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To cite this article: Didier Lesueur, Marimar Lázaro Blázquez, Daniel Andaluz Garcia & Aurelio Ruiz Rubio (2017): On the impact of the filler on the complex modulus of asphalt mixtures, Road Materials and Pavement Design, DOI: [10.1080/14680629.2017.1288653](https://doi.org/10.1080/14680629.2017.1288653)

To link to this article: <http://dx.doi.org/10.1080/14680629.2017.1288653>



Published online: 10 Feb 2017.



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On the impact of the filler on the complex modulus of asphalt mixtures

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(Received 8 March 2016; accepted 10 January 2017)

Mineral fillers have been used in asphalt mixtures from their very beginning. Rapidly, formulators observed that the filler could have a strong influence on the final mixture. Nowadays, mineral fillers are essentially characterised by their ability to stiffen the bitumen, leading to the development of the celebrated “Rigden air voids” *RV* (EN 1097-4), now the corner stone of the European specifications for fillers in asphalt mixtures. If the way the filler modifies the rheological properties of mastics is now well described, the relationship between mastic and mixture properties remains poorly understood. Therefore, this paper describes a systematic study on the impact of increasing filler contents on asphalt mixtures. Experimental results are presented for two very different asphalt mixture formulas, a regular semi-dense Asphalt Concrete (AC) and an open-graded AC for very thin layers (BBTM). The complex modulus of each formula was measured as a function of filler content with two materials having very different stiffening behaviour, that is, limestone filler (LF) and hydrated lime (HL). For both formulas and regardless of the type of filler, the modulus versus filler content curves exhibited a well-defined maximum. The filler content at which the maximum was found was strongly filler dependent, with HL formulas peaking at 4 wt.% and LF formulas peaking at 10 wt.%. An original interpretation based on reduced variables was proposed, showing that the maximum in modulus occurred for reduced volume fraction of filler close to 66%. This suggests that, before the peak, modulus increased with filler content as a consequence of a stiffer mastic, and after the peak, modulus started to decrease due to poor aggregate coating as a consequence of too-viscous a mastic. As a practical consequence, the studied mix formulas could accept higher filler loadings than currently specified, which would potentially stiffen the mixtures by ~20%. Therefore, one way to benefit from these findings without changing the specifications would be to use blends of HL and LF. Of course, these findings must be validated with other mixture formulas and raw materials, and similar systematic study on the filler impact on the resistance to fatigue and moisture damage would be needed before implementing the conclusions based on modulus only.

Keywords: mineral filler; hydrated lime; modulus; asphalt mixture; mixture design

1. Introduction

Mineral fillers have been used in asphalt mixtures from their very beginning (Richardson, 1914). The filler was naturally present in the sand and, given the usual compositions back then, eventually ended up representing 5–10% of the mineral matter in the mix. Quite rapidly, formulators observed that the filler could have a strong influence on the final mixture. They recognised that the filler was well dispersed in the bitumen, forming what is now called the mastic and that this mastic was acting as the glue between the larger aggregate. So, they started to develop

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specific test methods in order to identify the key properties of the filler that could develop into specifications.

Nowadays, mineral fillers are essentially characterised by their ability to stiffen the bitumen. This clarifies that the main role for the filler is to thicken the bitumen film. This effect was already recognised by P. J. Rigden of the British Road Research Laboratory in 1947 (Rigden, 1947) to be linked to the volume fraction of the filler and to be well correlated with its overall porosity. This led to the development of the celebrated test method for measuring the porosity in dry compacted filler also known as the “Rigden air voids” RV (EN 1097-4). Here, the porosity is expressed as the total volume fraction of voids in the packed filler, therefore including the porosity between particles and the internal porosity of the particles. This method is now the corner stone of the European specifications for fillers in asphalt mixtures (EN 13043) and it has been demonstrated that it correlates quite well with more direct measurements of bitumen stiffening based on empirical measurements such as the increase in ring and ball softening temperature (Grabowski & Wilanowicz, 2008; Lesueur, Petit, & Ritter, 2013; Vansteenkiste & Vanelstraete, 2008) and was recently proposed to be likewise implemented in the USA (Faheem, Hintz, Bahia, Al-Qadi, & Glidden, 2012).

If the way filler modifies the rheological properties of mastics has been well described in the literature (Abbas, Masad, Papagiannakis, & Shenoy, 2005; Hesami, Jelagin, Kringos, & Birgisson, 2012; Liao, Airey, & Chen, 2013), the relationship between mastic properties and mixture properties remains poorly understood (Di Benedetto, Olard, Sauzéat, & Delaporte, 2004; Liu, You, Dai, & Mills-Beale, 2011).

