**AVALIAÇÃO DO COMPORTAMENTO AO DANO POR FADIGA
DE MATRIZES DE AGREGADO FINO PREPARADAS COM
LIGANTES ASFÁLTICOS MODIFICADOS**

A presente tese foi submetida ao Departamento de Engenharia de Transportes da Escola de Engenharia de São Carlos – Universidade de São Paulo (STT/EESC-USP) como parte dos requisitos para a obtenção do título de Doutor em Ciências.

Área de Concentração: Infraestrutura de Transportes

Orientador: Professor Associado Adalberto Leandro Faxina

AUTORIZO A REPRODUÇÃO TOTAL OU PARCIAL DESTE TRABALHO, POR QUALQUER MEIO CONVENCIONAL OU ELETRÔNICO, PARA FINS DE ESTUDO E PESQUISA, DESDE QUE CITADA A FONTE.

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FINE AGGREGATE MATRICES PREPARED WITH MODIFIED
ASPHALT BINDERS

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Advisor: Adalberto Leandro Faxina (Associate Professor)

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RESUMO

NG, A. K. Y. (2017). **Avaliação do comportamento ao dano por fadiga de matrizes de agregado fino preparadas com ligantes asfálticos modificados**. Tese (Doutorado em Ciências) – Departamento de Engenharia de Transportes, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos.

O processo de trincamento por fadiga ocorre devido ao carregamento dinâmico repetido do tráfego de veículos pesados. Este fenômeno tem o início por meio de microtrincas e se propaga por meio de duas condições: (i) após a ruptura adesiva, quando a trinca ocorre na interface entre agregado e mástique, e/ou (ii) após a ruptura coesiva, quando o processo de trincamento ocorre no mástique. Com base nesta interpretação para o trincamento por fadiga em mistura asfáltica, pesquisadores vêm usando matrizes de agregado fino (MAFs) para estimar o comportamento da mistura asfáltica completa quanto ao dano por fadiga. Boa correlação é observada entre as propriedades da MAF e da mistura asfáltica completa (MAC) em estudos relacionados ao dano por umidade, fadiga e deformação permanente. Com relação a resistência de pavimentos flexíveis, é importante avaliar o efeito do uso de ligantes asfálticos modificados e do envelhecimento do ligante nas propriedades da mistura asfáltica, uma vez que ligantes modificados podem melhorar o comportamento da mistura asfáltica quanto ao dano por fadiga, e o envelhecimento do ligante asfáltico pode enrijecer o material tornando-o mais frágil, reduzindo a vida de fadiga das misturas asfálticas. Levando em consideração as evidências apresentadas, este estudo tem por objetivo avaliar o efeito de ligantes asfálticos modificados e o nível de envelhecimento na vida de fadiga das MAFs, mástiques e ligantes asfálticos. Estas três escalas da mistura asfáltica completa foram compostas por quatro ligantes asfálticos (CAP 50/70, CAP+PPA, CAP+SBS e CAP+borracha) envelhecidos a curto e a longo prazo. As propriedades das três escalas quanto ao dano por fadiga foram avaliadas por meio dos conceitos da teoria do dano contínuo em meio viscoelástico (VECD), uma vez que esta teoria é capaz de prever o comportamento da mistura asfáltica independentemente do modo de carregamento (uniaxial ou torsional, tensão ou deformação controlada) e da amplitude do carregamento aplicado ao material para induzir o dano. De modo geral, os resultados indicaram que o uso de ligantes asfálticos modificados melhoram o comportamento das MAFs quanto ao dano por fadiga e o envelhecimento é capaz de comprometer o desempenho das MAFs quanto ao trincamento por fadiga. Na escala do ligante e do mástique asfáltico, o CAP+borracha apresentou o melhor desempenho à fadiga, ocupando o primeiro lugar no ordenamento final, e o CAP+SBS o pior desempenho, ocupando a última posição. Entretanto, na escala da MAF, as MAFs preparadas com CAP+SBS apresentaram o melhor desempenho à fadiga, ocupando o primeiro lugar no ordenamento final, e as MAFs preparadas com CAP 50/70 apresentaram o pior desempenho, ocupando o último lugar no ordenamento final. A melhor correlação entre as três escalas com relação ao envelhecimento a curto e a longo prazo, foi obtido entre os ligantes asfálticos e mástiques envelhecidos no PAV com as MAFs envelhecidas a longo prazo por 30 dias.

Palavras-chave: Matrizes de agregado fino, mástiques, ligantes asfálticos modificados, envelhecimento a curto prazo, envelhecimento a longo prazo, dano contínuo em meio viscoelástico (VECD).

ABSTRACT

NG, A. K. Y. (2017). **Evaluation of the fatigue damage behavior of fine aggregate matrices prepared with modified asphalt binders**. PhD. Dissertation (Doctor of Philosophy) – Department of Transportation Engineering, São Carlos School of Engineering, University of São Paulo, São Carlos. Brazil

The fatigue cracking process occurs by the repeated dynamic loading from the traffic of heavy vehicle. This phenomenon initiates as microcracks and develops under two circumstances: (i) after adhesive failure, when the crack occurs at the interface aggregate-mortar, and/or (ii) after cohesive failure, when the crack develops within the mortar. Based on such interpretation of the cracking phenomenon in asphalt concrete mixtures, researchers have been using the fine aggregate matrices (FAMs) to estimate the fatigue behavior of the asphalt concrete. Good agreement is observed between the properties of the FAM and asphalt concrete properties in studies related to moisture damage, fatigue cracking and permanent deformation. Regarding the fatigue resistance of the flexible pavements, it is important to investigate the effect of the use of modified binders and the binder aging on the fatigue properties of the asphalt concrete, once that the modified binder can enhance the fatigue behavior of the asphalt concrete, and the binder aging hardens the asphalt binder and turns it into a fragile material, with negative effects on the fatigue life of the asphalt concrete. Based on these evidences, this study has the objective of evaluating the effect of modified binders and aging level on the fatigue life of the FAMs, asphalt mastics and asphalt binders. The three scales are comprised of four asphalt binders (neat, AC+PPA, AC+SBS and AC+rubber) aged in short- and long-term. The fatigue properties of the three scales were evaluated by means of the viscoelastic continuum damage (VECD) concepts, once that this theory is able to predict the asphalt concrete behavior independent of loading mode (uniaxial or torsional), control mode (stress-control or strain-control), and amplitude loading applied to induce the damage. The overall results indicate that the addition of modified binder enhances the fatigue behavior and that extended aging is capable of compromise the fatigue performance. At the scales of the binder and the mastic, the AC+rubber presented the best fatigue performance, occupying the first position in the final rank order, and the AC+SBS presented the worst performance, occupying the last position. However, at the FAM scale, the FAMs prepared with the AC+SBS presented the best fatigue performance, occupying the first position in the final rank order, and the FAMs prepared with the neat binder presented the worst behavior, occupying the last position. The best correlation between the three scales regarding the short- and long-term aging was obtained between binder and mastics aged in the PAV with the FAMs aged in long-term for 30 days.

Keywords: Fine aggregate matrices, asphalt mastics, modified asphalt binders, short-term aging, long-term aging, viscoelastic continuum damage (VECD).

LIST OF FIGURES

Figure 2.1 – Stress-pseudo strain hysteresis in: (a) Strain-control mode; (b) Stress-control mode	58
Figure 3.1 – Aggregate gradation of the HMA and the FAM	70
Figure 3.2 – Binder contents of the HMA and of the FAMs according to some methods available in the literature	77
Figure 3.3 – (a) Mastic covering the aggregate after extraction with kerosene for the mixture compounded with the AC+rubber, and (b) particles of the mixture compounded with the AC+PPA with no mastic on the top	79
Figure 3.4 – Aggregate gradation for the HMA, the FAM, and the fines glued to the coarse portion.....	83
Figure 3.5 – Air voids distribution of the FAM samples extracted from the SGC specimens for the four asphalt binders	86
Figure 4.1 – Gradation distribution for the FAM and HMA	92
Figure 4.2 – Fabricated trays for long-term condition of FAM mixtures.....	94
Figure 4.3 – SGC Servopac	95
Figure 4.4 – FAM samples extracted from SGC specimens	95
Figure 4.5 – DSR model MCR-302 DSR	96
Figure 4.6 – FAM samples attached to the clamps	96
Figure 4.7 – Depicts of LVE range test	97
Figure 4.8 – Determination of the LVE range for the FAM prepared with the unmodified asphalt binder and aged in long-term (30 days).....	98
Figure 4.9 – Fitting of a four-serie Prony series to G' versus ω data	100
Figure 4.10 – Curve $G(t)_{predicted}$ versus time and adjust of the power law model.....	100
Figure 4.11 – Increment deformation in the LAS test.....	107
Figure 4.12 – Fatigue model.....	108
Figure 4.13 – Curve pseudo stiffness versus damage accumulation	109
Figure 4.14 – Comparison between the oscillation torque and da/dN curve (a), and oscillation torque curve and oscillation stress curve	110
Figure 4.15 – Increment deformation in the modified LAS test	111
Figure 5.1 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the neat binder as a function of the f/a ratio	115
Figure 5.2 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+PPA as a function of the f/a ratio and aging level.....	116
Figure 5.3 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+SBS as a function of the f/a ratio and aging level.....	117
Figure 5.4 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+RUBBER as a function of the f/a ratio and aging level.....	118
Figure 5.5 – A_f values for the asphalt mastics aged in short- and long-term	119
Figure 5.6 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the neat binder as a function of the aging level and the f/a ratio.....	121
Figure 5.7 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+PPA as a function of the aging level and f/a ratio.....	122
Figure 5.8 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+SBS as a function of the aging level and the f/a ratio.....	123
Figure 5.9 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+rubber as a function of the aging level and the f/a ratio.....	124
Figure 5.10 – A_f values for the asphalt mastics as a function of the aging level and the f/a ratio	125

Figure 5.11 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.00$	127
Figure 5.12 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.15$	127
Figure 5.13 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.30$	128
Figure 5.14 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.45$	129
Figure 5.15 – Comparison of the a_f values for the asphalt mastics as a function of the type of asphalt binder, aging level and f/a ratio	130
Figure 5.16 – Comparison of the fatigue curves as a function of f/a ratio for the mastics produced with the neat binder aged in short- and long-term.....	132
Figure 5.17 – Comparison of the fatigue curves as a function of f/a ratio for the mastics produced with the AC+PPA aged in short- and long-term	132
Figure 5.18 – Comparison of the fatigue curves as a function of f/a ratio for the mastics produced with the AC+SBS aged in short- and long-term	133
Figure 5.19 – Comparison of the fatigue curves as a function of f/a ratio for the mastics produced with the AC+rubber aged in short- and long-term	133
Figure 5.20 – Comparison of the fatigue curves as a function of aging level for the mastic produced with the neat binder for the f/a ratio equal to 0.00, 0.15, 0.30 and 0.45.....	134
Figure 5.21 – Comparison of the fatigue curves as a function of aging level for the mastics produced with the AC+PPA for the f/a ratio equal to 0.00, 0.15, 0.30 and 0.45.....	135
Figure 5.22 – Comparison of the fatigue curves as a function of aging level for the mastics produced with the AC+SBS for the f/a ratio equal to 0.00, 0.15, 0.30 and 0.45.....	135
Figure 5.23 – Comparison of the fatigue curves as a function of aging level for the mastics produced with the AC+rubber for the f/a ratio equal to 0.00, 0.15, 0.30 and 0.45.....	136
Figure 5.24 – Comparison of the fatigue curves as a function of the type of asphalt binder for mastic with $f/a=0.00$ and short- and long-term aging.....	137
Figure 5.25 – Comparison of the fatigue curves as a function of the type of asphalt binder for mastic with $f/a=0.15$ and short- and long-term aging.....	138
Figure 5.26 – Comparison of the fatigue curves as a function of the type of asphalt binder for mastic with $f/a=0.30$ and short- and long-term aging.....	138
Figure 5.27 – Comparison of the fatigue curves as a function of the type of asphalt binder for mastic with $f/a=0.45$ and short- and long-term aging.....	139
Figure 5.28 – Rank order of the asphalt mastics for the two strain levels (2 % and 20 %) and short-term aging.....	140
Figure 5.29 – Rank order of the asphalt mastics for the two strain levels (2 % and 20 %) and long-term aging	140
Figure 5.30 – Rank order of the asphalt mastics for short- and long-term aging	141
Figure 5.31 – Final rank order for the asphalt mastics.....	141
Figure 5.32 – Rank order of the RTFOT-aged asphalt binders for the two strain levels (2 % and 20 %)......	142
Figure 5.33 – Rank order of the PAV-aged asphalt binders for the two strain levels (2 % and 20 %)......	142
Figure 5.34 – Rank order of the asphalt binders for short- and long-term aging.....	143
Figure 5.35 – Final rank order for the asphalt binders.....	143

