construc. Build. Mat.* 152, 65–73. https://doi.org/10.1016/j.conbuildmat.2017.06.101.
29. Suresha, S.N.; Ningappa, A. (2018) Recent trends and laboratory performance studies on FAM mixtures: A state-of-theart review. *Construc. Build. Mat.* 174, 496–506. https://doi.org/10.1016/j.conbuildmat.2018.04.144.
30. Tauste-Martínez, R.; Moreno-Navarro, F.; Sol-Sánchez, M.; Rubio-Gámez, M.C. (2021) Multiscale evaluation of the effect of recycled polymers on the long-term performance of bituminous materials. *Road Mater. Pavem.* 22 [sup1], S99-S116. https://doi.org/10.1080/14680629.2021.1906737.
31. EN 933-1. (2012) Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method. AENOR, Asociación Española de Normalización y Certificación, Madrid.
32. EN 933-8. (2012) Tests for geometrical properties of aggregates - Part 8: Assessment of fines - Sand equivalent test. AENOR, Asociación Española de Normalización y Certificación, Madrid.
33. EN 1097-6. (2014) Tests for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption. AENOR, Asociación Española de Normalización y Certificación, Madrid.
34. EN 1097-3. (1999) Tests for mechanical and physical properties of aggregates - Part 3: Determination of loose bulk density and voids. AENOR, Asociación Española de Normalización y Certificación, Madrid.
35. Cavalcanti De Sousa, P. (2010) Automated protocol for the analysis of dynamic mechanical analyzer date from fine aggregate asphalt mixes (Doctoral dissertation, Texas A & M University).
36. EN 13108-2. (2007) Bituminous mixtures - Material specifications - Part 2: Asphalt Concrete for very thin layers. AENOR, Asociación Española de Normalización y Certificación, Madrid.
37. EN 12697-6. (2012) Bituminous mixtures - Test methods for hot mix asphalt - Part 6: Determination of bulk density of bituminous specimens. AENOR, Asociación Española de Normalización y Certificación, Madrid.
38. EN 12697-31. (2020) Bituminous mixtures - Test methods - Part 31: Specimen preparation by gyratory compactor. AENOR, Asociación Española de Normalización y Certificación, Madrid.
39. Leiva-Padilla, P.; Moreno-Navarro, F.; Iglesias-Salto, G.; Rubio-Gamez, M.C. (2020) Recovery capacity of electroconductive asphalt mortars under the influence of magnetic fields. *Mater. Today Commun.* 25, 101527. https://doi.org/10.1016/j.mtcomm.2020.101527.
40. Tauste-Martínez, R.; Hidalgo, A. E.; García-Travé, G.; Moreno-Navarro, F.; Rubio-Gámez, M.D.C. (2022) Influence of type of filler and bitumen on the mechanical performance of asphalt mortars. *Materials.* 15 [9], 3307. https://doi.org/10.3390/ma15093307.
41. Canet, J.M. (2012) Resistencia de materiales y estructuras. Centro Internacional de Métodos Numéricos en Ingeniería: Barcelona, Spain.