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Effect of Fillers and their Fractional Voids on Fundamental Fracture Properties of Asphalt Mixtures and Mastics

A laboratory investigation was performed to evaluate the influence of filler type and Rigden fractional voids on fundamental fracture limits of asphalt mixtures and mastics. Fracture properties of 14 different asphalt mixtures and mastics composed by the combination of seven different fillers and two asphalt binders, were evaluated using: a visco-elastic fracture mechanics-based crack growth law for mixtures; the Bending Beam Rehometer for mastics at low temperatures and a Modified Direct Tension Test (MDTT) for mastics at intermediate temperatures. A Digital Image Correlation System (DIC) was employed to detect strain distribution and damage evolution in mastics. Experimental results indicate that the filler type and Rigden factional voids affect the fracture limits and the definition of strain distribution and damage evolution of both mixtures and mastics, while other properties result more dependent on the physio-chemical interaction between filler and asphalt binder.

Keywords: HMA mixtures; mineral filler; rigden void; fracture; digital image correlation

Introduction

It has long been recognized that Hot Mix Asphalt (HMA) mechanical behaviour is strongly related to the properties of the mastic and the interaction between asphalt binder and mineral filler (Anderson and Goetz, 1973; Craus et al., 1976). Filler in asphalt mixture has the role of filling the voids between coarse aggregates and interacts physio-chemically with the asphalt binder, influencing the performance and the workability of asphalt mixture (Delaporte et al, 2008; Faheem and Bahia, 2009; Faheem et al., 2012; Kim et al, 2003; Zhang et al., 2016). As discussed by many authors (Jiménez et al., 2011; Wang et al., 2011; Yi-qiu et al., 2010; Zeng et al., 2008) the stiffness of the mastic affects the ability of the mixture to resist permanent deformation at higher temperatures, influences stress development and fatigue resistance at intermediate temperatures, and influences stress development and fracture resistance at low temperatures. Mineral filler fractional voids value has been used as an indicator of filler stiffening effect since the introduction of the test by Rigden in 1947. He considered the asphalt required to fill the voids in the dry compacted bed as fixed asphalt, while asphalt in excess of that amount was defined as free asphalt, indicating that the percent free asphalt is the main factor defining the consistency of the filled system. Many studies were later conducted to evaluate the influence of the filler's fractional voids on the performance of mastic and mixtures (Kim and Little, 2004, Lackner et al., 2005, Little and Petersen 2005). All these studies agree that the stiffness of the mastic is higher than that of the binder and that such stiffening effect increases as the fractional voids increase. More recently, Faheem et al. (2010 and 2012) performed an important study to evaluate the effect of Rigden Void (RV) test values on the stiffening effect of fillers as determined by measuring the viscosity of the unfilled binders and filled mastics system. They found that the RV can demonstrate the potential of stiffening effect of fillers, but showed that, when the same filler is blended with different asphalt binders, the measured RVs of the fillers cannot provide sufficient guidance on the interaction between the filler and the binder.

Very few studies were conducted to better understand the role of fillers and their fractional voids on the cracking behaviour of asphalt mixtures and mastics. To this scope, accurate description of strain evolution and distribution in mastics is essential for revealing significant information on the binder-filler interaction.

The present study evaluates the influence of mineral fillers and their fractional voids on fundamental fracture properties of asphalt mixtures and mastics. The objectives of this research were:

- Evaluate how Rigden Void of fillers influences the low temperature properties of mastics.
- Evaluate how Rigden Void of fillers influences the fundamental cracking properties of asphalt mixtures using and appropriate crack growth law.
- Evaluate how the interaction between asphalt binder and filler influences the mastic cracking behavior at intermediate temperatures using appropriate Digital Image Correlation analyses.

Seven different fillers where associated to two asphalt binders (one unmodified and one polymer modified) to obtain 14 asphalt mixtures and mastics. The filler fractional voids were calculated according to the European Norms procedure (EN 1097-4).

The cracking performance of the mixtures at intermediate temperature were evaluated using the visco-elastic fracture mechanics-based cracking model "HMA Fracture Mechanics" (Roque et al. 2002; Zhang et al. 2001). According to this model, only five tensile mixture properties, easily obtainable from the Superpave Indirect Tensile Test (IDT), are required to control the cracking performance of asphalt mixtures. They are the tensile creep rate as represented by the power law creep compliance relationship (m-value), the resilient modulus, the creep compliance, the dissipated creep strain energy to failure ($DCSE_f$) and the total energy to fracture (FE).

The behavior of the mastics at low temperatures was estimated conducting the Superpave Bending Beam Rehometer (BBR) test (AASHTO T 303 2002) over a wide range of low temperatures. The cracking behaviour of the mastics at intermediate temperatures was investigated using a Modified Direct Tension Test (MDTT) developed by Montepara et al. (2011). Strain localization and damage distribution were observed using an in-house developed DIC software code, called DICe, which was completely re-designed (Dall'Asta et al. 2016) from the first DIC code developed by Birgisson et al. (2006 & 2009).

The results showed that the filler type and Rigden factional voids values do not affect some parameters, which result more dependent on other properties (i.e. resilient modulus and creep compliance of mixtures and stiffness of mastic at low temperatures). Conversely, fundamental fracture limits of both asphalt mixtures and mastics, and the definition of strain distribution and damage evolution during damage, result affected by both the filler nature and Rigden Voids.

Experimental Methods

The influence of the Rigden Voids on mixture's cracking behavior was evaluated at low temperatures for mastics, and at intermediate temperatures for both asphalt mixtures and mastics. The Bending Beam Rheometer (BBR) test was performed to determine the stiffness and m-value of mastics at low temperatures (-30°C, -24°C, -18°C, -12°C and -6°C). The cracking properties of asphalt mixtures at intermediate temperature were evaluated applying a fundamental failure mechanism entitled HMA Fracture Mechanics, proposed by Zhang et al. (2001) and Roque et al. (2002). The cracking behaviour of the mastics was investigated using a Modified Direct Tension Test (MDTT) developed on purpose, to identify crack initiation and interpret mastic fracture response at intermediate temperature (Montepara et al. 2011). Strain localization and damage distribution were observed using a new Digital Image Correlation System (DIC) developed at the University of Parma (Dall'Asta et al. 2016), obtaining 2D full-field strain maps of both mastics and HMAspecimens during tensile loading.