Therefore, this paper describes a systematic study on the impact of increasing filler contents on asphalt mixtures. In order to do so, a brief background section first reminds known results on mastic rheology and on the relationships between asphalt mixtures composition and modulus. Then, experimental results are presented for two very different asphalt mixture formulas, a regular semi-dense Asphalt Concrete (AC) and an open-graded AC for very thin layers (BBTM). The complex modulus of each formula was measured as a function of filler content with two materials having very different stiffening behaviour, that is, limestone filler (LF) and hydrated lime (HL). Finally, an original interpretation based on reduced variables is proposed allowing reaching new conclusions regarding the current filler contents in asphalt mixtures.

2. Background

2.1. *Stiffening effect of mineral filler in bitumen*

The stiffening effect of mineral fillers in bitumen has also been studied at length and is still being evaluated using modern rheological techniques (Abbas et al., 2005; Hesami et al., 2012; Liao et al., 2013). Still, to our knowledge, no recent study went further than the impressive work by W. Heukelom and P. W. O. Wijga of the Koninklijke Shell Laboratorium in Amsterdam (The Netherlands) as early as 1971 (Heukelom & Wijga, 1971). They definitely confirmed that the volume fraction of the filler is the key parameter controlling the stiffening of the mastic. This fact has indeed been known for the rheology of suspensions for decades (see for example, Coussot, 2005, for an overview).

Heukelom and Wijga also showed that the viscosity versus volume fraction curve could be accurately described by a single input parameter, now identified as ϕ_m , the maximum packing fraction of the filler (Lesueur, 2009). Even if not strictly similar to RV , because of the differences in packing details in the presence or not of a suspending liquid, this parameter is therefore very close in concept, and, as a first approximation, they can be equated through the following

simple relation:

$$\phi_m \approx 1 - RV. \quad (1)$$

Several studies have proposed or reviewed models to quantify the effect on mineral filler on mastic viscosity (Abbas et al., 2005; Hesami et al., 2012; Liao et al., 2013). It is not the purpose of this work to survey the existing literature, and we will therefore only focus on the main physical parameters at stakes.

As proposed by Heukelom and Wijga (1971) and validated in other works (Lesueur, Dekker, & Planche, 1995), the viscosity η of a mastic is a function of the viscosity η_0 of the neat bitumen and of the volume fraction ϕ of filler:

$$\eta = \eta_0 \left(1 - \frac{\phi}{\phi_m} \right)^{-2}, \quad (2)$$

where ϕ_m is the maximum packing fraction of the filler as before (see Equation (1)). Using this equation, ϕ_m can be shown to be the inverse of the intrinsic viscosity $[\eta]$, the parameter that quantifies the stiffening effect of the filler. It has been documented (Lesueur et al., 2013) that HL ($[\eta] \sim 3-10$) is about twice as stiffening as other mineral fillers ($[\eta] \sim 2.5-5$). This explains the formulation rule described later on in Section 2.1, where the HL content was chosen at half the value for mineral filler in order to reach the same stiffening.

As a practical consequence of Equations (1) and (2), the data for different filler contents can now be scaled using a reduced filler volume fraction ϕ_R defined as follows:

$$\phi_R = \frac{\phi}{1 - RV}. \quad (3)$$

Using this reduced filler volume fraction, data should be made independent of the filler stiffening effect.

2.2. Impact of mineral filler content on the modulus of asphalt mixtures

As said before, if the role of the filler on mastic rheology is well understood, this is not so with the link between mastic and mixture properties. Several attempts have been made, but none of them gives, for example, a way to simply relate mastic modulus to mixture modulus knowing other relevant mixture parameters such as mastic volume fraction and air voids (Di Benedetto et al., 2004; Liu et al., 2011).

Therefore, the only way to estimate mixture complex modulus $E^*(\omega)$ from composition remains to rely on early correlations such as the one from L. Francken and J. Verstraeten with the Belgian Road Research Center (Francken & Verstraeten, 1974):

$$E^*(\omega) = E_{FV} \left(\frac{V_{ag}}{V_b} \right)^{0.55} \exp \left(-\frac{v}{v_0} \right) R^*(\omega), \quad (4)$$

where $E_{FV} = 14.36$ GPa and $v_0 = 17.12$ are two constants obtained by curve fitting, and V_{ag} , V_b and v are respectively the volume of aggregate, the volume of binder and the air voids in the mixture. E_∞ is the high-frequency limiting modulus and $R^*(\omega)$ is a complex function of the frequency ω depending on binder properties only (Francken & Verstraeten, 1974). Note that the correlation was based on 72 mixtures with air voids ranging from 1.5% to 32% (Francken & Verstraeten, 1974). This makes it one of the most complete equation of this form ever published, hence its choice. However, the approach could be performed in principle with any other such correlation provided it takes into account formulation variables such as air voids and binder

content. Also, extrapolation to air void contents outside of the studied range should be made with great care, given that its intended use is more to interpolate data within the studied range.