Figure 6.1 – Comparison of $ G^* $ (Pa) of the samples aged in short-term	146
Figure 6.2 – Comparison of $ G^* $ (Pa) of the samples aged in 30 days.....	147
Figure 6.3 – Comparison of $ G^* $ (Pa) of the samples aged in 60 days.....	147
Figure 6.4 – Comparison of the average $ G^* $ values for the FAMs produced with the four asphalt binders as a function of the aging level.....	148
Figure 6.5 – Comparison of the average δ values for the FAMs produced with the four asphalt binders as a function of the aging level.....	148
Figure 6.6 – Comparison of the m values of the samples aged in short-term	150
Figure 6.7 – Comparison of the m values of the samples aged in 30 days.....	150
Figure 6.8 – Comparison of the m values of the samples aged in 60 days.....	151
Figure 6.9 – Comparison of the average m values of the materials as a function of the aging level.....	151
Figure 6.10 – Comparison of the α values of the samples aged in short-term.....	152
Figure 6.11 – Comparison of the α values of the samples aged in 30 days	152
Figure 6.12 – Comparison of the α values of the samples aged in 60 days	153
Figure 6.13 – Comparison of the α values of the materials as a function of the aging level ..	153
Figure 6.14 – Curves C vs. S and the average curves C vs. S for the FAMs prepared with the neat binder and aged in short-term.....	154
Figure 6.15 – Curves C vs. S and the average curves C vs. S for the FAMs prepared with the AC+PPA and aged in short-term	154
Figure 6.16 – Curves C vs. S and the average curves C vs. S for the FAMs prepared with the AC+SBS and aged in short-term	155
Figure 6.17 – Curves C vs. S and the average curves C vs. S for the FAMs prepared with the AC+rubber and aged in short-term	155
Figure 6.18 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 30 days, prepared with the neat binder	156
Figure 6.19 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 30 days, prepared with the AC+PPA	156
Figure 6.20 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 30 days, prepared with the AC+SBS	156
Figure 6.21 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 30 days, prepared with the AC+rubber.....	157
Figure 6.22 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 60 days, prepared with the neat binder	157
Figure 6.23 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 60 days, prepared with the AC+PPA	158
Figure 6.24 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 60 days, prepared with the AC+SBS	158
Figure 6.25 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 60 days, prepared with the AC+rubber.....	158
Figure 6.26 – Average of C vs. S curves of the FAMs produced with the four asphalt binders and aged in (a) short-term, (b) long-term for 30 days, and (c) long-term for 60 days	159
Figure 6.27 – Effect of aging on the FAMs produced with the (a) neat binder, (b) AC+PPA, (c) AC+SBS, and (d) AC+rubber	160
Figure 6.28 – Fatigue curves and average fatigue curves of the FAMs produced with the (a) neat binder, (b) AC+PPA, (c) AC+SBS, and (d) AC+rubber, aged in short-term.....	162

Figure 6.29 – Fatigue curves and average fatigue curves of the FAMs produced with the (a) neat binder, (b) AC+PPA, (c) AC+SBS, and (d) AC+rubber, aged in long-term for 30 days.....	163
Figure 6.30 – Fatigue curves and average fatigue curves of the FAMs produced with the (a) neat binder, (b) AC+PPA, (c) AC+SBS, and (d) AC+rubber, aged in long-term for 60 days.....	164
Figure 6.31 – Average fatigue curves of the FAMs produced with the four asphalt binders and aged in short-term.....	165
Figure 6.32 – Average fatigue curves of the FAMs produced with the four asphalt binders and aged in 30 days	166
Figure 6.33 – Average fatigue curves of the FAMs produced with the four asphalt binders and aged in 60 days	166
Figure 6.34 – Average fatigue curves for the FAMs produced with the (a) neat binder, (b) AC+PPA, (c) AC+SBS and (d) AC+rubber as a function of the aging level ...	167
Figure 6.35 – Rank order of the FAMs for the two strain levels (0.1 % and 10 %) and short-term aging	168
Figure 6.36 – Rank order of the FAMs for the two strain levels (0.1 % and 10 %) and 30-days aging	169
Figure 6.37 – Rank order of the FAMs for the two strain levels (0.1 % and 10 %) and 60-days aging	169
Figure 6.38 – Rank order of the FAMs for short-term aging.....	169
Figure 6.39 – Rank order of the FAMs for 30-days aging.....	170
Figure 6.40 – Rank order of the FAMs for 60-days aging.....	170
Figure 6.41 – Final rank order for the FAMs.....	170

LIST OF TABLES

Table 3.1 – Calculations to obtain the FAM binder content according to the method proposed by Coutinho et al. (2011) and adapted by Freire (2015) and some additional information	78
Table 3.2 – Specific surface coefficients and the percentage of mineral aggregate for each sieve interval	85
Table 4.1 – Mineral aggregate characteristics	91
Table 4.2 – Mineral aggregate proportions for the FAM and HMA	92
Table 4.3 – Parameter used in the viscosity test	93
Table 4.4 – Mixing and compaction temperatures	93
Table 4.5 – LVE range for the FAM samples	98
Table 4.6 – Relative density for the filler and asphalt binders	106
Table 4.7 – Filler/asphalt ratios of the asphalt mastics, in volume	106
Table 5.1 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the neat binder as a function of the f/a ratio and aging level	114
Table 5.2 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+PPA as a function of the f/a ratio and aging level	115
Table 5.3 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+SBS as a function of the f/a ratio and aging level	116
Table 5.4 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+rubber as a function of the f/a ratio and aging level	117
Table 5.5 – A_f values for the asphalt mastics as a function of the f/a ratio and aging level ...	119
Table 5.6 – Relationships between the a_f values for the asphalt mastics produced with f/a = 0.15, 0.30 e 0.45 in relation to the asphalt binder (f/a = 0.00)	119
Table 5.7 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the neat binder as a function of the aging level and the f/a ratio	121
Table 5.8 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+PPA as a function of the aging level and the f/a ratio	122
Table 5.9 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+SBS as a function of the aging level and the f/a ratio	123
Table 5.10 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+rubber as a function of the aging level and the f/a ratio	123
Table 5.11 – A_f values for the asphalt mastics as a function of the aging level and the f/a ratio for the asphalt mastics, and the relationships between the a_f values for the PAV- and RTFOT-aged materials	125
Table 5.12 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for f/a=0.00, and the relationships between the parameters for the modified binders divided by the parameters for the neat binder	126
Table 5.13 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for f/a=0.15, and the relationships between the parameters for the modified binders divided by the parameters for the neat binder	127
Table 5.14 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for f/a=0.30, and the relationships between the parameters for the modified binders divided by the parameters for the neat binder	128

Table 5.15 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.45$, and the relationships between the parameters for the modified binders divided by the parameters for the neat binder	128
Table 5.16 – A_f values for the asphalt mastics as a function of the type of asphalt binder, aging level and f/a ratio	129
Table 5.17 – Relationships between the a_f values of the mastics produced with the modified binders divided by the a_f values of the mastic produced with the neat binder as a function of the aging level and the f/a ratios	130
Table 5.18 – Fatigue model for the asphalt mastics as a function of the type of asphalt binder, aging level and f/a ratio	131
Table 6.1 – Viscoelastic properties of the materials	145
Table 6.2 – Relaxations properties and damage evolution rate of the materials	149
Table 6.3 – Parameters A and B of the fatigue models	161
Table 6.4 – Final fatigue models	161
Table 7.1 – Correlations between the linear viscoelastic properties with the fatigue characteristics for the FAMs	173
Table 7.2 – Correlations between the A and B values of FAMs and binders	174
Table 7.3 – Correlations between the A and B values of FAMs and mastics ($f/a = 0.15$)	174
Table 7.4 – Correlations between the A and B values of FAMs and mastics ($f/a = 0.30$)	174
Table 7.5 – Correlations between the A and B values of FAMs and mastics ($f/a = 0.45$)	174
Table 7.6 – Correlations between the N_f values of the FAMs and the a_f values of the asphalt binders	175
Table 7.7 – Correlations between the N_f values of the FAMs and the a_f values of the asphalt mastics for $f/a=0.15$	175
Table 7.8 – Correlations between the N_f values of the FAMs and the a_f values of the asphalt mastics for $f/a=0.30$	176
Table 7.9 – Correlations between the N_f values of the FAMs and the a_f values of the asphalt mastics for $f/a=0.45$	176
Table 7.10 – Final rank order for the three scales	177

TABLE OF CONTENTS

1	INTRODUCTION	21
1.1	CONTEXTUALIZATION OF THE RESEARCH AND PROBLEM STATEMENT	21
1.2	APPROACH OF THE PROBLEM.....	24
1.3	OBJECTIVES	25
1.3.1	Main objective	25
1.3.2	Specific objectives	25
1.4	EXPERIMENTAL PLAN OUTLINE	26
1.5	CHAPTERS OF THE DISSERTATION	27
2	LITERATURE REVIEW	29
2.1	FAM – FINE AGGREGATE MATRIX	29
2.1.1	Micromechanical computational modeling.....	34
2.1.2	Viscoelastic continuum damage theory	37
2.1.3	Rheological properties	40
2.2	FAM DESIGN CHARACTERISTICS	41
2.2.1	Correlation between FAM and asphalt concrete.....	41
2.2.2	Nominal maximum aggregate size for FAMs.....	43
2.2.3	Compaction methods	44
2.2.4	Air voids content.....	46
2.2.5	Long term aging procedures for FAMs	49
2.3	LINEAR VISCOELASTIC PROPERTIES	51
2.4	VISCOELASTIC CONTINNUM DAMAGE THEORY (VECD).....	53
2.4.1	Work potential theory	53
2.4.2	Elastic-viscoelastic correspondence principles.....	55
2.4.3	Viscoelastic continuum damage	56
2.4.4	Fatigue life prediction model.....	60
2.5	ASPHALT MASTIC.....	60

3	STUDY OF FAM DESIGN METHODS.....	67
3.1	INTRODUCTION.....	67
3.2	MATERIALS AND TEST PROCEDURES	69
3.3	DETERMINATION OF THE FAM BINDER CONTENT	70
3.3.1	Method Proposed by Castelo Branco (2008)	71
3.3.2	Method proposed by Coutinho et al. (2011) and later adapted by Freire (2015)	72
3.3.3	Method proposed by Sousa et al. (2013).....	73
3.3.4	Determination of the FAM binder content by means of the specific surface of the mineral aggregate.....	74
3.3.5	Preparation of the FAM samples.....	76
3.4	RESULTS AND FINDINGS	76
3.4.1	Study of the FAM Design Methods	76
3.4.2	Method Proposed by Castelo Branco (2008)	77
3.4.3	Method Proposed by Coutinho et al. (2011) and Adapted by Freire (2015).....	77
3.4.4	Method Proposed by Sousa et al. (2013).....	81
3.4.5	Procedure based on the specific surface of the mineral aggregate.....	84
3.4.6	Air voids from samples produced using the FAM binder content obtained by means of the proposed procedure	85
3.4.7	Remarks on the determination of the FAM binder content by means of the procedure based on the specific surface method.....	87
3.5	CONCLUSIONS	89
4	MATERIALS AND METHOD	91
4.1	MINERAL AGGREGATES	91
4.2	ASPHALT BINDERS	92
4.3	FAM MIXTURES.....	94
4.3.1	FAM design method and preparation of the mixtures.....	94
4.3.2	Aging of the FAM mixtures	94
4.3.3	Compaction method	95
4.3.4	Sample preparation.....	95
4.4	TESTS IN THE DSR.....	96