Bending Beam Rehometer (BBR) Test

BBR test was conducted to investigate the effect of the different fillers on mastics at low temperatures. The mastic beams (125 mm long, 12.5 mm wide and 6.25 mm thick) were submerged in a constant temperature bath and kept at test temperature for 60 min. A constant weight of 100 g was then applied to the mastic beam, which was supported at both ends, and the deflection of center point was measured continuously. Creep stiffness (S) and creep rate (m) were measured at several loading times ranging from 8 to 240 s.

Asphalt Mixture Cracking Properties

According to the HMA Fracture Mechanics framework, failure of asphalt mixtures is governed by two fundamental properties: Fracture Energy density threshold (FE) and Dissipated Creep Strain Energy threshold ($DCSE_f$). These two properties are easily obtainable from three mechanical mixture tests performed at 10°C in an indirect tension test configuration: resilient modulus (Roque and Buttlar 1992), creep compliance (Buttlar and Roque 2004) and tensile strength (Roque et al. 1997). The FE limit is determined as the area under the stress-strain curve, while the $DCSE_f$ is the fracture energy minus the elastic energy at the time of fracture.

The $DCSE_f$ is a measure of how much micro-damage mixture can take before it results in a macrocrack initiation. In order to predict top-down cracking performance of the mixture in the field, an Energy Ratio criterion was proposed by Roque et al. (2004). The Energy Ratio is defined as follows:

$$ER = \frac{DCSE_f}{DCSE_{min}} \quad (1)$$

where $DCSE_f$ is the dissipated creep strain energy threshold of the mixture and $DCSE_{min}$ is the minimum dissipated creep strain energy required, a function of the creep compliance power low parameters. Basically, $DCSE_{min}$ is a measure of how much damage will the material accumulate in the filed during service life. For a good filed performance of the mixture ER > 1 is required.

Mastic Fracture Test

The cracking behavior of the mastics was investigated using a Modified Direct Tension Test (MDTT) developed on purpose, to identify crack initiation and interpret mastic fracture response at intermediate temperature. The test was developed modifying the Standard SuperPave™ DTT test for asphalt binders. All the details can be found elsewhere (Montepara et al. 2011).

MDTT tests were performed on three replicates at 15°C using an MTS closed-loop servo-hydraulic loading system adopting a 2.5kN load cell. The specimen was fixed at one end and pulled from the other end applying a constant stroke of 1.68 mm/sec until rupture occurs. The engineering stress was computed according to the SuperPave™ binder specification:

$$\sigma_f = \frac{P_f}{A_0} \tag{2}$$

where: σ_f = failure stress; P_f = measured load at failure; A_0 = original cross-sectional area.

Failure is defined as the point on the stress-strain curve where the load reaches its maximum. The rapid loading rate and the interpretation of the test only up to fracture allow for a continuum representation. Strains were obtained from DIC system, interpolating all the strain values of the grid points located at the 46x20 mm specimen central cross-sectional area. The test configuration is shown in Figure 1.

Mastic Strain Analysis

Mastic strains during loading were obtained using an in-house developed DIC software, code called DICe, which implements an innovative Least Squares Matching approach that uses higher order polynomial shape functions to model the displacement field between the reference and the measured image of the DIC sequence, proposed also by other authors in different application fields (Bethmann and Luhmann, 2010). The DIC system has shown to achieve satisfactory accuracy compared to strain gauges, resulting in 0.04% accuracy in compressive/tensile strains and 0.03% accuracy in shear strains (Dall'Asta et al 2016).

A digital camera Basler piA1600-35gm (resolution 1608x1308, focal length 8mm, pixel size 7.4 micrometers, 35 fps@max resolution), directly connected to the testing control system, is located on a support inside the climatic chamber where tests are performed. The chamber is provided with a proper LED lighting system which assures good illumination without heating up the specimen. Since the crack phenomenon is very fast and short-lasting (1÷2 seconds), the camera was properly set up to acquire the images in a smaller area of the sensor (300x500 pixel) reducing the bandwidth required for transmitting each frame and, consequently, allowing a higher frame rate (ca. 80 fps). Thanks to the elongated shape of the specimen, once provided an optimal imaging geometry, the reduced size of the images still allowed the complete acquisition of the whole specimen surface. The images are automatically processed by the software, providing accurate displacement/strain fields. To achieve high accuracies in the strain field measurements, the specimen surface must present a well-contrasted grey scale speckle pattern, easily obtainable by a water paint-based treatment (Romeo 2013).

Materials

Fourteen asphalt mixtures and fourteen respective mastics were used in this study. All the mixtures were 12.5-mm nominal maximum size, produced with limestone, marly limestone and calcarenite and composed by the same aggregate type and gradation (Figure 2). Two different asphalt binders were used in this research: N is an unmodified binder graded as PG 58-22 while M is a SBS polymer modified binder graded as PG64-22 (3.5% of SBS linear polymers).

Fillers

Seven fillers were associated to the two binders: a limestone (not pure) filler labeled as B; a limestone filler containing high percentages of magnesium carbonate, labeled as D; a filler obtained from the grinding of coal rocks, labeled as R; a fly ash filler, labeled as FA; a pure limestone filler labeled as L; the combination of pure limestone filler and 20% of hydrated lime, labeled as HL and a stabilized fly ash, labeled as S obtained from Municipal Solid Waste Incinerator (MSWI). The method to inert fly ash from MSWI with a low temperature process has been developed and patented by Bontempi et al. (2010a and 2010b) and Zacco et al. (2012), within a project supported by LIFE program of the European Community (LIFE + 2008 project ENV/IT/000434).