Therefore, the measured complex modulus $E_m^*(\omega)$ can be reduced by the following formula:

$$E_R^*(\omega) = \frac{E_m^*(\omega)}{E_{FV}(V_{ag}/V_b)^{0.55} \exp(-(v/v_0))}. \quad (5)$$

With this definition, the reduced modulus $E_R^*(\omega)$ represents the ratio between its measured value to that calculated by the Francken–Verstraeten correlation. Therefore, it should be made essentially formulation independent (i.e. no variation due to binder content or air voids differences) but would still depend on binder properties, since it should indeed represent the $R^*(\omega)$ function in Equation (4). In other words, the use of the reduced modulus makes it possible to compare mixture formulas even if they have different air voids and binder content.

3. Materials and procedures

3.1. Materials

The study was based on two binders, a neat bitumen from the Repsol refinery of Puertollano (Spain) corresponding to a 50/70 penetration grade (EN 12591) and a polymer-modified bitumen (PMB) from the same refinery corresponding to a 45/80–60 grade (EN 14023). Their main properties are given in Table 1.

Two types of mixtures were used. First, a standard AC corresponding to an AC 16 surf according to EN 13808-1, and more precisely an AC 16 surf S in the Spanish practice (according to article 542 of FOM/2523/2014) was first prepared with 12/18, 6/12 and 0/6 siliceous river gravel from Jarama (Spain), using an additional 0/6 limestone sand from Hanson quarry (Spain) and the 50/70 bitumen. Both sands, initially with 12.7 and 11.3 wt.% of filler respectively, were washed on a 63 microns sieve in order to remove the filler. Then, a controlled amount of filler was added to the mixture (Table 2). It was either LF or HL, at respectively 4–6–8–10–12 wt.% and 2–3–4–6 wt.% content adjusted from defillerised mixture design as described in Table 2. The LF was a high-purity filler (> 98 wt.% CaCO₃) from Tricalsa (Spain) and the HL was a high-purity calcic HL CL1 (CL 90 S according to EN 459-1) supplied by Lhoist (Belgium). Their properties are given in Table 2. Particle size was measured in methanol using a Coulter LS 230 laser diffractometer. Surface area was measured by the Blaine method (EN 196-6) for all fillers except for HL, for which the preferred method is by nitrogen adsorption using the Brunauer Emmett Teller (BET) method due to its high internal porosity (Lesueur et al., 2013). For filler having little internal porosity, Blaine and BET surface areas are essentially the same (Arvaniti et al., 2015).

The difference in the filler content between the mixtures made of LF and lime took into consideration the higher stiffening effect of HL; as mentioned in the background section, it is well

Table 1. Main properties of the binders used in the study.

Property	Method	Materials		
		Units	50/70	PMB
Penetration	EN 1426	1/10 mm	68	59
R&B	EN 1427	°C	50.0	63.6
Elastic recovery	EN 13398	%	–	84
Density	EN 3838	Mg/m ³	1.033	1.029

Table 2. Fillers used in the study.

Property	Method	Materials		
		Units	LF	HL
Available lime	EN 459-2	%	—	93.2
Dry porosity (Rigden air voids RV)	EN 1097-4	%	30.2	61.9
Particle density	EN 1097-7	Mg/m ³	2.72	2.25
Mean diameter (d50)	laser	µm	8.9	5.3
Blaine surface area	EN 196-6	m ² /g	1.1	—
BET surface area	BET	m ² /g	—	15.8

documented that a mastic made with \times wt.% HL has more or less the same viscosity has a mastic made with $2 \times$ wt.% of LF (Lesueur et al., 2013). Note that the filler content for AC 16 was always in the limits given in the EN 13108-1 standard, that is, between 0 and 12 wt.%. However, the usual filler content would have been between 3 and 7 wt.% as required in article 542 of Spanish specification FOM/2523/2014. Therefore, the filler content was voluntarily extended beyond standard practice in order to cover more values. In all cases, two filler contents, 4 and 6 wt.% were in common for both fillers, allowing for a direct comparison at these values.

Also, regardless of the filler content, the binder content was maintained constant in order to limit the number of moving parameters. It was fixed at 5.1 parts per hundred aggregate (pph) which corresponded to the value found from the reference formulation study for this mixture with unwashed sand (giving a filler total content of 6.0 wt.%). This means that the overall mastic volume fraction in the mixture was therefore increasing with increasing filler content (Table 3). Note that all volume fractions were calculated from air voids and mass composition data given in Table 3, using the densities given for the binders in Table 1, for the fillers in Table 2 and for the aggregate in Table 3. The impact of this will be discussed later on in this paper. The various compositions of AC 16 used in the study are described in Table 3.