4.4.1	Determination of the linear viscoelastic range of the samples.....	97
4.4.2	Fingerprint tests – linear viscoelastic properties.....	98
4.4.3	Damage tests	101
4.5	PROCEDURE OF ANALYSIS	102
4.5.1	Damage analysis	102
4.5.2	Prediction of fatigue life	103
4.6	ASPHALT MASTICS	105
4.6.1	Production of the asphalt mastics	105
4.6.2	Aging Mastic	106
4.6.3	DSR test	107
4.6.4	Linear amplitude sweep test (LAS)	107
5	ASPHALT BINDERS AND ASPHALT MASTICS.....	113
5.1	EFFECT OF THE FILLER/ASPHALT RATIO.....	113
5.1.1	Parameters A and B of the fatigue model	113
5.1.2	Fatigue damage tolerance index (a_f)	118
5.2	EFFECT OF THE AGING LEVEL.....	120
5.2.1	Parameter A and B of the fatigue model.....	120
5.2.2	Fatigue damage tolerance index (a_f)	124
5.3	EFFECT OF THE TYPE OF ASPHALT BINDER.....	126
5.3.1	Parameter A and B of the fatigue model.....	126
5.3.2	Fatigue damage tolerance index (a_f).....	129
5.4	FATIGUE CURVES.....	131
5.4.1	Effect of filler/asphalt ratio.....	131
5.4.2	Effect of the aging level.....	134
5.4.3	Effect of the type of asphalt binder.....	137
5.5	RANK ORDER BASED ON THE N_F VALUES	139
6	FINE AGGREGATE MATRICES.....	145
6.1	LINEAR VISCOELASTIC PROPERTIES	145
6.2	RELAXATION PROPERTIES AND DAMAGE EVOLUTION RATE.....	149

6.3	CHARACTERISTIC CURVES	153
6.4	FATIGUE MODELS.....	160
6.5	RANK ORDER BASED ON THE N_F VALUES	167
7	CORRELATIONS BETWEEN SCALES	173
8	CONCLUSIONS	179
8.1	FATIGUE BEHAVIOR OF THE ASPHALT MASTICS	180
8.2	FATIGUE BEHAVIOR OF THE ASPHALT BINDERS	181
8.3	FATIGUE BEHAVIOR OF THE FINE AGGREGATE MATRICES	181
8.4	RANK ORDER AND CORRELATIONS	184
8.5	FINAL REMARKS	185
8.6	SUGGESTIONS FOR FUTURE WORKS	187
9	REFERENCES.....	189

1 INTRODUCTION

1.1 CONTEXTUALIZATION OF THE RESEARCH AND PROBLEM STATEMENT

Most part of the Brazilian highways is composed of flexible pavements with a wearing course of asphalt concrete (AC). The AC is basically a mixture of asphalt binder, coarse and fine mineral aggregate particles, filler and, in some cases, additives (polymers, acids, fibers, reused materials, among others). The AC is a viscoelastic material because of the presence of the asphalt binder in its composition. The viscoelastic behavior of the AC is responsible for the material to behave as an elastic solid material under fast-moving loadings, and as viscous fluid material under slow-moving loading. Because of the viscoelastic behavior inherited from the asphalt binder, asphalt layers are prone to three main distress mechanisms: (i) fatigue cracking; (ii) rutting; and (iii) thermal cracking. Fatigue cracking is one of the most common distress mechanisms in flexible pavements, in Brazil and in the world (Medina, 1997; Y. H. Huang, 2004).

As far as the fatigue resistance of flexible pavements is concerned, there is a certain consensus in the literature that the main elements affecting this resistance are the asphalt binder and the mineral aggregate, the former more relevant than the latter. Due to the significant influence of the asphalt binder in the fatigue resistance of the asphalt concrete, researchers have been dedicating attention to modified asphalt binders, once that they are able to enhance the fatigue properties of the asphalt concrete. The polyphosphoric acid has been used since the 1970's, with the aim of increasing the rutting and fatigue resistance and decrease the thermal susceptibility without reducing the thermal cracking resistance of the asphalt concrete mixtures (Baumgardner, 2012; Baldino et al., 2013; Liu, Yan, You, Ge, & Wang, 2016). However, Edwards, Tasdemir, and Isacsson (2006, 2007) reported that the improvement in the mechanical properties of the asphalt concrete with the addition of the PPA depends on the composition of the base asphalt binder and the amount of PPA used to produce the modified binder. This was also observed by Pamplona (2013) after studying the incorporation of the PPA to binders obtained from different crude sources.

The styrene-butadiene-styrene copolymer (SBS) is another modifier widely used in Brazil and worldwide, because of its capability of increasing the resistance to fatigue cracking and rutting, and reducing the moisture susceptibility of the asphalt concrete mixtures (Fawcett &

McNally, 2001; Wen, Zhang, Zhang, Sun, & Fan, 2002; H. M. Park, Choi, Lee, & Hwang, 2009). On the other hand, the SBS presents some disadvantages, such as its high cost and the low resistance to aging, i.e., oxidation, once that the aging tends to reduce the molecular size of the SBS copolymer decreasing the elastic response of the asphalt concrete (Airey, 2003, 2004; Polacco, Stastna, Biondi, & Zanzotto, 2006).

The crumb rubber from the discarded tires is another efficient modifier. Besides the environmental advantages and the lower costs compared to other modifiers, the crumb rubber is capable of increasing the fatigue life and the thermal cracking resistance of the asphalt concrete mixtures and reducing the susceptibility to moisture damage (Epps et al., 1994; Hanson, Foo, Brown, & Denson, 1994; Kök & Çolak, 2011; Kök, Yilmaz, & Geçkil, 2013). Behnood and Olek (2017) evaluated the high- and low-temperature rheological properties of the neat binder and the asphalt binders produced with different proportions of SBS, PPA, and crumb rubber, and concluded that the three modifiers are capable of enhancing the high temperature-properties of the neat asphalt binder, while the crumb rubber is the modifier that decreases more the stiffness of the asphalt binder at intermediate and low temperatures.

Concerning the fatigue damage of the asphalt materials, it is also important to evaluate the effect of aging on the fatigue properties of the full mixtures, once that aging, by and large, is able to compromise the fatigue behavior of the asphalt concrete mixtures. The aging process initiates in the asphalt concrete production and continues along the pavement life. This effect occurs due to the transformation of maltenes in substances similar to asphaltenes, increasing the stiffness of the asphalt binder and resulting in more brittle material. Such stiffness increase can severely affect the fatigue life of the asphalt concrete. Bahia, Zhai, Bonnetti and Kose (1999) studied the effect of long-term aging on the properties of the asphalt binders aged in the PAV by means of time sweep tests in controlled strain mode and concluded that it increases the fatigue damage of the asphalt binder. Soenen and Eckmann (2000) observed that the fatigue resistance of the aged materials varies with the strain level suffered by the materials: the aged materials showed a high fatigue resistance at low strain level and a low fatigue resistance at high strain level.

The fatigue cracking process develops by means of the repeated dynamic loading from the traffic of heavy vehicles. This phenomenon initiates as microcracks due to traffic loading. Such microcracks give rise to macrocracks as the result of the crack propagation process and the coalescence of the microcracks. The presence of macrocracks reduces the structural performance of the pavement, with a negative impact on its service life. The final stage of the

cracking propagation on the asphalt layer is its complete failure. The microcracks are the begging of the fatigue process and develop in two circumstances: (i) after adhesive failure, when the crack occurs at the interface aggregate-mortar, and/or (ii) after cohesive failure, when the crack develops within the mortar. Based on such interpretation of the cracking phenomenon in asphalt concrete mixtures, it is plausible to use the fine aggregate matrices (FAMs) to estimate the fatigue behavior of the asphalt concrete mixtures. FAM is the matrix phase of the asphalt concrete composed of fine aggregates, filler, binder, and air voids. This phase represents an intermediate scale between the asphalt mastic and the asphalt concrete.

By assuming the hypothesis that the fatigue cracking initiates in the FAM scale, Y.-R. Kim, Little and Lytton (2003a), and Y.-R. Kim, Little and Song (2003b) started to study the fatigue cracking characteristics of the asphalt concrete mixtures using FAM specimens. The studies with FAM have been getting prominence since a good agreement between the FAM and AC properties was observed for the moisture characterization (Arambula, Masad, & Epps-Martin, 2007; Caro, Masad, Airey, Bhasin, & Little, 2008), and fatigue cracking and permanent deformation characterization (Motamed, Bhasin, & Izadi, 2012; Izadi, 2012; Coutinho, 2012; Gudipudi & Underwood, 2015; Im, You, Ban, & Kim, 2015; Nabizadeh, 2015; Haghshenas, Nabizadeh, Kim, & Santosh, 2016).

Other researchers have been using the FAM in order to evaluate the effect of healing on the fatigue properties of asphalt materials once that the healing increases the fatigue life of the asphalt concrete mixtures (Bhasin, Little, Bommavaram, & Vasconcelos, 2008; Palvadi, 2011; Palvadi, Bhasin, & Little, 2012). The effect of asphalt binder modified with warm mix asphalt additives on the moisture properties and fatigue properties of the asphalt materials has also been evaluated by means of studies with FAM, once that the reduction in the compaction temperature increases the fatigue resistance of the asphalt concrete mixtures (Vasconcelos, Bhasin, & Little, 2010; Tong, Luo, & Lytton, 2015; Cucalon, Kassem, Little, & Masad, 2017). FAMs have also been used to investigate the use of rejuvenating agents in asphalt concrete mixtures produced with recycled asphalt shingles (RAS) and recycled asphalt pavement (RAP), as an alternative to increase the fatigue life of the mixtures (Nabizadeh, 2015; Zhu, Alavi, Harvey, Sun, & He, 2017).

The effect of the long-term aging in the FAM properties must be studied, once that the aging of the asphalt binder is a relevant factor on the fatigue cracking resistance of asphalt concrete. Researchers have been using different techniques to simulate the long-term aging in FAM samples. Cravo, Correia and Silva, Leite and Motta (2016) simulated the thermal aging

in the FAM mixture produced with neat asphalt binder in the oven for 120 hours at 90° C, and the photochemical aging in a sunlight simulation chamber for 120 hours. Tong et al. (2015) placed the compacted FAM samples in a desiccator with the air at 60 °C in the chamber for 90 days in order to simulate the effect of long-term aging in the FAM mixtures prepared with warm-mix asphalt (WMA) additives. Arega, Bhasin and De Kesel (2013) aged the loose FAM mixture in an environmental room for 30 days at 60 °C, in order to simulate the long-term aging of FAMs prepared with WMA additives. Li, Karki, Hao and Bhasin (2015) followed the same aging procedure proposed by Arega et al. (2013) to reproduce the effect of long-term aging in the FAM mixtures produced with three different rock asphalts.

Apparently, fewer studies are available in the literature focusing on the evaluation of the effects that modified asphalt binders have on the fatigue life of the FAM. In the same manner, only a few studies are available in the literature regarding the effect of the aging level on the fatigue resistance of the FAM. These variables must be evaluated, once that, as a rule of the thumb, modified asphalt binder increases the fatigue life of the asphalt concrete mixtures and the extend aging reduces the fatigue resistance of the asphalt concrete.

Regarding the test parameters used to simulate the fatigue life of the asphalt materials, the loading rate or the frequency applied to the materials must also be taken into account, once that viscoelastic materials present different responses at different levels of frequency and loading (Bahia et al., 1999). In other words, the fatigue resistance is dependent upon a specific test configuration, including loading mode, loading frequency and loading amplitude. In order to overcome this limitation, the viscoelastic continuum damage (VECD) theory can be adopted. By means of this theory, it is possible to characterize the fatigue damage in asphalt concrete mixtures regardless of the loading mode and the test conditions (S. W. Park, Kim, & Schapery, 1996; (Lee & Kim, 1998a; Daniel & Kim, 2002).