Following are the properties of four materials:

- Filler "B" (not pure limestone) is composed of $CaCO_3$ (90%), $CaMg(CO_3)_2$ (6%) and SiO_2 (4%) with a density of 2.73 g/cm^3 and a Rigden Void of 37.0%
- Filler "D" is composed of CaCO3 (60%) and MgCO3 (40%), with a density of 2.84 g/cm^3 and a Rigden Void of 38.21%

- Filer "R" (not pure limestone) is composed of $CaCO_3$ (>80 %), Cl- (<0.004 %), S (<0.002 %) and H2O (<0.5 %) with a density of 2.71 g/cm^3 and a Rigden Void of 36.30%.
- Fly ash "FA" filler is composed of SiO_2, Al_2O_3, Fe_2O_3, CaO, with a density of 2.37 g/cm^3 and a Rigden Void of 37.30%.
- Filler "L" is pure limestone composed of $CaCO_3$ (100%), with a density of 2.71 g/cm^3 and a Rigden Void of 40.16%.
- Filler "HL" composed of $CaCO_3$ (80%), and $Ca(OH)_2$ (20%) with a density of 2.64 g/cm^3 and a Rigden Void of 44.5%.
- Filler "S" is mainly composed of calcite, hannebachite ($2CaSO_3*H_2O$), crystalline and amorphous silicon oxide phases and soluble salts (sodium chlorine, NaCl and potassium chlorine, KCl) with a density of 2.57 g/cm^3 and a Rigden Void of 64.66%.

Fractional voids were calculated for the fillers according to the European Norms procedure (EN 1097-4) rather than the National Asphalt Pavement Association (NAPA) version, due to larger sample used and availability of equipment. A detailed description of mastics and asphalt mixtures is given in Table 1.

HMA Specimen preparation

Two aggregate batches of 4500 g of aggregates were prepared for each mixture to produce a total of 56-152 mm diameter cylindrical specimens. The batches were mixed (at 160°C for unmodified mixes and 170°C for modified mixes) with the design asphalt content percentage (5.2%) and heated for two hours at 135°C for short-term aging. The cylindrical specimens were obtained compacting the mixes to 6 (± 0.5) percent air voids into 152 mm diameter specimens using the Pine Gyratory Compactor. Each cylindrical specimen was sawn to obtain two effective plates, each 30 mm thick discarding the top and the bottom plates for reducing density gradient effects. For each mixture, four circular shaped specimens were used to perform resilient modulus, creep compliance, and strength test at 10° C according to the Superpave IDT procedure developed by Roque and Buttlar (1992) and Buttlar and Roque (1994).

Mastic Specimen preparation

The mastic specimens were prepared following the improved SuperPave^{TM} binder testing specimen preparation procedure suggested by Ho and Zanzotto (2000). The selected filler concentration was 60% by weight for all mastic formulations in order to maintain the same filler/mastic content as the asphalt mixtures.

For each specimen, 28 g of asphalt binder and 42 g of filler were prepared and heated at mixing temperature (160°C for unmodified binders and 170°C for modified ones) in separate tins for 30 minutes. Then, the filler was slowly added to the asphalt in the oven. A mechanical mixer, with a maximum nominal angular speed of 8,000 rpm, was used to blend the materials at mixing temperatures. The mixing process was carefully followed so that the filler was homogeneously dispersed in the binder. The mastic was continuously stirred as it cooled to prevent settling and then was poured to the preheated dog-bone shaped aluminum mold. The specimen is allowed to cool to room temperature for one hour and de-molded. It is then placed in the environmental control chamber for one hour at testing temperature before the test is performed.

Results and analysis

Rigden Voids and Low Temperature Properties of Mastics

BBR test was conducted at -30, -24, -18°C, -12 and -6°C for all blends in five replicates. Results of BBR low temperature stiffness at a loading time of 60 s, are shown in Figures 3 and 4 for unmodified and modified asphalt binder, respectively; while m-values are indicated in Table 2.

Generally, increasing stiffness means that the thermal stresses developed in the pavement due to low temperature also increase, and thermal cracking become more likely. On the other hand, decreasing m-value indicates declining the rate of stress relaxation, which also increases the probability of thermal cracking.

The results clearly show that mastic stiffness and m-value are not directly influenced by the Rigden Voids of fillers, but rather that both binder and filler type affect low temperature properties of mastics. The unmodified mastics generally exhibit higher stiffness than the modified ones. Filler B produces a very high stiffness when combined with the neat binder but exhibits the lowest stiffness when combined with the modified binder. Similarly FA, when combined with the neat binder, produces a high stiffness but not when combined with the modified binders. This indicates that binder modification mitigates the stiffening effect of some fillers at low temperatures. Finally, fillers HL and S exhibit lower m-values combined with both neat and modified binders, indicating low rate of stress relaxation.

In conclusion, Rigden Void of fillers does not govern low temperature properties of the mastics, which are mainly influenced by the interaction between binder and filler.

Rigden Voids and Cracking Properties of Mixtures

A summary of Superpave IDT test results and a detailed analysis of each mixture property is presented. All the tests were performed on three replicates at 10°C using an MTS closed-loop servo-hydraulic loading system. The relationship between filler Rigden Voids and mixture cracking performance is also described. All the results obtained from the Superpave IDT test are listed in Table 3.

Resilient Modulus

The resilient modulus is a measure of the material's elastic stiffness since it corresponds to the ratio of the applied stress to the recoverable strain with repeated loading. The results listed in Table 3 show that Rigden Voids and filler nature, have no significant effect on resilient modulus. The very low difference among the all values indicates that the elastic response at small strain and/or short loading is mainly governed by the aggregate skeleton, rather than by the interaction between asphalt binder and their single properties.

Creep Compliance

Creep compliance represents the time-dependent behaviour of asphalt mixture, thus it is commonly used to evaluate the rate of damage accumulation. The crack growth process is exhibited by higher rates of permanent deformation, thus mixtures with high creep rates show higher crack growth rates. Creep compliance curves are shown in Figures 5 and 6 for unmodified and modified mixtures, respectively. The curve trends are very similar regardless of the type of filler employed. The only presence of filler S (stabilized fly ash from MSWI) increases significantly the rate of permanent deformation leading to higher rate of micro-damage accumulation. This is likely due to the particular composition of the filler which chemically interacts with the asphalt binder causing significant permanent deformation. Conversely, the introduction of hydrated lime decreases the creep compliance for both unmodified and modified binders. The most important role is played by the type of binder; indeed modified mixtures show creep compliance significantly lower than those obtained with unmodified binders.