Second, an AC for very thin layer corresponding to a BBTM 11A according to EN 13108-2, was made with porphyric 6/12 aggregate and 0/3 sand from the Cuadrado quarry in Ávila (Spain) and the PMB. The porphyric aggregate was selected because of its very good mechanical properties making it very appropriate for a high-performance wearing course. Again, the sand was washed as described earlier in order to remove the 17.1 wt.% filler in the sand, and different formulas were made with increasing amounts of LF or HL, at respectively 4–6–8–10–12 wt.% and 2–4–6 wt.% content. According to EN 13108-2, filler content should lie between 7 and 9 wt.%. As previously discussed for AC 16, the filler content was therefore also voluntarily extended beyond usual practice and the overall mastic volume fraction in the mixture was therefore increasing with increasing filler content (Table 4).

Similar to the AC 16, the binder content was fixed at 5.5 pph which corresponded to the value found from the reference formulation study for this mixture with unwashed sand (filler content of 6.2 wt.%). Again, the overall mastic volume fraction in the mixture was therefore increasing with increasing filler content (Table 4), as will be later discussed in the paper. The various compositions of BBTM 11A used in the study are described in Table 4.

3.2. Test methods

All mixtures were prepared using the standard methods for mixing (EN 12697-35) and compaction (NLT 161). Mixing temperature was 163°C for AC 16°C and 175°C for BBTM, as recommended given the different binders used. Compaction temperatures were respectively

Table 3. AC 16 mixture designs used in the study. Binder content is given both based on the dry aggregate weight (pph) and % in the total mixture. % for aggregate fractions are wt.% based on total aggregate.

Property	Method	Materials	AC16								
		Units	LF4	LF6	LF8	LF10	LF12	HL2	HL3	HL4	HL6
Binder	—		50/70	50/70	50/70	50/70	50/70	50/70	50/70	50/70	50/70
Binder content	—	%	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85
Binder content	—	pph	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
Filler	—		LF	LF	LF	LF	LF	HL	HL	HL	HL
Filler content	—	%	4	6	8	10	12	2	3	4	6
12/18 Jarama	—	%	16	16	16	16	16	16	16	16	16
6/12 Jarama	—	%	36	36	36	36	36	36	36	36	36
Washed 0/6 Jarama	—	%	22	21	20	19	18	23	22.5	22	21
Washed 0/6 Hanson	—	%	22	21	20	19	18	23	22.5	22	21
Density	EN 12697-6	kg/m ³	2282	2314	2337	2391	2372	2279	2280	2283	2251
Air voids	—	vol.%	7.9	6.6	5.7	3.6	4.4	7.7	7.5	7.2	8.2
Mastic volume fraction	—	vol.%	13.9	15.8	17.6	19.6	21.1	12.7	13.6	14.6	16.3

Table 4. BBTM mixture designs used in the study. Binder content is given both based on the dry aggregate weight (pph) and % in the total mixture. % for aggregate fractions are wt.% based on total aggregate.

Property	Method	Materials	BBTM							
		Units	LF4	LF6	LF8	LF10	LF12	HL2	HL4	HL6
Binder	—		PMB							
Binder content	—	%	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
Binder content	—	pph	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Filler	—		LF	LF	LF	LF	LF	HL	HL	HL
Filler content	—	%	4	6	8	10	12	2	4	6
6/12 Cuadrado	—	%	66	66	66	66	66	66	66	66
Washed 0/3 Cuadrado	—	%	30	28	26	24	22	32	30	28
Density	EN 12697-6	kg/m ³	2403	2432	2443	2455	2293	2370	2397	2390
Air voids	—	vol.%	7.2	6.0	5.5	5.0	11.2	8.1	6.7	6.6
Mastic volume fraction	—	vol.%	15.5	17.4	19.2	21.0	21.2	14.0	16.2	18.1

150°C and 163°C. The specimens were compacted by static compaction under a 20 t load for 5 min in cylindrical moulds of 100 mm diameter. The final height was close to 210 mm, but the exact value varied depending on the mix formula, hence giving variations in final density, as measured by hydrostatic gravity (EN 12697-6). All final densities and corresponding air voids and mastic volume fractions (calculated from final density knowing composition, aggregate, filler and binder densities) are given in Tables 3 and 4.