1.2 APPROACH OF THE PROBLEM

The study of the rheological responses of the FAM scale was adopted in this research as a tool to characterize the fatigue damage accumulation. Such approach is based on the hypothesis that microcracks are the beginning of the fatigue process and that these microcracks start in discontinuities of the asphalt concrete, such as the air voids. The adoption of such approach was also motivated by experimental evidences showing good agreement between FAM and AC properties.

The decision for adopting the type of asphalt binder and the aging level as variables of interest in this research was based on the knowledge that the modified asphalt binders, in general, increase the fatigue life of the asphalt concrete mixtures, and that the extend aging, in general, reduces the fatigue resistance of the asphalt concrete. If the FAM properties have a good agreement with the AC properties, the study of the fatigue characteristics of the FAMs are going to be able to provide additional information on the fatigue behavior of the materials in terms of the influences imposed by the aging level and the binder modification.

The viscoelastic continuum damage (VECD) theory is a powerful tool that has been used to study the damage behavior of the asphalt materials, once that it permits the construction of the characteristic curve (C vs. S) of the materials. The main advantage of this theory is to build a unique characteristic curve for the materials that is independent of the loading mode (uniaxial or torsional), the control mode (stress-control or strain-control), and the loading amplitude applied to the FAM sample to induce the damage. The applicability of this theory in the characterization of fine aggregate matrices is also an issue that deserves deeper studies.

1.3 OBJECTIVES

1.3.1 Main objective

The main goal of this research is to evaluate the effect of different modified asphalt binders and different aging levels on the damage properties of three scales of the AC, which are the fine aggregate matrix, asphalt mastic and asphalt binder by means of the viscoelastic continuum damage (VECD) theory.

1.3.2 Specific objectives

The specific objectives of this research are:

- To compare the fatigue life of the asphalt binders, asphalt mastics, and FAMs prepared with modified asphalt binders aged in short- and long-term;
- To compare the linear viscoelastic properties ($|G^*|$ and α) of the FAMs prepared with modified asphalt binders in the unaged condition and aged in short- and long-term;
- To correlate the three scales using the parameters A and B of the fatigue model $N_f = A\gamma^B$ of the three scales, and using the fatigue damage tolerance index (a_f) of the binders and mastics with the fatigue life of the FAMs;

Another specific goal of this research arose with the difficulties found to define the asphalt binder content for the FAM produced with the modified asphalt binders. Due to these

difficulties was investigated the viability of using the specific surface concept (adapted from Arrambide and Duriez, 1959) to estimate the optimum binder content for the FAMs and compared with other FAM design methods presented in the literature.

1.4 EXPERIMENTAL PLAN OUTLINE

In order to achieve the objectives of this study, it was necessary to divide the experimental plan in two parts: the first one is related with the fabrication, aging conditioning and tests carried out with the FAMs, in order to evaluate the effects of the type of asphalt binder and the aging levels on the FAM properties. The second part follows the same pattern for the FAMs, but it is applicable to the asphalt binders and mastics.

The fine aggregate matrices were produced with basalt rock, the nominal maximum aggregate size of 2.00 mm, and four asphalt binders (neat binder, AC+PPA, AC+SBS, AC+rubber). The FAM samples were conditioned to short-term aging according to the procedure AASHTO R30. For the long-term aging conditioning, the loose FAM mixtures were placed in trays and conditioned in a ventilated oven at 60 °C for 30 and 60 days. The FAM samples were compacted in the Superpave gyratory compactor. After extraction by means of a diamond drill, the ends of the cylindrical samples were cut off. The linear viscoelastic properties of the samples were obtained by means of the frequency sweep test in controlled stress mode (15 kPa) at 25° C. The damage properties of the FAMs were evaluated by means of the time sweep test under different stress levels at 1 Hz and 25 °C, and the VECD theory.

The asphalt mastics were produced with basaltic rock and the same four asphalt binders. Four filler/asphalt ratios (0.00, 0.15, 0.30 and 0.45), in volume, were used to produce the asphalt mastics. The asphalt binders and mastics were conditioned to the rolling thin-film oven (RTFO) test to simulate the short-term aging as per ASTM D2872-12e1. In sequence, the RTFOT residue was aged in the pressurized aging vessel (PAV) to simulate the long-term aging as per ASMT 6521-13. The rheological characterization of the asphalt mastics was carried out in the dynamic shear rheometer (DSR). The linear viscoelastic properties of the asphalt binders and mastics were obtained by means of frequency sweep tests. In sequence, with the same sample, the linear amplitude sweep (LAS) test in controlled strain mode, proposed by Hintz (2012), was carried out in order to define the damage properties of the asphalt materials. The frequency and time sweep tests were run at 25° C.

1.5 CHAPTERS OF THE DISSERTATION

Chapter 1 presents the initial considerations of this dissertation, the contextualization of the study and the statement of the problem, the approach of the problem, the main and secondary objectives, the experimental plan outline and the structure of the dissertation. Chapter 2 presents some relevant studies related to FAM in order to evaluate the moisture, permanent deformation, fatigue, healing and damage characteristics. It is also presented a discussion regarding the volumetric properties adopted for the fabrication of the FAMs and the aging procedures used to simulate the long-term aging in FAM samples. An introduction of the concepts of the viscoelastic continuum damage theory is also presented in this chapter. Some studies with asphalt mastic were presented in order to illustrate the importance of this topic on the study of the fatigue performance of asphalt concrete mixtures.

Chapter 3 will discuss the applicability of some FAM design methods present in the literature for the FAMs prepared with modified asphalt binders, the limitations in the replication of those methods when modified asphalt binder are used, and the viability of using the specific surface concept to estimate the FAM binder content. Chapter 4 provides a detailed description of the materials and procedures used to produce the FAM samples and asphalt mastics, the description of the procedures adopted to age the three scales in short- and long term, the details about the tests carried out with the three scales, and an explanation of how the VECD will was used to treat the data.

Chapter 5 presents the results for the FAMs prepared with the four asphalt binders and aged in the three aging levels. These results cover the linear viscoelastic properties, the relaxation rate and the damage evolution rate, the characteristic curves (curve C vs. S), the fatigue models, and the rank order for the materials considering the effects of the type of asphalt, the aging level and the strain level on the fatigue life. Chapter 6 presents the results for the asphalt binders and mastic prepared with the four asphalt binders, both aged in short-and long-term. These results cover the effect of the f/a ratio, the aging level, and the type of asphalt binder on the parameters A and B of the fatigue models and on the fatigue damage tolerance index (a_f), followed by the rank order of the materials. At the end of this chapter, correlation between the fatigue characteristic of the three scales are presented. Chapter 7 is dedicated to the conclusions of the research, the final remarks and the suggestions for future work. At the end of the document, a list of the references mentioned in the text is presented.

2 LITERATURE REVIEW

The main objects of this chapter are (i) a brief presentation of studies that assess moisture, permanent deformation, fatigue, and healing characteristics for different materials by means of samples of fine aggregate matrix; (ii) presentation of studies discussing about the different nominal maximum aggregate sizes for the mineral aggregate, the volumetric properties and the aging process adopted for the FAMs; (iii) presentation of the concepts used to define the linear viscoelastic properties of the materials, (iv) an introduction of the viscoelastic continuum damage (VECD) theory that has been adopted in this study to assess the damage characteristics of the FAM samples, and (v) presentation of some relevant studies on asphalt mastics.

2.1 FAM – FINE AGGREGATE MATRIX

Fatigue cracking is one of the most common distresses found in asphalt pavements. This phenomenon initiates as microcracks that coalesce to form macrocracks as the result of the crack propagation process. The microcracks are the begging of the fatigue process and are supposed to start in the fine aggregate matrix (FAM). Y.-R. Kim et al. (2003a) and Y.-R. Kim et al. (2003b) followed this approach and started to study the fatigue cracking characteristics of asphalt concrete mixtures using FAM specimens.

FAM is the matrix phase of the asphalt concrete composed of fine aggregates, filler, binder, and air voids. This phase represents an intermediate scale between the asphalt mastic and the asphalt concrete. Y.-R. Kim et al. (2003a) and Y.-R. Kim et al. (2003b) assumed that the FAM can be associated with the fatigue behavior of the asphalt concrete, since the damage in the AC initiates as microdamage in the form of microcracks in the matrix phase. The fine aggregate matrix presents an internal structure that is more homogenous than the one represented by the asphalt concrete (Masad, Zollinger, Bulut, Little, & Lytton, 2006). Another advantage of this matrix is the reduced size of the samples, which represents a considerable reduction in material consumption and laboratory work compared to the amount of material and time required to work with asphalt concrete specimens.

Due to the advantages and assumptions mentioned above, Y.-R. Kim et al. (2003a) and Y.-R. Kim et al. (2003b) studied the effect of mineral fillers in the asphalt concrete mixtures regarding the fatigue and healing behaviors using samples made of sand asphalt. In these studies, the FAM samples were produced with mineral aggregate particles smaller than 1.18 mm (sieve #10) and a binder content of 8 %. Regarding the FAM binder content, the

authors took into account the binder content required to produce a “film thickness” of about 10 microns around the mineral aggregate particles. The first FAM samples were prepared with two different neat binders or mastic (filler asphalt proportion of 10 %) and mixed with Ottawa sand at the mixing temperature. The FAMs were compacted in a specially fabricated mold with 50 mm in height and 12 mm in diameter, at the compaction temperature, with air voids of approximately 17 %.

Following the studies previously cited, Y.-R. Kim and Little (2005) proposed a protocol using FAM samples tested in the dynamic mechanical analyzer (DMA), in order to characterize the fatigue behavior of the asphalt concrete mixtures in the dry and wet conditions. The dynamic tests were carried out in controlled strain mode, with low strain level to characterize the linear viscoelastic properties of the material, and high strain level to induce damage in the sample. The procedure was used to identify the effect of filler type (limestone and hydrated lime), and modifier type (SBS, EVA, ELVALOY, and crumb-rubber) in the asphalt concrete. The fatigue life for each mixture was estimated using a mechanical model for fatigue life prediction based on the continuum damage mechanics as proposed by Lee, Daniel and Kim (2000) and adapted by the authors for the torsion loading. They concluded that the hydrated lime (as filler) and rubber (as asphalt modifier) increased the fatigue life of the asphalt concrete mixtures due to the lower rate of the damage evolution and higher capacity to accumulate damage during the damage tests.

Researchers from Texas A&M University made a lot of progress in the studies related to FAMs in order to investigate the fatigue cracking, moisture damage, and healing characteristics of asphalt concrete mixtures using the DMA (Zollinger, 2005; Masad et al., 2006; Bhasin, 2006; Arambula et al., 2007; Little, Bhasin, & Hefer, 2007; Masad, Castelo Branco, Little, & Lytton, 2008; Caro et al., 2008; Castelo Branco, Masad, Bhasin, & Little, 2008; Vasconcelos et al., 2010; Vasconcelos, Bhasin, Little, & Lytton, 2011). One of the main contributions presented by this research group is related to the compaction method for the FAM samples. Zollinger (2005), in an attempt to reproduce the compaction procedure proposed by Y.-R. Kim et al. (2003a) and Y.-R. Kim et al. (2003b), reported some problems regarding the air voids distribution along the sample length. The FAM samples compacted in the specially fabricated mold presented higher air voids at the ends of the samples, resulting in cracks in the sample edges.

In order to overcome this issue, a new fabrication method was developed by Zollinger and other researchers. In this new procedure, the cylindrical FAM samples are extracted from

the specimens compacted in the Superpave Gyrotory Compactor (SGC). The loose FAM mixture is compacted in the SGC mold of 152 mm in diameter until achieving the air voids of 11 % and height of 85 mm. The extraction the FAM samples from the SGC specimens is considered efficient, once it is possible to produce a more uniform sample and to control the air voids during the sample preparation, besides being a less time-consuming process. Due to these reasons, the compaction method for the FAM mixtures presented by Zollinger (2005) has been adopted in studies with FAM.