In summary, the results highlight that the creep compliance of mixtures is not affected by the Rigden Void of fillers, but rather by the type of asphalt binder and the particular interaction between binder and filler in the mastic.

Energy-Based Parameters

Energy-based parameters are easily determined from the stress-strain response of a tensile strength test, as discussed by Roque et al. (2002). Fracture Energy (FE) density is the energy per unit volume required to fracture a mixture and it is determined as the area under the stress-strain curve at first fracture, while Dissipated Creep Strain Energy (DCSE) at failure is defined as the fracture energy minus the elastic energy at the time of fracture.

Results listed in Table 3 show that tensile strengths generally increase with the increase of Rigden Voids, while tensile strains at failure exhibit the opposite trend. More interestingly, as shown in Figure 7, mixtures containing fillers with Rigden Voids higher than 4% show an increase of more than 50% in both Fracture Energies and Dissipated Creep Strain Energies with respect to those mixtures containing fillers with Rigden Voids lower than 4%. This is true for both unmodified and polymer modified mixtures. Energy Ratio parameters, which govern the trend of the mixture to resist to top-down cracking, are clearly more dependent to the type of asphalt binder employed.

Mastic Fracture Behaviour

From MDTT test, fracture energies were computed as the area under the stress-strain curve at the point of failure, which is defined as the point on the curve where the load reaches its maximum. The rapid loading rate and the interpretation of the test only up to fracture allow for a continuum representation. Strains were obtained from DICe, interpolating all the strain values of the grid points located at the 46x20 mm specimen central cross-sectional area.

Tensile strengths, strains at failure and fracture energies are listed in Table 4. The results confirm what previously observed from IDT tests: mastics composed by filler with Rigden Voids higher than 4% show higher fracture energies, for both unmodified and modified binders (Figure 8). According to the test results, fillers have shown to play an important role in defining failure parameters: mastics containing filler S (stabilized flay ash from MSWI) show high tensile strengths and low deformability exhibiting a brittle behavior; mastics composed by filler L (pure limestone) show good tensile resistance and high deformability, which are both increased by the addition of hydrated lime (filler HL). The remaining mastics exhibit lower fracture energies; some of them make the mastic more brittle with high tensile resistance and small strains to failure (filler C), others increase ultimate strain showing lower resistance to failure (filler R). This is true for both unmodified and polymer modified mixtures. Figure 9 show full-field tensile (yy) strain maps at crack initiation for 4 mastics, obtained from the combination of unmodified asphalt binder and the 4 fillers that better describe the 4 more typical behavior. Same trends were obtained with mastics composed by polymer modified asphalt binder. Filler S allows mastics to localize strains in a small area corresponding to the localization of impending fracture, where exhibits high strain concentration, resulting in a brittle behavior whit high fracture limits. Filler HL allows the strains to distribute more in a restricted area, leading to high failure limits together with a significant deformability. Filler C makes the mastic more brittle leading to a fracture point at low values of failure strains which are, at the same time, highly distributed. Finally, filler R causes highly distributed damage in a large area leading to high deformability but low tensile strength resistance.

Summary and Conclusion

The influence of mineral fillers and their fractional voids on asphalt mixture and mastics fundamental cracking failure limits were investigated. Fourteen asphalt mixtures and mastics composed by the combination of two asphalts (one unmodified and one SBS polymer modified) and seven different fillers were examined. According to the HMA Fracture Mechanics visco-elastic cracking model, the following findings on mixtures cracking behaviour were obtained:

- The type of filler and Rigden Voids do not affect Resilient Modulus of mixtures indicating that the elastic response at small strain and/or short loading is mainly governed by the aggregate skeleton, rather than by the interaction between asphalt binder and fillers and their single properties.
- The type of filler and Rigden Voids generally do not affect creep-related performance. Conversely, the rate of damage accumulation mainly depends on the asphalt binder nature. The only filler S increases significantly the rate of permanent deformation due to the particular composition of the filler, which probably causes an important chemical reaction that should be investigated further.
- Energy based parameters (fracture energy and dissipated creep strain energy) have shown to be affected by the filler nature and Rigden Voids. In detail, mixtures containing fillers with Rigden Voids higher than 4% show significantly higher energy limits (more than 50%). Conversely, tensile strengths have shown to not depend directly on the filler nature but rather on the interaction between filler and asphalt binder. Finally the Energy Ratio, governing the mixture resistance to top-down cracking is more dependent to the type of asphalt binder employed.

Stiffening effect of fillers at low temperatures were investigated performing the BBR on mastics. It was observed that filler nature and Rigden Voids do not govern low temperature properties of the mastics, which are mainly influenced by the interaction between binder and filler.

Mastic fracture behavior was examined performing the MDTT test associated with the Digital Image Correlation software DICe. According to the test results, mastics composed by filler with Rigden Voids higher than 4% show higher fracture energies, for both unmodified and modified binders, as obtained from mixtures. Moreover, fillers have shown to play an important role in defining failure parameters, especially in defining strain distribution and evolution during damage, showing the own capability of releasing deformability to the mastic.

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Table 1. Mastic/Asphalt Mixture definition

Mastic/Mixture Label	Binder	Filler
NB	Natural - PG58-22	Limestone (not pure)
ND	Natural - PG58-22	Limestone + Magnesium carbonate
NR	Natural - PG58-22	Coal rocks
NFA	Natural - PG58-22	Fly ash
NL	Natural - PG64-28	Limestone (pure)
NHL	Natural - PG64-28	Limestone + Hydrated Lime (20%)
NS	Natural - PG64-28	Inertized MSWI fly ash
MB	SBS Modified - PG64-22	Limestone (not pure)
MD	SBS Modified - PG64-22	Limestone + Magnesium carbonate
MR	SBS Modified - PG64-22	Coal rocks
MFA	SBS Modified - PG64-22	Fly ash
ML	SBS Modified - PG64-22	Limestone (pure)
MHL	SBS Modified - PG70-22	Limestone + Hydrated Lime (20%)
MS	SBS Modified - PG70-22	Inertized MSWI fly ash