Three specimens were manufactured for each mixture formula. They were placed at least 24 h in a climatic chamber at 15°C before testing. The complex modulus was measured at 15°C following Spanish standard NLT 349, that is, in tension–compression mode using a load-controlled set-up on an Infratest hydraulic press. Samples were initially loaded with a static compression load of 2000 N and then with a sinusoidal load of maximum amplitude 1400 N at 5, 10 and 15 Hz. Deformation were recorded by means of two extensometers with initial length 100 mm, placed on the specimens by means of two annuli with 3-connection points each on the samples. The modulus was recorded after 1000 cycles for each frequency. The value recorded for each formula corresponds to the mean of the three specimens.

4. Results

4.1. *Effect of increasing filler content on AC mixtures*

The results obtained for the modulus at 15°C and 10 Hz of the AC 16 formulas are given in Table 5 and Figure 1. Clearly, and regardless of filler type, the curves of the modulus as a function of filler content exhibit a well-defined maximum. The filler content at which the maximum modulus was reached depended strongly on the filler type: 10 wt.% for LF and 4 wt.% for HL. Note that the mastic volume fraction at the maximum was essentially lower for the HL formulas (14.6 vol.%) than for the FL formulas (19.6 vol.%), as a consequence of the lower filler concentration and lower density for the HL. Also, the air voids were generally higher for the FL formulas (Table 5), a factor known to decrease the modulus value, as illustrated by Equation (4).

Moreover, the value of the modulus varies strongly as a function of filler content (Table 5 and Figure 1): from 9345 to 12,430 MPa for FL formulas and from 3431 to 9942 MPa for HL formulas. The peak modulus was therefore higher for FL (12,430 MPa) than for HL (9942 MPa). A very low value was observed for the high lime content formula (6 wt.%).

The fact that the curve of the modulus versus filler content exhibits a maximum has already been observed by Moutier (1991) and was therefore repeated in the French mixture design guide (Delorme, De La Roche, & Wendling, 2007). Still, to our knowledge, no systematic study and no interpretation regarding this maximum has been provided so far. The scarce literature on the topic is even contradictory, since the dense mixtures tested with increasing filler contents from 4 to 12 wt.% by Tayebali, Malpass, and Khosla, (1998) showed rather a continuous increase in modulus (deduced from repeated shear data) with filler content. Meanwhile, the dense mixtures with 3–8 wt.% filler by Al-Suhaibani, Al-Mudaiheem, and Al-Fozan (1992) showed sometimes a maximum and sometimes a continuous increase in modulus (deduced from rut depth and/or Hveem stability). Therefore, even if this maximum in modulus is presented in the French design guide as a known fact, it is far from being fully documented in the literature.

4.2. *Effect of increasing filler content on BBTM mixtures*

The results obtained for the modulus at 15°C and 10 Hz of the BBTM formulas are given in Table 6 and Figure 2. As already observed for the AC16, the curves of the modulus as a function of filler content exhibit a well-defined maximum that depends on filler type: 10 wt.% for LF and

Table 5. Complex modulus at 15°C and 10 Hz for all AC 16 formulas.

Property	Method	Materials	AC16	AC16	AC16	AC16	AC16	AC16	AC16	AC16	AC16
		Units	LF4	LF6	LF8	LF10	LF12	HL2	HL3	HL4	HL6
Filler			LF	LF	LF	LF	LF	HL	HL	HL	HL
Filler content	—	wt.%	4	6	8	10	12	2	3	4	6
Air voids	—	vol.%	7.9	6.6	5.7	3.6	4.4	7.7	7.5	7.2	8.2
Mastic volume fraction	—	vol.%	13.9	15.8	17.6	19.6	21.1	12.7	13.6	14.6	16.3
Norm of the modulus	NLT 349	MPa	9345	10,146	10,960	12,430	9906	8139	8477	9942	3431
Phase angle	NLT 349	°	18.1	17.5	14.1	13.8	18.1	16.7	17.5	16.4	23.6