Following the fabrication method presented by Zollinger (2005), Zollinger (2005) and Masad et al. (2006) studied the effect of moisture damage in asphalt concrete mixtures. They proposed an index that relates the crack growth due to moisture damage as a function of a chemical property (bond energy) and mechanical properties [compliance and rate of accumulation of dissipated pseudostrain energy (DPSE or WR)] of the mixture. The researchers adopted the micromechanics approach to investigate the chemical properties and the continuum damage mechanics to evaluate the mechanical properties. The micromechanics is based on the fracture mechanics approach. In this approach, the crack length is a physical element that grows continuously. The fracture mechanics approach was used to define the crack growth model by the Paris law for viscoelastic materials, where the DPSE is written in terms of the J-integral. For the researchers, the mixture with a good combination between the asphalt binder and mineral aggregate presents the ratio of the adhesive bond energy under dry conditions to the adhesive bond energy under wet conditions $\left| \Delta G^{a(D)} / \Delta G^{a(W)} \right|$ higher than 0.8.

Using the micromechanics approach, Zollinger (2005) and Masad et al. (2006) were able to identify the mixtures with good and poor performance. The researchers defined the mixture performance (i) by the ratio of the shear modulus at failure to the initial shear modulus (G'/G) (Lytton, 2004) and (ii) by the ratio of the number of cycles to failure under wet to dry condition $[N_{f(wet)} / N_{f(dry)}]$. For the mixtures with good resistance to moisture damage, the ratio for G'/G is high, i.e., the dynamic modulus at failure is close to the initial dynamic modulus. However, the parameter G'/G for the eight mixtures investigated by Zollinger (2005) and Masad et al. (2006) did not correlate well with the mixtures performance observed in the field, indicating that is not appropriate to define a 50 % reduction in the mixture stiffness as a fatigue failure criterion.

Furthermore, Zollinger (2005) and Masad et al. (2006) reported that it is inaccurate to calculate the DPSE or WR based only on the changes in the viscoelastic properties (WR1). This observation was done due to the nonuniform permanent deformation observed during the test

once the stress-pseudostrain relationship has been applied in the continuum damage mechanics approach to separate the dissipated energy resulting from damage from the viscoelastic energy.

Regarding the observations made by Zollinger (2005) and Masad et al. (2006) on the DPSE or WR, Masad et al. (2008) developed a new method that is able to separate the dissipated energy due to permanent deformation from the viscoelastic energy. Masad et al. (2008) assumed that during the damage process, the dissipated energy can be associated with three mechanisms: (i) an increase in the phase angle between loading cycles (WR1), (ii) a change in the phase angle for the same loading cycle due to permanent deformation (WR2), and (iii) a difference in the pseudo-stiffness of the material before and after damage (WR3).

Based on the considerations to calculate the DPSE, Masad et al. (2008) proposed two fatigue damage parameters using the fracture model based on Paris's law for viscoelastic materials. These two parameters are (i) the projected crack growth index $\Delta R(N_f)$ at a fixed number of cycles and (ii) the ratio of $\Delta R(N_f)$ to $\text{Log}(N)$. They adopted these two parameters due to the lower coefficient of variation in comparison to the other parameters presented in the literature. Based on the previous assumptions, Masad et al. (2008) developed a procedure to characterize the asphalt concrete mixtures resistance to fatigue cracking using FAM samples based on the DPSE and in the concepts of the modified Schapery's theory. The proposed method is capable of unifying the results from the tests run in controlled-stress and controlled-strain modes.

Many researchers validated the method suggested by Masad et al. (2008). Castelo Branco et al. (2008), and Castelo Branco (2008) replicated the method for different levels of strain and stress to investigate the fatigue resistance of asphalt concrete mixtures. The values for the crack growth index $R(N)$ from the tests performed in the controlled-stress and controlled-strain modes were similar, confirming that the method proposed by Masad et al. (2008) is independent of the loading mode. In order to compare the susceptibility of four asphalt concrete mixtures to moisture damage, Caro et al. (2008), following the method proposed by Masad et al. (2008), used the ratio of the $\Delta R(N)$ parameter for the wet FAM samples to the dry FAM samples. The results were analyzed using a probabilistic approach, and the authors reported a good correlation between the results for the FAM and the asphalt concrete results.

Vasconcelos et al. (2010) adopted the approach proposed by Masad et al. (2008) to assess the effect of the reduction of the compaction temperatures of six warm mix asphalts (WMA) produced with synthetic zeolite under fatigue cracking and moisture damage. One of the main

findings of this study was that the reduction in the compaction temperature reduces the fatigue resistance of the mixtures.

However, Cucalon et al. (2017) characterized different FAMs (aggregate type, binder type) modified with some additives for warm mix asphalts and concluded that (i) in regard to modification, WMA additives increase the fatigue resistance of the asphalt concrete before and after aging, (ii) regarding moisture damage, the FAM mixes with similar performance in the dry condition may not present the same performance in the wet condition and (iii) the WMA additives can perform differently when combined with different aggregates. The conclusion regarding the effect of different types of aggregate in the WMA mixture performance reported by Cucalon et al. (2017) can justify the conclusion made by Vasconcelos et al. (2010) about the effect of using WMA additives, once Vasconcelos et al. (2010) investigated only one type of aggregate.

Tong et al. (2015) evaluated the effect of aging and water vapor diffusion in the fatigue crack growth of the unmodified FAM mixtures and FAMs modified with WMA additives, by means of the controlled-stress repeated direct tensional (RDT) method proposed by Tong, Luo, and Lytton (2013). This procedure proposes to characterize the FAM samples to moisture damage using the micromechanics approach defining the DPSE based on the modified Paris law. Tong et al. (2015) conditioned the FAM samples at two relative humidity levels (0 % and 100 %), to simulate the effect of moisture damage, and two aging conditions (0 and six weeks in the desiccators at 60 °C), to simulate the effects of aging in the mixture. Based on the results from the controlled-stress repeated direct tensional (RDT), the author concluded that moisture and aging are significant factors for fatigue cracking growth in the FAM, and that the FAM samples presented a faster crack growth for a higher level of relative humidity. Concerning the application of the protocol proposed by Tong et al. (2013), the authors concluded that the new protocol is more efficient than the torsional test because the complexity of the stress state within the sample is reduced.

Regarding the healing properties of the FAMs, Bhasin et al. (2008) proposed a new framework able to predict the effect of healing in the FAM mechanical properties, combining material properties and mechanical properties based on the crack growth mechanism. Six FAMs produced with two types of aggregate (granite and gravel) and three types of bitumen (PG 58-28, PG 64-16, and PG 58-10) were tested to evaluate the healing effect in the mechanical properties of the FAMs. The test procedure proposed by Bhasin et al. (2008) consists of nine rest periods of four minutes after cycles that correspond to 2.5, 5, 10, 15, 20, 25, 30, 40, and

50 % of the fatigue life value of the specific material tested without rest periods. A relative increase in the fatigue life due to the introduction of the rest periods was observed for the FAMs. It was found that it correlates well with the results for the asphalt binders, indicating that the framework proposed by Bhasin et al. (2008) is capable of characterizing the effect of healing in the mechanical properties of the FAMs.

2.1.1 Micromechanical computational modeling

Some researchers discuss the limitations presented by the analytical micromechanics approach to characterize the damage of asphalt concrete mixtures. Y.-R. Kim, Allen and Little (2005) and Aragão, Kim, Karki and Little (2010) mention that in the analytical micromechanics some properties of the asphalt concrete, such morphological characteristics of the particles as heterogeneity and interactions between the mixture elements, are not properly related to the material response. This limitation can lead to some unreliable results because of the simplifying hypotheses that must be adopted. In order to overcome such limitations, the computational micromechanical modeling approach has been adopted to predict the damage in the asphalt concrete resulting from mechanical loading.

This approach takes into account the (i) morphological characteristics of the aggregate particles, (ii) mixture heterogeneity, and (iii) inelastic mechanical behavior. A finite element modeling (FEM) technique has been developed to explicitly simulate cracking in the viscoelastic medium as a gradual phenomenon using the cohesive zone model (CZM) concept. To simulate the crack growth and the damage evolution due to mechanical load, an interface fracture is modeled based on a micromechanical nonlinear viscoelastic cohesive zone model (CZM). Properties related to each mixture element and damage resulting from loading are used as inputs.

Another advantage of the computational micromechanical modeling is related to the number of tests. It is not necessary to run a new set of tests with the full mixture in order to simulate a different mixture, once the micromechanical modeling uses properties of each phase of the mixture as input for the model. For that reason, it is only necessary to run tests to characterize the properties of each mixture phase. Regarding the phases that comprise the asphalt concrete, a typical asphalt concrete structure can be divided into two phases: the coarse aggregate and the matrix phase. In order to define the linear viscoelastic and fracture properties of the matrix phase, the FAM has been used to represent the second element of the asphalt concrete.

Due to the limitations presented by the analytical micromechanics approach, Aragão et al. (2010) proposed a FEM computational model to predict the dynamic modulus of the asphalt concrete. To take the effect of the mixture heterogeneity and the inelastic behavior of the materials into account, the authors characterized separately the properties of (i) aggregate particles, (ii) matrix phase, and (iii) asphalt concrete, by means of laboratory tests. Some digital image analysis techniques were used to study the microstructure that comprises the asphalt concrete.

Aragão et al. (2010) produced FAM samples with aggregate particles smaller than 0.30 mm to represent the matrix phase of the asphalt concrete. The FAM samples were designed with the same apparent density for the asphalt concrete specimen and were extracted from SGC specimens. Dynamic frequency sweep tests were performed to define the linear viscoelastic properties of the matrix phase, one of the inputs for the computational modeling proposed by the authors.

Aragão et al. (2010), based on the dynamic modulus predicted by the proposed computational micromechanics modeling, concluded that at higher loading frequencies the predicted dynamic modulus matches the dynamic modulus from the experimental test. However, at lower frequencies, the predicted dynamic modulus presented a considerable deviation from the experimental values.

In order to predict the cracks that arise from the fracture damage, Aragão, Kim, Lee and Allen (2011) took the effect of the microscale fracture damage of the matrix phase into account, besides other factors cited by the authors. FAM Mode I fracture test were conducted to determine cohesive zone fracture properties used as model input.

The Mode I fracture test was carried out following the procedure suggested by Freitas (2007) to measure fracture properties in viscoelastic solids. In summary, using (i) the linear elastic properties of aggregate particles, (ii) the linear viscoelastic properties of asphalt matrix phase, and (iii) the cohesive zone fracture properties as inputs for the FEM model, Aragão et al. (2011) obtained good correlations between predicted and experimental values.

In order to investigate other complex characteristics of the asphalt concrete, Aragão and Kim (2012) recommended a new procedure to characterize the Mode I fracture behavior of the asphalt concrete. In this new protocol, the matrix phase is subjected to a wide range of loading rates (1, 5, 10, 25, 50, 100, 200, 400, and 600 mm/min) at an intermediate temperature to evaluate the effects of rate dependence of the asphalt concrete.

Aragão and Kim (2012) tested the FAM in the form of semi-circular bending (SCB) test geometry at 21°C to characterize the cohesive zone fracture properties of the mixture. The test results were obtained from the digital image correlation (DIC) system. This system was used to monitor the initial notch tip of the SCB specimen. The DIC results were simulated using finite element modeling combined with material viscoelasticity and cohesive zone fracture model. Aragón and Kim (2012) obtained good agreement between DIC results and numerical simulations and concluded that the FAM fracture properties are clearly rate-dependent at intermediate temperatures.

Based on the conclusion presented by Aragón and Kim (2012) that the FAM fracture properties are rate-dependent, Y.-R. Kim and Aragón (2013) proposed to implement a rate-dependent cohesive zone model in the finite element modeling to predict the mechanical behavior of asphalt concrete mixtures. The authors compared the results of three-point bending tests of asphalt concrete beam specimens at 21°C with microstructure simulations and obtained a good agreement with experimental results, except for the low displacement condition.