Table 2. BBR m-values of mastics

	m-value (@60 s)				
Temp [°C]	**-30**	**-24**	**-18**	**-12**	**-6**
NB	0.129	0.175	0.279	0.419	0.606
ND	0.128	0.211	0.296	0.429	0.612
NR	0.144	0.162	0.274	0.397	0.579
NFA	0.133	0.185	0.296	0.391	0.573
NL	0.113	0.165	0.253	0.404	0.545
NHL	0.120	0.167	0.208	0.356	0.539
NS	0.120	0.161	0.209	0.330	0.497
MB	0.181	0.211	0.294	0.426	0.547
MD	0.163	0.200	0.291	0.416	0.533
MR	0.154	0.190	0.291	0.432	0.558
MFA	0.173	0.185	0.276	0.403	0.563
ML	0.137	0.200	0.288	0.424	0.516
MHL	0.142	0.183	0.258	0.357	0.509
MS	0.114	0.183	0.209	0.361	0.501

Table 3. Superpave IDT results

Asphalt Mixture	Resilient Modulus [GPa]	Creep Compliance [1/GPa]	Tensile Strength [Mpa]	Faliure strain (µstrain)	Fracture Energy [kJ/m^3]	DCSE$_f$ [kJ/m^3]	DCSE$_{min}$ [kJ/m^3]
NB	18.32	2.45	1.71	1.224	1.43	1.345	1.399
ND	17.22	2.18	2.26	0.917	1.36	1.213	1.269
NR	17.36	2.14	1.60	1.335	1.38	1.307	1.164
NFA	18.31	2.37	2.08	1.078	1.44	1.326	1.336
NL	17.25	2.23	2.49	1.350	1.68	1.500	1.430
NHL	16.35	1.98	2.12	1.690	2.15	2.011	1.292
NS	16.80	3.72	2.65	1.010	1.98	1.771	1.847
MB	18.86	0.74	1.69	0.904	1.07	0.990	0.379
MD	19.14	0.99	1.30	1.549	1.74	1.705	0.335
MR	17.04	0.83	2.13	0.838	1.30	1.165	0.439
MFA	17.89	1.04	1.32	1.453	1.29	1.235	0.531
ML	16.30	1.12	2.56	1.750	2.86	2.658	0.877
MHL	15.32	0.82	2.45	1.965	2.99	2.788	0.866
MS	17.50	2.85	3.01	1.468	2.58	2.116	1.132

Table 4. Mastic MDTT results

Asphalt Mixture	Tensile Strength [Mpa]	Faliure strain (µstrain)	Fracture Energy [kJ/m^3]
NB	0.46	9.18	4.35
ND	0.41	12.75	4.29
NR	0.33	17.32	4.87
NFA	0.50	7.73	4.12
NL	0.52	15.62	5.12
NHL	0.58	16.32	6.30
NS	0.73	11.24	6.22
MB	0.43	12.34	3.12
MD	0.57	10.32	4.98
MR	0.40	13.23	3.98
MFA	0.63	7.43	4.01
ML	0.75	13.87	8.32
MHL	0.83	14.30	9.35
MS	0.76	12.12	8.12

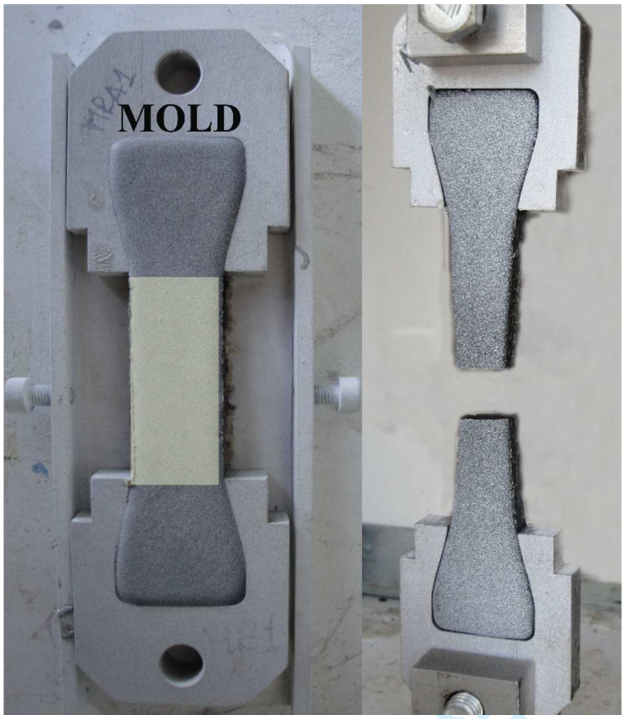

Figure 1. MDDT test configuration (on the left the area of interest for DIC)