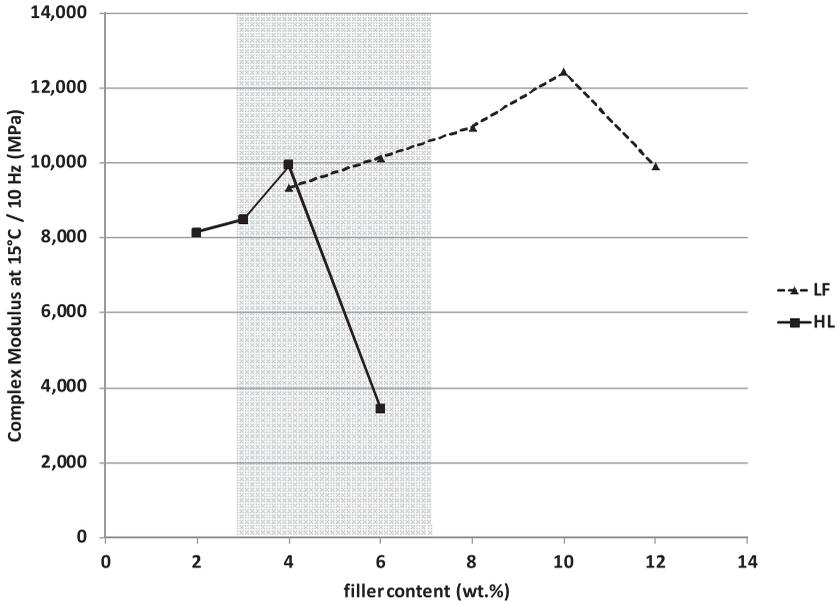


Figure 1. Norm of the complex modulus at 15°C and 10 Hz for all AC 16 mixtures as a function of filler type (LF = limestone filler/HL = hydrated lime) and content in the mixture. The grey zone corresponds to the filler content recommended for this type of mixture in current Spanish specifications.

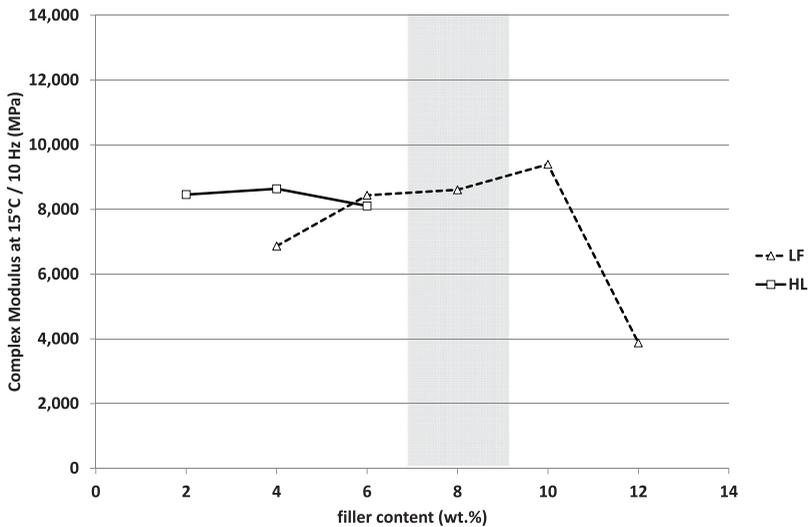


Figure 2. Norm of the complex modulus at 15°C and 10 Hz for all BBTM mixtures as a function of filler type (LF = limestone filler/HL = hydrated lime) and content in the mixture. The grey zone corresponds to the filler content recommended for this type of mixture in current European specifications.

4 wt.% for HL. The maximum is therefore the same for both mixtures. Again, the mastic volume fraction at the maximum was essentially lower for the HL formulas (16.2 vol.%) than for the FL formulas (21.0 vol.%), as a consequence of the lower filler concentration and lower density for the HL. Air voids at the maximum were also higher for the HL formulas (Table 6).

Table 6. Complex modulus at 15°C and 10 Hz for all BBTM formulas.

Property	Method	Materials	BBTM							
		Units	LF4	LF6	LF8	LF10	LF12	HL2	HL4	HL6
Filler			LF	LF	LF	LF	LF	HL	HL	HL
Filler content	—	wt. %	4	6	8	10	12	2	4	6
Air voids	—	vol. %	7.2	6.0	5.5	5.0	11.2	8.1	6.7	6.6
Mastic volume fraction	—	vol. %	15.5	17.4	19.2	21.0	21.2	14.0	16.2	18.1
Norm of the modulus	NLT 349	MPa	6870	8438	8607	9394	3877	8459	8639	8109
Phase angle	NLT 349	°	18.5	18.6	18.5	18.2	13.7	18.1	17.1	16.4

Also, the value of the modulus varied strongly as a function of filler content for the FL formulas, but somewhat less for the HL formulas (Table 6 and Figure 2): from 3877 to 9394 MPa for FL formulas and from 8109 to 8639 MPa for HL formulas. The peak modulus was still higher for FL (9394 MPa) than for HL (8639 MPa). This time, a very low value was observed for the high limestone content formula (12 wt.%).