Y.-R. Kim and Aragón (2013) suggested, as future work, some improvements to the proposed model and one of them was related to the characterization of mode-dependent fracture properties. Im, Ban and Kim (2014) presented an experimental and numerical approach for the characterization of fracture properties of FAM in Mode I and Mode II at intermediate temperature using the SCB geometry test. The authors used extended finite element method (XFEM) techniques to integrate the experimental results from SCB test to simulate arbitrary crack growth, one of the drawbacks of the FEM, to obtain a more realistic characterization of the asphalt concrete. Im et al. (2014) discussed the importance of including the mode-dependent fracture properties in the characterization of the asphalt concrete, once the experimental results and model simulations pointed out that the fracture properties of the asphalt concrete are mode-dependent. The fracture properties of the fracture modes have shown to be very different: for example, the cohesive zone fracture toughness in Mode II is three times greater than in mode I. In other words, the FAMs showed higher resistance in shear mode fracture than in opening-mode fracture.

This study from Im et al. (2014) was extended for the mixed-mode fracture test by Ban, Im and Kim (2015). However, the results predicted by the model showed some divergences from the experimental data. The authors explain that this difference can be related to the approaches used in the modeling, once that they believe that this difference between the results

can decrease with the combination of the computational modeling proposed by Im et al. (2014) with a material inelasticity model and a three-dimensional simulation.

Aragão, Hartmann, Kim, Motta and Haft-Javaherian (2014) improved the numerical-experimental approach recommended by Araújo and Kim (2012) in order to investigate the influence of different loading configurations to characterize Mode I fracture. The loading configurations evaluated by Araújo et al. (2014) were (i) the SCB test; (ii) the single-edge notched beam [SE(B)] test; (iii) the disk-shaped compact tension test [DC(T)], and (iv) the indirect tension test. The FAM was prepared with an asphalt binder PG 70-28 and fine aggregates smaller than 2.00 mm. Based on the simulated and experimental results of the FAMs tested at -10°C and displacement rate of 1 mm/min, the authors concluded that the fracture properties are not dependent on loading configurations and geometric characteristics. However, it is important to extend this study to other conditions as (i) unmodified binders, (ii) different temperatures and (iii) different loading rates, as mentioned by the authors of this work.

For the purpose of investigating the effect of moisture damage, researchers combined the FAM cohesive zone fracture properties with moisture diffusion coefficient, as Fickian moisture diffusion (Caro, Masad, Bhasin, & Little, 2010; Ban, Kim, & Rhee, 2013), and with adhesive failure properties of FAM-aggregate interface (Wang, Wang, & Chen, 2014). All of the researchers previously mentioned concluded that the effect of moisture damage must be considered to characterize fracture properties of the asphalt concrete, once in some conditions, the moisture damage is the distress mechanism that has more influence on the failure of the mixture.

2.1.2 Viscoelastic continuum damage theory

The fatigue life (N_f) is another way to characterize the mechanical behavior of the FAM mixes. This parameter is used to define the fatigue cracking resistance of the FAM based on the numbers of load cycles for the failure of the mixture. The N_f is the number of cycles of a specific load required (i) to reduce the initial mixture modulus in 50 % (Kanaan, Ozer, & Al-Qadi, 2014; Arega et al., 2013) or (ii) to achieve the peak value for the phase angle (Reese, 1997). Some researchers have defined the fatigue life of the FAMs directly from the time sweep data. However, this approach characterizes the fatigue life of the mixture for a specific loading configuration (e.g., amplitude, frequency, loading mode) applied in the test. In order to overcome this drawback, the viscoelastic continuum damage theory (VECD) has been used to characterize the fatigue damage of the FAMs.

In the continuum damage mechanics approach, a damaged body is assumed as a homogeneous continuum, where the changes are measured in microscale and quantified by means of internal state variables (ISV) (Schapery, 1984). Later, the elastic continuum damage theory was extended to the viscoelastic media by using the elastic-viscoelastic correspondence principles (Schapery, 1990), which eliminate the time-dependence of the viscoelastic materials transforming the physical variables in pseudo variables. Lee et al. (2000) developed a mechanistic fatigue prediction model based on the VECD concepts for the controlled strain loading mode, and it was adapted by Daniel and Kim (2002) for different loading conditions (cyclic and monotonic), different amplitudes and rates (strain amplitudes and strain rates), and different frequency levels. Kim and co-workers presented evidence that the VECD theory can characterize the fatigue damage and healing of the asphalt concrete mixtures regardless of the loading mode (uniaxial or torsional), control mode (stress-control or strain-control), and amplitude loading (S. W. Park et al., 1996; Lee & Kim, 1998a; Daniel & Kim, 2002), i.e., a single characteristic curve C vs. S independent of the loading conditions.

Palvadi (2011) and Palvadi et al. (2012) were the first to apply the VECD approach to characterize the FAM samples. The FAM samples were submitted to (i) three rates of monotonic and cyclic loading, and (ii) two loading amplitudes for cyclic loading at intermediate temperature (25 °C) in the DSR. The authors validated the VECD theory to characterize damage in FAM samples based on the similarity of the characteristic curves (C vs. S) for a given FAM for both loading modes and different amplitudes.

In these same studies, Palvadi (2011) and Palvadi et al. (2012) proposed a test procedure to investigate the healing characteristics of FAM samples. This test procedure consists of four rest periods (5, 10, 20 and 40 minutes) in three levels of stiffness (20, 30 and 40 % reduction of C). In this method, four specimens of each FAM mix are tested in order to apply a specific rest period in a specific sample. They concluded that the healing percentage of each FAM mix is a material characteristic, once that the values for this parameter were similar independently of the sequence of application of the rest period and damage level.

In an attempt to improve the procedure proposed by the previous authors, Karki, Li and Bhasin (2015) and Karki, Bhasin and Underwood (2016) developed an integrated testing procedure. This procedure is capable of quantifying damage and healing characteristics using a single specimen without separating the damage and healing tests under shear (DSR) and uniaxial (DMA) loading mode. Karki et al. (2015) and Karki et al. (2016) were the first to apply the simplified viscoelastic continuum damage (S-VECD) theory to characterize FAM mixes.

The authors highlighted that the characteristic curve (C vs. S) is a unique material property due to the similarity of the curves for a given material independently of the loading conditions (different amplitudes and frequencies) and the introduction of rest periods during the test.

Freire, Babadopulos, Castelo Branco and Bhasin (2017) applied the S-VECD theory to evaluate the effect of different nominal maximum aggregate sizes of the mineral aggregate particles in the fatigue resistance of the FAM to identify which one best represents the asphalt concrete damage characteristics. The authors adopted the G^R failure criterion to analyze the fatigue cracking resistance of the FAMs. The G^R failure criterion is the rate of change of the average released pseudostrain energy ($\overline{W}_r^R$) during the whole test (Sabouri & Kim, 2014), and N_f is defined by the S-VECD approach. The main finding was that the fatigue life curves for the FAM produced with mineral aggregate particles smaller than 2.00 mm and the asphalt concrete presented a similar slope. Based on the similarity between the slopes of the fatigue curves for the FAM and HMA, the authors concluded that the FAMs produced with a NMAS of 2.00 mm can be used to reproduce the asphalt concrete mixtures fatigue resistance.

In Brazil, researchers adapted the linear amplitude sweep test (LAS) method proposed by Johnson (2010), based on the VECD approach, to characterize the fatigue resistance of the FAMs. The investigations evaluated the effect (i) of different particle size distribution (Coutinho, 2012), (ii) different nominal maximum aggregate size (Freire, 2015; Freire, Coutinho, & Castelo Branco, 2015), and (iii) the thermal and photochemical aging (Cravo, 2016; Cravo et al., 2016).

However, Freire et al. (2015) did not recommend the use of the LAS test to analyze the fatigue resistance of the FAM mixes due to the difficulty to achieve the failure, once that the torque capacity of the DSR is low and unable of taking the sample to failure. The authors observed that for the higher strain amplitudes of the LAS test the equipment needs to work near its capacity due to the high stiffness of the FAM samples.

Regarding the FAM mixes containing high reclaimed asphalt pavement (RAP) and recycled asphalt shingle (RAS), Nabizadeh (2015) and Zhu et al. (2017) concluded that the use of these materials decreases the fatigue life of the mixture due to the hard binder present in the RAS and RAP. The use of the rejuvenating agent (petroleum tech, green tech and agriculture tech) in the FAM mixes containing RAS and RAP was investigated by Nabizadeh (2015) and Zhu et al. (2017) as an alternative to increase the fatigue life of the FAMs. Nabizadeh (2015) concluded that the rejuvenating agents resulted softer mixtures with improved fatigue life (especially for the FAMs with high RAP contents). Zhu et al. (2017) observed the same

behavior in the case of the FAM with RAS mixed with another rejuvenating agent derived from a petroleum source. The combination of the warm mix asphalt (WMA) additive with the petroleum tech rejuvenator was evaluated by Nabizadeh (2015), and this combination resulted in the softest FAM compared with other rejuvenators (green tech and agriculture tech).

With the aim of investigating the fatigue cracking of the asphalt binders in the FAM scale without the physicochemical interaction with the mineral aggregate, Motamed et al. (2012) used rigid particles, such as glass beads, in substitution for the mineral aggregate to produce the FAM samples. This new technique resulted in similar fatigue cracking characteristics between the FAMs and the asphalt concrete mixtures produced with the same asphalt binder. The author concluded that the glass beads can be used in substitution for the mineral aggregate when the binder properties are the main interest of the study.

2.1.3 Rheological properties

Some researchers took the changes in the rheological properties of the mixture into account in order to understand the effect of some volumetric properties of the FAM, as binder content and air voids. Underwood and Kim (2011) assessed the rheological properties of each scale by means of frequency sweep tests, in order to compare the binder, mastic, FAM and asphalt concrete scales. Based on the dynamic shear modulus ($|G^*|$) and phase angle (δ), the FAM was the scale that best represented the full mixture, for presenting similar slope of the dynamic shear modulus mastercurve. The other scales (binder and mastic phase) did not present similarity in the rheological properties for being a material more viscoelastic than the full mixture and the FAM.

Based on the reductions of the $|G^*|$ values, Underwood and Kim (2013a) studied the effect of the air voids and binder content on the rheological properties of the FAM, and concluded that the FAM is more sensitive to the variations of the binder content, in the order of 20 to 35 %, rather than air voids (5 to 12 %). In addition, Izadi (2012) looked at the slope of the curve $|G^*|$ vs. $\log(\text{time})$ and concluded that the fatigue cracking characteristics of the FAM are more related to the binder content rather than the fine aggregates fraction.

The effect of the use of RAP, RAS, and rejuvenator in the FAMs was investigated by He, Alavi, Jones and Harvey (2016) based on changes on the $|G^*|$ values and master curves. He et al. (2016) obtained similar conclusions to those presented by Nabizadeh (2015) and Zhu et al. (2017). The addition of RAP and RAS decreased the fatigue life of the FAMs on account of the

hard binder present in these mixtures, and the rejuvenator can be used as an alternative to reduce the stiffness due to the aged binder and increase the fatigue life of the FAMs.

Other researchers studied the characteristics of the FAM mixes at low temperature by means of the BBR test. Gong, Romero, Dong and Sudbury (2016) used the m -values (material relaxation parameter), the creep modulus and the absorption to investigate the effect of different gradations, binder contents, and temperatures on the FAM characteristics. Those authors concluded that the BBR is an effective tool to evaluate the FAM properties at low temperature and that the aforementioned parameters can be used to distinguish the FAM with the best performance at low temperatures.

Li et al. (2015) investigated the performance of the FAM produced with rock asphalt at low temperatures based on the $|G^*|$, master curves, creep stiffness and m -value. They observed that the FAM mixes produced with rock asphalt can have a good performance at higher temperatures due to the increase in the stiffness of the mixture. Regarding aging, the rock asphalt concrete mixtures were less affected by the long-term aging, probably because the natural composition of the rock asphalt.

In order to evaluate the performance of FAMs at high temperatures, Pazos (2015) submitted FAM samples with different types of fine aggregate (gravel and limestone) to the *Multiple Stress Creep and Recovery* (MSCR) test at 70 °C. Based on the percent recovery and non-recoverable creep compliance (J_{nr}), Pazos (2015) concluded that the limestone increases the resistance of the FAM to permanent deformation.