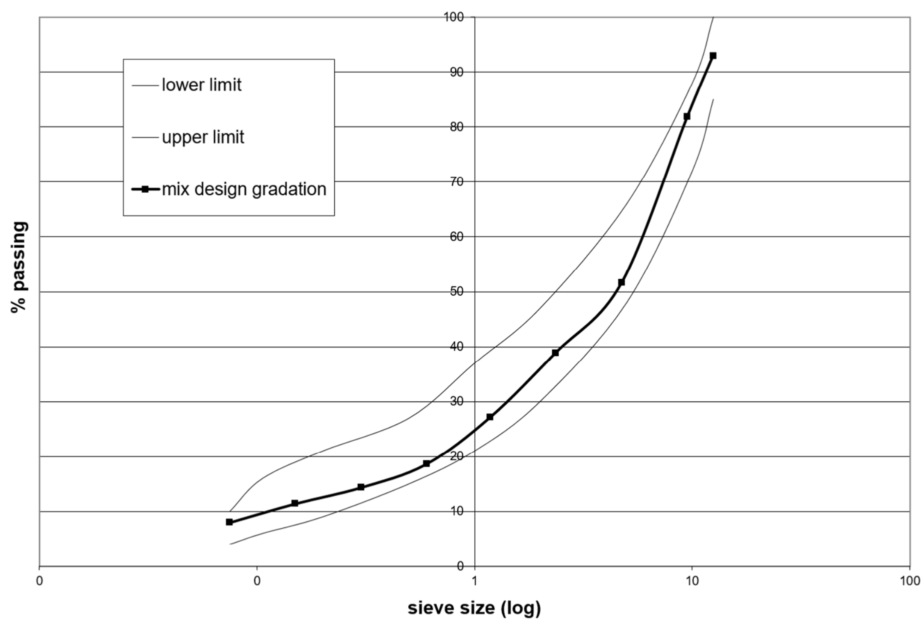

Figure 2. Aggregate gradation of the mixtures

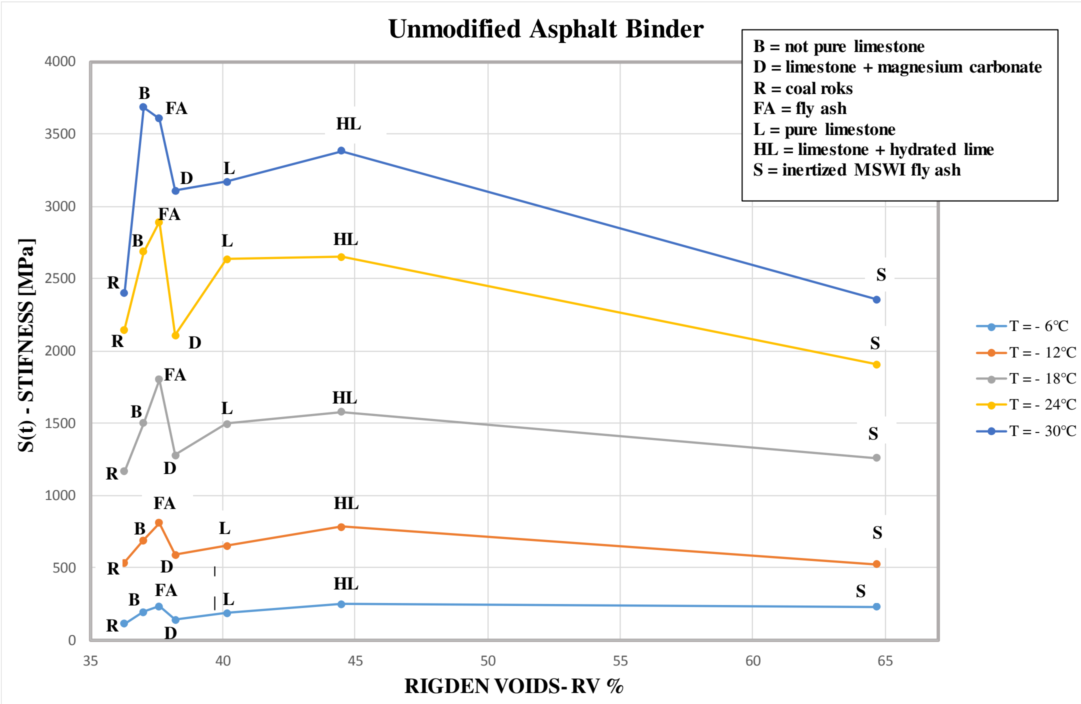

Figure 3. Stiffness of unmodified asphalt mastics according to Rigden Voids

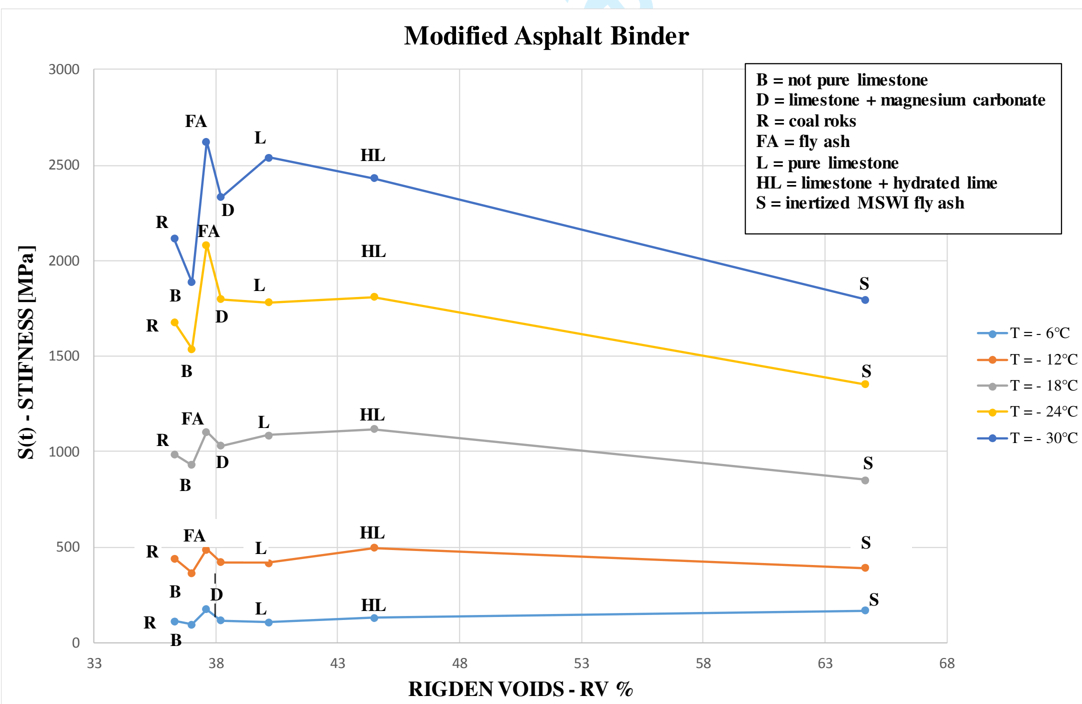

Figure 4. Stiffness of modified asphalt mastics according to Rigden Voids