5. Discussion

5.1. On the position of the maximum filler content

As just described, the fact that the maximum in modulus was much lower for the HL formulas than for the LF strongly suggests that the position of the maximum was linked to the stiffening behaviour of the filler. Therefore, the filler content was transformed into reduced volume fraction using Equation (3). As shown in Figure 3, with the use of these reduced variables, the maximum for all formulas now corresponds to values ranging from 60.3% to 72.1%, with an average of 65.9%. Therefore, and given the uncertainty with the Rigden values, the filler content and the maximum location, it can be reasonably concluded that this maximum was essentially constant for all studied mixtures with a value close to 66% for the peak reduced filler volume fraction.

In physical terms, it is interesting to note that reaching about 66% of reduced volume fraction corresponds to a stiffening factor of 8.6 in Equation (2). So, a proposed interpretation for this maximum is that it is linked to the point where the viscosity of the mastics becomes too high to ensure proper coating. Above this point, aggregate coating becomes more difficult due to a very high mastic viscosity, as manifested by the very low modulus values of some of the formulas (AC with 6% HL in Figure 1 or BBTM with 12% LF in Figure 2).

5.2. On the value of the maximum modulus

As described earlier, the modulus maximum for the HL formulas was clearly lower than for the LF formulas, regardless of mixture formula (Figures 1 and 2). However, it was also noted that the

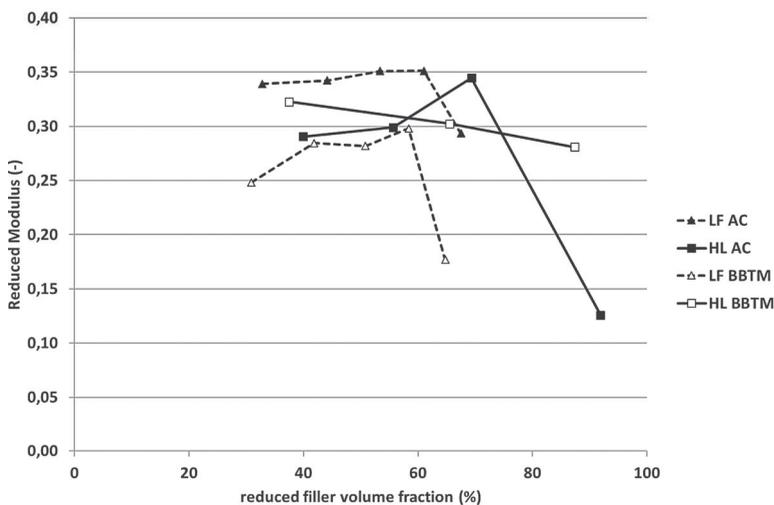


Figure 3. Reduced modulus as a function of reduced filler volume fraction for all mixtures. The definition of reduced variables is described in the text.

mastic volume fraction at the maximum modulus was significantly lower for the HL formulas. Also, the air voids were not strictly identical, with the HL formulas being generally less compact than the FL ones (Tables 5 and 6). Both parameters impact the modulus absolute value and one way to estimate their contribution is to use the reduced modulus as defined in Equation (5).

As shown in Figure 3, the reduced modulus for all AC16 formula was essentially constant regardless of filler type, with an average value close to 0.32. One point still remained somewhat lower, corresponding to the very low value already noticed for the 6% HL formula (Figure 3). It was proposed earlier that the very low modulus value observed for this formula (3431 MPa – Table 5), was a clear sign that the mixture experienced poor coating due to viscous a mastic. So, finding this point again outside of the correlation confirms that this mixture was not comparable with the other ACs.

As regards the reduced modulus for the BBTM formulas, the data in Figure 3 showed a quite similar picture with an almost constant value for the reduced modulus, this time close to 0.29. Two points remained somewhat outside of the correlation, corresponding on one hand to the very low value already noticed for the 12% LF formula (Figure 3). Again, it was observed earlier that the very low modulus value observed for this formula (3877 MPa – Table 6), was a clear sign that the mixture experienced poor coating due to viscous a mastic. So, finding this point again outside of the correlation confirms that this mixture was not comparable with the other BBTMs. On the second hand, finding the data for the 4% FL formula significantly lower than the rest of the correlation, highlights that this formula was also probably not comparable with the others, because too low a filler content in such open-graded formulas favours binder draindown, resulting in an uneven film thickness.

As a conclusion, the use of the reduced modulus as a tool to compare data proved completely appropriate. Interestingly, the almost constant value found for each mixture formula confirmed that the differences in peak modulus as a function of filler type are a consequence of the mixture details (mastic volume fraction and air voids) and not directly due to filler type. Then, both formulas exhibited different average reduced modulus values, ~ 0.32 for the AC and 0.29 for the BBTM, as expected given the differences in binder type and properties (Table 1).