2.2 FAM DESIGN CHARACTERISTICS

2.2.1 Correlation between FAM and asphalt concrete

The use of FAM in order to characterize the asphalt concrete properties has been getting prominence since researchers have found a good relationship between the FAM and asphalt concrete properties. Underwood and Kim (2011) evaluated the effect of different compositions for the four material scale (binder, mastic, FAM, and asphalt concrete) using linear viscoelastic properties, as dynamic shear modulus ($|G^*|$) and phase angle (δ). Six FAMs were produced with different asphalt binder contents (8.27, 9.7, and 11.16 %), different air voids contents (4 to 9.1 %), and with mineral aggregate (granite) of nominal maximum aggregate size (NMAS) of 2.36 mm. Based on the results of the six FAMs, the authors concluded that the dynamic modulus and the phase angle for the FAM and asphalt concrete are similar, and due to this

similarity the FAMs presented the same trend of the asphalt concrete mixtures behavior at different test conditions.

This correspondence between the FAM and asphalt concrete properties was also observed for the moisture characterization (Arambula et al., 2007; Caro et al., 2008) and fatigue cracking and permanent deformation characterization (Motamed et al., 2012; Coutinho, 2012; Gudipudi & Underwood, 2015; Nabizadeh, 2015; Haghshenas et al., 2016; Im et al., 2015).

In order to investigate the inherent fatigue cracking resistance of modified asphalt binders (PPA, SBS, PPA+SBS, and PPA+Elvaloy), Motamed et al. (2012) submitted FAM samples produced with modified asphalt binders and glass beads to torsional loading (controlled strain mode – 275kPa) at 10 Hz and 16 °C. The rationale for use glass beads in substitution of the mineral aggregate is to simulate the same state of stress to which the binder is submitted in the asphalt concrete structure. The fatigue characterization of the FAM and the asphalt concrete was carried out with basis on the viscoelastic continuum damage theory (VECD), in order to make a qualitative comparison between the two phases, once the VECD theory provides a true failure characterization of the material. Motamed et al. (2012) compared the fatigue cracking resistance between FAM and asphalt concrete via fatigue life (number of cycles to achieve 50 % of the initial modulus), and observed that the FAM presented the same rank order for fatigue life of the asphalt concrete produced with the same modified asphalt binders. It can be concluded that the FAM is able to characterize the asphalt concrete mixtures in a qualitative way.

Regarding the good correlation for the damage properties between FAM and asphalt concrete, Gudipudi and Underwood (2015) observed a good agreement for the damage characteristic curves (*C* vs. *S*) between FAM and asphalt concrete. The tests were carried out with FAM samples and asphalt concrete specimens in tension-compression loading at three different levels of strain and temperature (10, 19, and 25 °C). The authors reported that the *C* vs. *S* curves for the FAM and asphalt concrete were similar for the tests carried out at 10 and 19 °C, but the *C*-values at failure for the FAMs were lower compared to the asphalt concrete. It was not possible to compare results from tests with FAM and asphalt concrete carried out at 25 °C, once the damage curve for both materials (FAM and asphalt concrete) presented a significant variation that can be related to some viscoplasticity or another mechanism (Gudipudi & Underwood, 2015).

2.2.2 Nominal maximum aggregate size for FAMs

As far as aggregate gradation is concerned, the main assumption in studies with FAM is that it represents the fine portion of the aggregate gradation of the asphalt concrete. Studies conducted in the EUA have been using aggregates passing sieve #16 (1.18 mm) once sieve #16 is part of the sieve series of USA standard for asphalt concrete. The following references are examples of studies conducted with material passing sieve #16: (Zollinger, 2005; Masad et al., 2008, 2006; Arambula et al., 2007; Bhasin et al., 2008; Caro et al., 2008, 2010; Castelo Branco et al., 2008; Castelo Branco, 2008; Vasconcelos et al., 2010, 2011; You, Adhikari, & Kutay, 2009; Palvadi, 2011; Caro, Beltrán, Alvarez, & Estakhri, 2012; Palvadi et al., 2012; Im, 2012; Izadi, 2012; Souza, Kim, Souza, & Castro, 2012; Tong et al., 2013, 2015; Arega et al., 2013; Kanaan et al., 2014; Aragão et al., 2014; Im et al., 2015; Gudipudi & Underwood, 2015; Nabizadeh, 2015; Karki, Kim, & Little, 2015; Karki, Kim, & Little, 2015; Cravo et al., 2016; Karki et al., 2016; Haghshenas et al., 2016; Cucalon et al., 2017).

Other researchers adopted different nominal maximum aggregate size (NMAS) to produce FAMs for different reasons. Aragão et al. (2010) adopted the aggregates passing sieve #50 (0.30 mm), because it was not possible to capture the aggregate gradation finer than 0.30 mm by the digital image process. Motamed et al. (2012) used glass beads with MNS of 1.00 mm (#18), 0.5 mm (#35) and 0.1 mm (#140) to study the binder properties without the interaction with the mineral aggregate.

Some researchers investigated the fatigue properties (Underwood & Kim, 2011; Gong et al., 2016; He et al., 2016; Zhu et al., 2017) and creep stiffness (Dai & You, 2007) of asphalt concrete mixtures using FAM produced with NMAS of 2.36 mm (#8). He et al. (2016) and Zhu et al. (2017) commented that the use of aggregate particles smaller than 1.18 mm (#16) is not practical due to a large amount of material needed to be separated and discarded to prepare the FAM samples. Dai and You (2007) assumed the hypothesis that fine aggregate is all the aggregate particles passing sieve #8 (2.38 mm).

While the previous authors made their assumptions based on practical reasons and hypotheses, Underwood and Kim (2011) provided a rationale for use of aggregate particles passing sieve #8 (2.38 mm), based on the packing principles presented by Vavrik, Pine, Huber, Carpenter and Bailey (2001). The packing theory is used to define the primary control sieve for the Bailey method, and this method is adopted to analyze and create aggregate gradations in the asphalt concrete. The packing theory assumes that the ideal aggregate diameter is the one that fits the space generated by the coarse aggregate, and this space is represented by the division

of the coarse aggregate NMAS by three. By adopting such theory, for an asphalt concrete with NMAS of 9.5 and 12.5 mm, it is suitable to produce FAM samples with mineral aggregates of NMAS of 2.36 mm (for the American standards) and 2.00 mm (for the Brazilian standards), once that the previous sieve has the opening of 4.75 mm.

In Brazil, the FAM samples are produced with aggregate particles passing sieve #10 (2.00 mm) since sieve #16 (1.18 mm) is not part of the sieve series of Brazilian standards for asphalt concrete mixtures (Coutinho, 2012; Pazos, 2015). Due to this condition, Freire et al. (2014), Freire (2015), Freire et al. (2015), and Freire et al. (2017) investigated the influence of different NMAS, i.e., #16 (1.18 mm), #10 (2.00 mm) and #5 (4.00 mm), in the fatigue properties of the FAMs.

Freire et al. (2017) compared the damage characteristic of three different FAM structures with the asphalt concrete produced with NMAS of 12.5 mm, in order to identify which FAM structure better represents the asphalt concrete. The VECD theory was used to define the damage characteristics of the FAM and the asphalt concrete. Freire et al. (2017) concluded that the NMAS of #10 (2.00 mm) for the aggregate particles is suitable for the FAM samples, once that the fatigue life curves for both (FAM and asphalt concrete) presented similar slope. In other words, similar evolution damage trend between the FAM samples with NMAS of 2.00 mm and the asphalt concrete with NMAS of 12.5 mm have been observed. Another reason for adopting this particle size is the ratio between the aggregate size and the sample diameter of 1:6, which is lower than the minimum of 1:3 recommended by Y. R. Kim, Seo, King and Momen (2004). Based on the studies about the adequate NMAS for the FAM presented in this section, the FAMs evaluated in this research were produced with fine aggregate particles passing sieve #10 (2.00 mm).

2.2.3 Compaction methods

Regarding the FAM samples compaction, the first studies with FAM conducted by Y.-R. Kim et al. (2003a) and Y.-R. Kim et al. (2003b) proposed a static compaction method. In this procedure, the loose sand-asphalt mixture of 11.5 grams is placed in a fabricated mold and compacted by static pressure, in order to produce samples with dimensions of 50 mm in height and 12 mm in diameter. The rationale for use of this compaction method is to produce FAM samples with a smooth surface and without significant flaws, once the smooth surface reduces the random propagation and initiation of the fatigue cracking when the sample is submitted to torsional loading (Y.-R. Kim et al., 2003b).

You et al. (2009) also adopted the static compaction method to produce FAM samples. The viscoelastic properties of the FAM were used as inputs for the two-dimensional (2D) and three-dimensional (3D) Distinct Element Method (DEM), in order to predict the dynamic modulus ($|E^*|$) for the asphalt concrete at different temperatures (4, -6, and -18 °C) and loading frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz). The dynamic modulus predicted by 2D DEM and 3D DEM for the asphalt concrete were compared to the experimental data and the 3D DEM was able to predict similar $|E^*|$ values for the asphalt concrete for a specific interval of temperature and loading frequencies.

Nabizadeh (2015) and Haghshenas et al. (2016) evaluated the chemical and mechanical properties of the FAM mix produced with 65 % of RAP and 35 % of virgin aggregate with asphalt binder modified with three rejuvenators (agriculture-tech, petroleum-tech, and green-tech rejuvenator) and one warm mix asphalt (WMA) additive. Regarding the fatigue resistance, a comparison between FAM and asphalt concrete was carried out by means of fatigue life prediction models based on the continuum damage mechanics. The fatigue resistance for the FAM was measured by means of a torsional shear time sweep test in controlled strain mode with strain levels of 0.15, 0.20, and 0.25 % for most of the mixtures, except the CRW1 that was tested at strain levels of 0.30, 0.35, and 0.40 %. Nabizadeh (2015) and Haghshenas et al. (2016) reported a good relationship between fatigue life of the FAM samples produced by the static compaction method and the asphalt concrete mixtures. Similar results were also observed by Motamed et al. (2012) for the FAMs prepared with modified asphalt binder and glass beads.

However, Zollinger (2005), in an attempt to reproduce the compaction procedure proposed by Y.-R. Kim et al. (2003a) and Y.-R. Kim et al. (2003b), observed some issues related to the distribution of the air voids throughout the length of the sample. The static compaction method resulted in FAM samples with a higher concentration of air voids at the ends of the sample, leading to cracks at the sample edges. In order to overcome this issue, Zollinger (2005) together with other researchers proposed a new method to produce FAMs by means of the extraction of the FAM samples from a specimen compacted in the Superpave Gyratory Compactor (SGC).

In this procedure, the loose FAM mixture is compacted in the SGC mold of 152 mm in diameter until achieving the air void of 11 % and height of 85 mm. It is necessary to trim each side of the SGC specimens to obtain more homogenous air voids distribution along the sample length, once that a large air void content is located at the ends of the SGC specimens (Masad, Muhunthan, Shashidhar, & Harman, 1999; Masad, Jandhyala, Dasgupta, Somadevan, &

Shashidhar, 2002). The extraction of FAM samples from the SGC specimens is considered efficient, once it is possible to produce a more uniform sample and control the air voids during the sample preparation, besides being a less time-consuming process. Due to these reasons, the compaction method for the FAMs presented by Zollinger (2005) has been adopted in subsequent studies with FAM.

Some researchers adopt a fixed number of gyrations as a criterion to stop the compaction of the FAM mixtures in the SGC. Kanaan et al. (2014) fixed 150 gyrations for the compaction of the FAM mixtures produced with two percentages of recycled asphalt shingles (RAS) - 2.5 % and 7.1 % from two RAS sources - and two asphalt binders (PG 64-22 and PG 46-32). By adopting this stop criterion, the FAM samples presented air voids ranging from 8 % to 10 %. The lowest air voids were observed for the FAM produced with the binder PG 46-34 and without RAS, and the highest air voids were observed for the FAM produced with the binder with PG 64-22. For Kanaan et al. (2014), such range of air void contents is suitable for FAM samples.