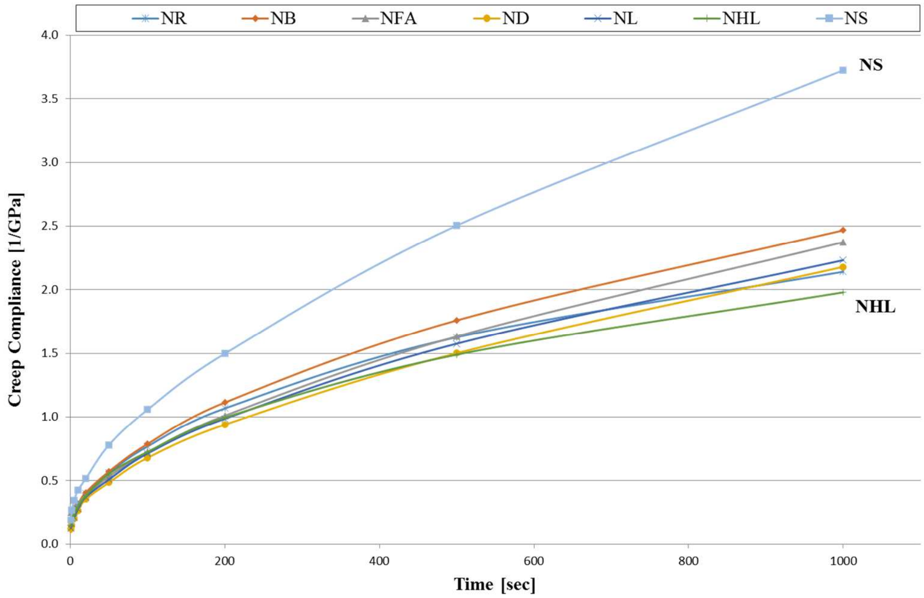

Figure 5. Creep Compliance Curves for unmodified mixtures

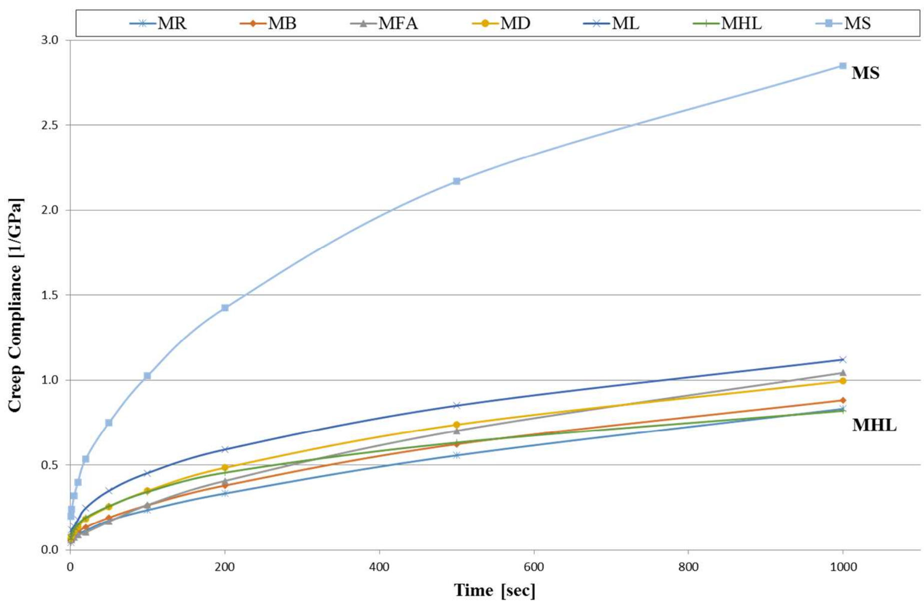

Figure 6. Creep Compliance Curves for modified mixtures

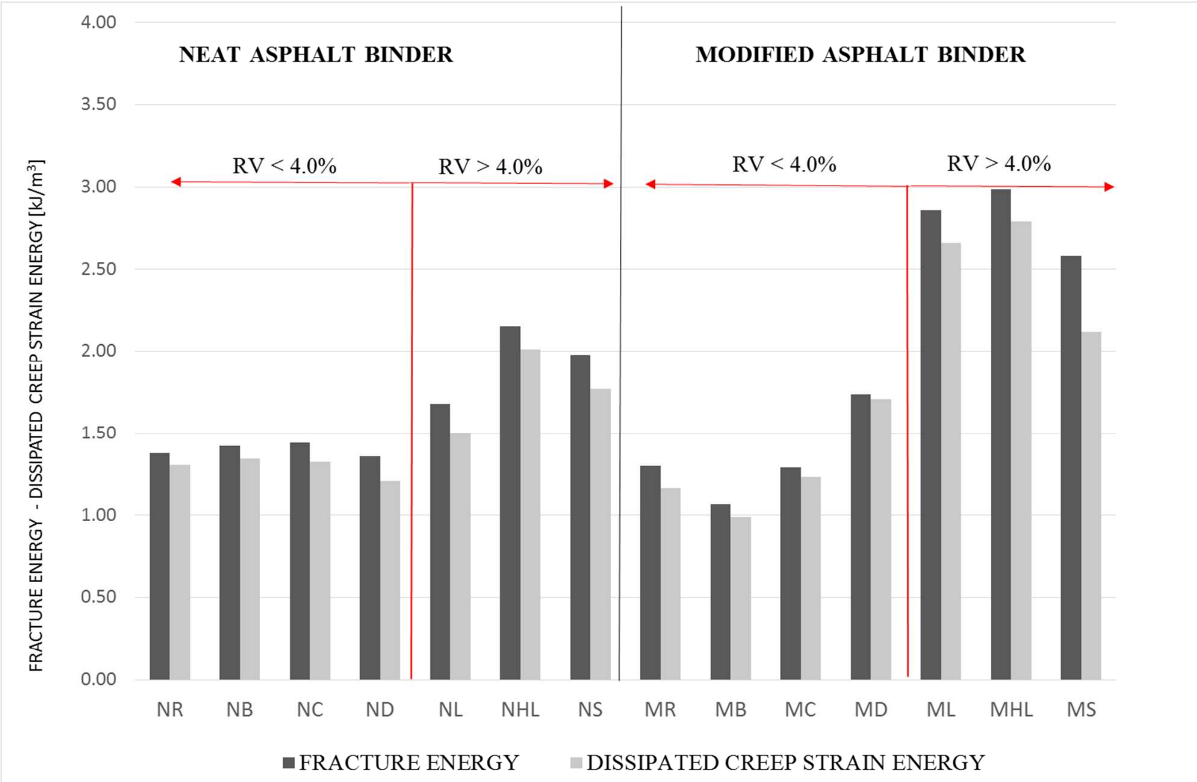

Figure 7. Fracture Energy and Dissipated Creep Strain Energy of mixes in function of Rigden Voids