5.3. *Practical consequences*

It is interesting to stress that the location of the peak modulus always remained outside of the grey zone for LF for both AC and BBTM (Figures 1 and 2). This means that the current specifications are far from this maximum and that in terms of modulus, stiffer mixtures could potentially be achieved by only increasing the filler content. This was especially true for the AC formulas, for which the recommended filler content from this work, would be 6–9 wt.% instead of the current 3–7 wt.% (Figure 1). This would lead to a $\sim 20\%$ increase in modulus (Figure 1).

Of course, other mixture properties such as resistance to moisture damage and fatigue resistance should also be validated, but it might very well be beneficial for these properties too, given the facts that the filler, if well-chosen, improves moisture resistance (Airey, Collop, Zoorob, & Elliott, 2008; Lesueur et al., 2013), and also acts as obstacle to crack propagation (Lesueur et al., 1995; Smith & Hesp, 2000).

Another way to look at the data is to observe that in the end, adding HL to 1–3 wt.% as a substitute for the filler, as is currently done in practice (Lesueur et al., 2016), allows to maintaining the overall filler content within the specified filler content (the grey zone in Figures 1 and 2) while displacing the maximum to this zone. It is therefore an astute way to optimise mixture mechanical properties without changing the current specifications on filler content. In other words, it seems that formulators already made use of the findings of this paper when trying to increase the stiffness of asphalt mixtures by substituting part of the mineral filler by HL. Still, a

better way to do so in the future for a given aggregate gradation, would be to first identify the filler content giving rise to the maximum in modulus using the naturally available mineral filler. In some cases, it will be the one from the aggregate, in other cases, it will be some added filler, probably LF in many locations. From then on, it would be possible to displace this maximum by using a right combination of HL and the filler. This optimisation would be all the more efficient that other mixture properties could then also be adjusted separately by playing with two kinds of fillers.

6. Summary of findings and conclusions

This paper presented results on the effect of increasing amounts of filler in two different mixture formulas, a regular AC 16 and an open-graded BBTM 11A. Two fillers were compared, LF with Rigden air voids of 30.2% and HL with Rigden air voids of 61.9%.

For both formulas and regardless of the type of filler, the modulus versus filler content curves exhibited a well-defined maximum. The filler content at which the maximum was found was strongly filler dependent, with HL formulas peaking at 4 wt.% and LF formulas peaking at 10 wt.%. To our knowledge, this is the first systematic study on the location of this maximum and the first attempt to understand its origin.

The use of a reduced volume fraction of filler, taking into account the filler stiffening potential as quantified by the Rigden air voids, showed that the maximum in modulus occurred for reduced volume fraction of filler close to 66%. This suggested that, before the peak, the modulus increased with the filler content as a consequence of a stiffer mastic, and after the peak, the modulus started to decrease due to poor aggregate coating as a consequence of too-viscous a mastic. The point at which the mastic becomes too-viscous would therefore be related to a ~ 10 -fold increase in viscosity as compared to the neat binder.

The use of a reduced modulus, taking into account variations in binder content and air voids, showed that the maximum modulus value for a given binder type, remained essentially controlled by mixture composition in terms of binder content and air voids, and that the filler type had no direct effect on it.

Apart from the results at stakes, the use of this set of reduced variables is clearly new to the asphalt community, and the soundness of this approach will likely be challenged in future works.

As a practical consequence of this work, it was observed that the studied mix formulas, especially the regular AC, could potentially accept higher filler loadings based on modulus. As a matter of fact, the studied AC 16 could accept 6–9 wt.% instead of the current specifications of 3–7 wt.%. This would stiffen the mixture by $\sim 20\%$, but would also need a modification in the specifications.

Therefore, one way to benefit from these findings without changing the specifications would be to use 7 wt.% of a filler composed of a blend of 40% HL and 60% LF. This way, the maximum would be moved close, but above, 7 wt.%, with an expected modulus increase of order $\sim 20\%$ as compared to the 100% LF formula.

Of course, these findings must be validated with other mixture formulas and raw materials. Still, former studies confirmed the presence of this maximum and we are therefore confident that it will be manifested in all asphalt mixtures.

Furthermore, maximising the modulus is appropriate for pavement design only if the fatigue life remains at least unchanged or, even better, improves. So, a similar study has therefore to be performed to measure the impact of increasing filler content on fatigue life, in order to check whether the proposed practical consequences make full sense. Still, published results suggest that increasing filler loading could be beneficial for fatigue resistance as well (Lesueur et al., 1995; Smith & Hesp, 2000).

Finally, the choice and quantity of filler also impacts moisture resistance of the mixture. So, the effect of increasing filler loadings also has to be studied systematically before validating the potential interest of increasing the filler content in asphalt mixtures. For this parameter again, published results suggest that this could be beneficial as well (Airey et al., 2008; Lesueur et al., 2013).

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