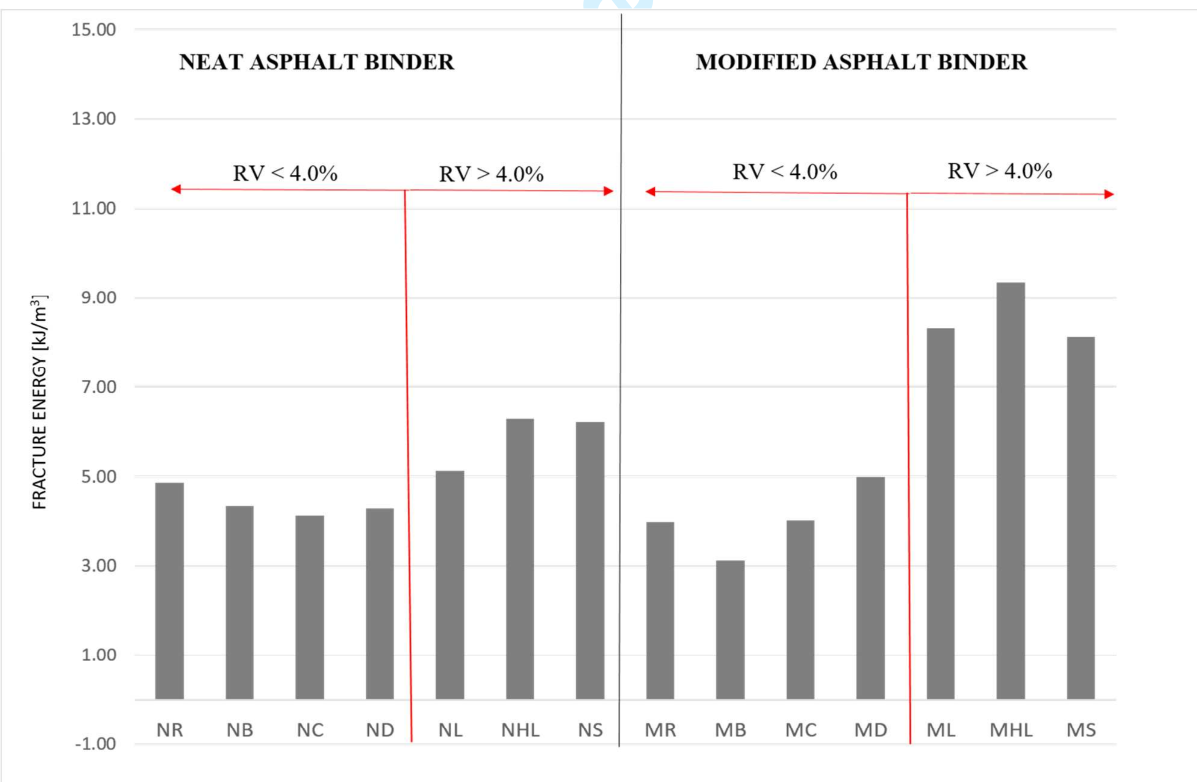

Figure 8. Fracture Energy of mastics in function of Rigden Voids

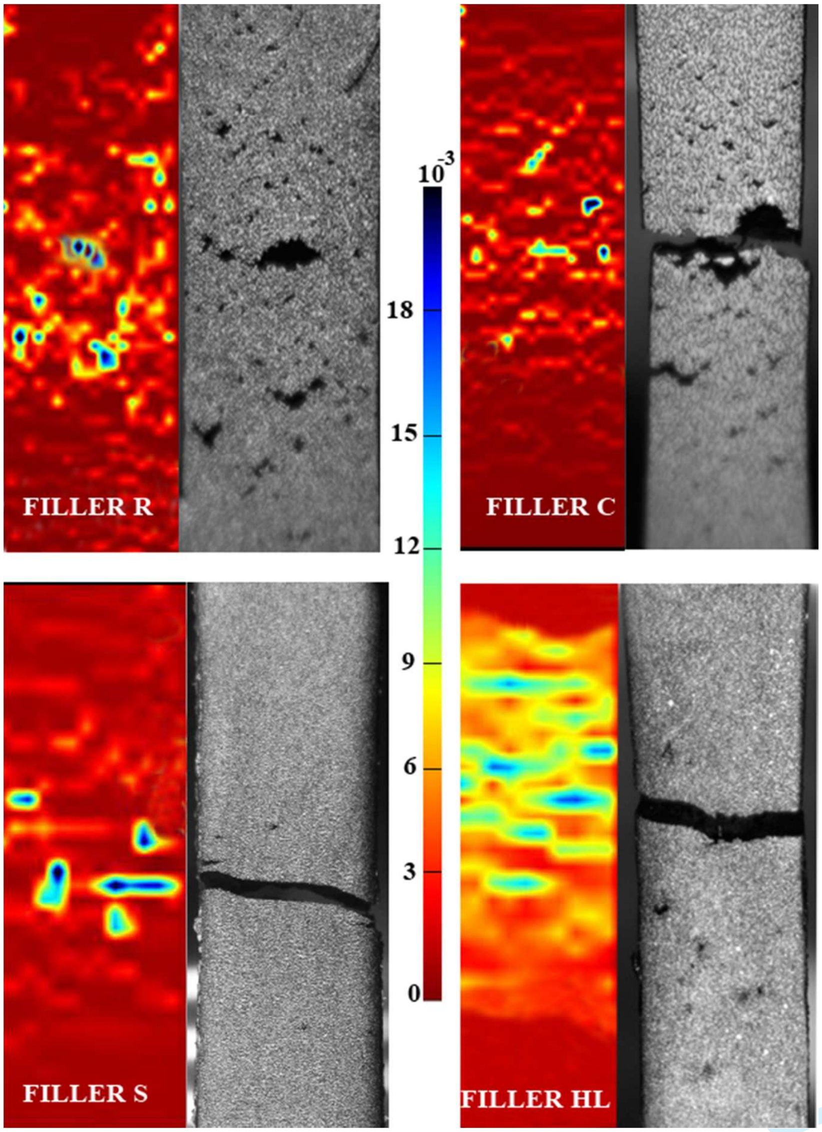

Figure 9. Crack patterns of mastics containing more critical fillers and unmodified binder