The effect of gyration level in the low-temperature properties of the FAMs was one of the variables assessed by Gong et al. (2016). FAM beams with 127 x 12.7 x 6.34 mm were cut from SGC specimens compacted at three compaction levels (30, 50, and 70 gyrations) and tested in the Bending Beam Rheometer (BBR). By means of the absorption parameter, it was seen that the moisture damage is higher for the FAMs with higher air voids, and this tendency becomes more remarkable with the increase of temperature.

Other researchers compact the FAM mixtures in the SGC mold of 100 mm in diameter until no change is observed in the specimen height with additional gyrations (Sousa, Kassem, Masad, & Little, 2013; Cucalon et al., 2017). Sousa et al. (2013) produced FAM mixtures with different types of mineral aggregate (limestone, granite, gravel and limestone/gravel), and the FAM samples extracted from the SGC specimens presented air voids from 2.5 to 3.5 %. Cucalon et al. (2017) achieved air voids of 3 % for the FAM samples produced with aggregate from different sources (limestone and gabbro), different asphalt binders (PG 64-22 and PG 76-22), and different WMA additives (foaming, organic wax and two chemical additives).

2.2.4 Air voids content

The air voids content is another criterion used for the production of FAMs in the SGC. In this case, the air voids content can be related to the FAM specimens compacted in the SGC or to the FAM samples extracted from the SGC specimens.

Zollinger (2005) was the first to propose the interruption of the compaction of the FAM specimens in the SGC with basis on the air voids content. Six FAMs produced with six mineral aggregate sources (granite, quartzite, sandstone, river gravel, gravel+limenstone+RAP and gravel+RAP) and two asphalt binders (PG 64-22 and PG 76-22), were compacted until the SGC specimens presented air void content of 11 % and height of 85 mm. Bhasin et al. (2008) compacted six FAM specimens with height of 75 mm and air voids content of 13 %, in order to extract FAM samples produced with three asphalt binder (PG 58-28, PG 58-10, and PG 64-16) and two mineral aggregates (granite and siliceous gravel) to evaluate the effect of healing on the mechanical properties of the FAMs. Y.-R. Kim and Aragão (2013) used the rate-dependent cohesive zone fracture properties of FAM specimens with air void content of 1.5 % to simulate the fracture properties of the asphalt concrete, based on a computational microstructure model.

The air voids content for the FAM samples extracted from the SGC specimens is also used as a criterion in the compaction procedure for the FAMs. Little et al. (2007) compacted the FAM mixtures in the SGC in order to obtain FAM samples with air voids of 13 ± 1 %. He et al. (2016) and Zhu et al. (2017) extracted FAM samples with air voids content ranging from 10 to 13 % and justified that the higher air void contents were adopted to produce FAM samples less stiff, due to the torque limitations of the DSR.

Gudipudi and Underwood (2015) produced FAM samples with two asphalt binders (PG 64-22 and PG 76-16) with mineral aggregates from Phoenix, Arizona area and air voids of 6 ± 0.5 %, in order to evaluate the relationship between the viscoelastic and mechanical properties of the FAM mixtures and asphalt concrete mixtures. This air voids content of 6 % for the FAM samples was adopted, assuming that 52 % of the total air voids of the asphalt concrete mixtures are present in the FAM phase. The upscaling of the viscoelastic and fatigue properties of the two phases was carried out by means of homogenized continua approach, and the authors observed a good relationship between the asphalt concrete phases by taking the assumption made for the air void contents for the FAM scale into account.

Other researchers assumed that all air voids of the asphalt concrete is within the FAM phase, and according to this hypothesis the FAM samples presents air void of 4 % (Castelo Branco, 2008; Freire, 2015; Im et al., 2015; Freire et al., 2014, 2015, 2017). Assuming that the FAM samples have the same air voids of the asphalt concrete mixtures, Freire et al. (2017) observed that the FAM samples with NMAS of 2.00 mm and the asphalt concrete with NMAS of 12.5 mm present the same trend for the evolution damage, and Im et al. (2015) observed a

good correlation for the viscoelastic and viscoplastic deformation characteristics between the FAM and asphalt concrete.

On the other hand, Karki et al. (2015) does not agree with the hypothesis that all air voids present in the asphalt concrete are within the FAM phase, and claim that the air voids are randomly distributed throughout the asphalt concrete, generating air voids with different sizes between the aggregate particles and FAM phase, and within the FAM phase. Taking this assumption into account, Karki et al. (2015) produced FAM samples with two different air voids content (1.0 and 5.5 %), assuming that the effect of the air voids is not significant in the FAM phase. Those researchers simulated the dynamic modulus for the asphalt concrete through a computational micromechanics modeling proposed in the study and reported a good agreement between the experimental modulus and the simulated modulus from the properties of the FAM produced with air voids of 1 %. This finding indicates that FAM produced with 1 % of air voids can represent the matrix phase in the asphalt concrete.

Some researchers evaluated the effect of the volumetric composition on some properties of the FAM samples, once that it is not well known which is the air voids content that better represents the FAM phase in the asphalt concrete. Underwood and Kim (2011) assumed that 100, 75, and 50 % of the air voids of the asphalt concrete are within the FAM phase, in order to evaluate the effect of different volumetric compositions in the linear viscoelastic dynamic shear modulus ($|G^*|$) of the FAMs. Different combinations of asphalt binder contents (8.27, 9.7, and 11.16 %) and air void contents (4.5, 6.5, and 9.1 %) resulted in six FAMs. It was observed an increase of the linear viscoelastic dynamic shear modulus with the reduction in the air void content, at a rate of 7 % increase in modulus to 1 % reduction in air void content. This was more noticeable for the FAM with higher asphalt binder content (11.16 %), showing that the FAMs with a higher binder content is more susceptible to air void variations.

Underwood and Kim (2013a) made additional comparisons for the six FAMs presented by Underwood and Kim (2011). They evaluated the tensile properties for the six FAMs and compared the linear viscoelastic dynamic modulus and damage properties of the FAM with the damage properties for the asphalt concrete. These researchers concluded that the linear viscoelastic and damage properties of the FAMs are more susceptible to the variations of the asphalt binder content rather than the air void within the FAM samples, drawing the attention to the importance of the hypotheses taken into account regarding the asphalt binder content suitable for the FAMs. A detailed discussion of the design methods presents in the literature

and the design method adopted to determine the asphalt binder content for the FAMs will be presented in Chapter 3 of this dissertation.

Underwood and Kim (2013b) investigated the air voids content that better represents the FAM phase in the asphalt concrete, by means of morphological observation from digital and scanning electron microscopy images and meso-gravimetric tests of the asphalt concrete mixtures. The authors concluded that FAM phase contains from 40 to 70 % of the air voids present in an asphalt concrete. Taking into account such range and the conventional target air voids for asphalt concrete of 4 %, it can be assumed that the FAM air voids could range from 1.6 to 2.8 %, and for an asphalt concrete with air voids of 7 %, the FAM air voids could range from 2.8 to 4.9 %.

2.2.5 Long term aging procedures for FAMs

The long-term aging has been considered in studies with FAMs, once the aging of the asphalt binder is a relevant factor for the fatigue cracking resistance of asphalt concrete mixtures. Cravo et al. (2016) evaluated the effect of long-term aging on the fatigue life of FAMs produced with unmodified asphalt binder. Compacted FAM samples were placed in an oven for 120 hours at 90 °C, in order to simulate the thermal aging, and in a sunlight simulation chamber (Suntest) for 120 hours, to simulate the photochemical aging. The authors observed that the FAM samples submitted to the photochemical aging presented higher stiffness compared to the FAM samples submitted to the thermal aging, even for a short-term test. Based on the linear amplitude sweep test (LAS), the FAM mixture aged in the Suntest presented a higher fatigue life at low strain amplitudes, however, with the increase of the strain amplitude, the FAMs submitted to thermal aging and the FAMs not aged presented higher fatigue life. This behavior can be related to the higher stiffness of the FAM submitted to photochemical aging, once that mixtures with higher stiffness are more prone to fatigue cracking in test run in controlled strain mode.

Tong et al. (2015) proposed a repeated direct tensional (RDT) method to evaluate the fatigue resistance of conventional FAMs and FAMs prepared with WMA additives considering the effects of water vapor diffusion and aging. In order to simulate the effect of long-term aging, the authors placed the compacted FAM samples in a desiccator with the air at 60 °C in the chamber for 90 days. They observed that both FAMs (unmodified and modified with WMA additives) presented a similar reduction in the fatigue resistance due to the long-term aging, i.e.,

the WMA additives did not improve the fatigue resistance of the FAMs, once similar fatigue crack growth indices were observed for the unmodified and modified FAMs.

Arega et al. (2013) aged the loose FAM mixture in an environmental room for 30 days at 60 °C, in order to simulate the long-term aging for the FAMs modified with WMA additives (organic wax, micro-foaming, and two chemical origin). The long-term aging conditions of 30 days at 60 °C were adopted based on an investigation about the oxidation level of unmodified and modified asphalt binders aged in the environmental room and in the PAV. The carbonyl area (metric for oxidation) for the asphalt binders aged in the environmental room at 60 °C for 22, 35 and 65 days and in the PAV were calculated by the attenuated total reflection (ATR) method by means of Fourier Transform Infra-Red (FTIR) spectroscopy.

The measurements for the carbonyl area for each asphalt binder in each aging condition indicated that the aging level in the environmental room at 60 °C for 35 days is similar to the aging level after the PAV test. This result was observed only for the unmodified asphalt binder and for the asphalt binder modified with Sasobit. For the asphalt binders modified with the other WMA additives (Cecabase, Evotherm 3G and Rediset), the aging level after the PAV was slightly higher compared to the aging level in the environmental room at 60 °C for 35 days. Based on these results, Arega et al. (2013) considered that the aging of the loose mix in an environmental room at 60 °C for 30 days is adequate to simulate the long-term aging in the FAMs. Regarding the dynamic shear modulus and the fatigue life for the FAMs, the authors reported a good correlation between these properties after short-term aging and after long-term aging, i.e., the rank order of fatigue cracking resistance of the FAMs was similar even after the long-term aging. This suggests that the fatigue properties of the FAMs modified with the WMA additives can be evaluated in the short-term aging level.

Li et al. (2015) followed the same procedure suggested by Arega et al. (2013) to simulate the long-term aging in the FAMs produced with three different rock asphalts. The rheological properties were assessed by means of tests conducted in the DSR and in the BBR. The linear viscoelastic properties ($|G^*|$ and δ) showed that the rock asphalt significantly increase the stiffness of the FAMs. This increase can be partially related to the higher stiffness of the rock asphalt, once this material presents higher asphaltene content and high molecular weight. However, a negative effect in the low temperature resistance was observed due to the higher stiffness of the FAMs. Regarding the aging effect, Li et al. (2015) observed that the rheological properties did not change significantly with the long-term aging due to the natural aging of the rock asphalt. Based on these findings, the authors concluded that the rock asphalt increase the

stiffness of the FAMs and can be adopted as an alternative to improve the rutting resistance of the asphalt concrete.

2.3 LINEAR VISCOELASTIC PROPERTIES

The linear viscoelastic characterization of asphalt concrete mixtures is carried out by means of the measurement of relaxation or creep properties. The creep and relaxation tests measure the response of the materials to a constant load or displacement over time, i.e., they describe the material properties in the time domain, within the linear viscoelastic region. In the creep test, a constant load is applied to the specimen over time at a constant temperature, and the creep compliance, $D(t)$, is defined by the ratio of accumulated strain to the constant stress magnitude at a specific time. In the relaxation test, the specimen is submitted a constant strain for a given period of time at a constant temperature, and the relaxation modulus, $E(t)$, is defined by the ratio of the stress evolution to the constant strain magnitude. However, in some cases, is not possible to obtain an accurate response of the material in a short-time test with transient excitation, e.g., static loading. To overcome this limitation, tests with steady-state sinusoidal excitation are adopted, e.g., dynamic loading.

Viscoelastic materials under dynamic loading conditions provide frequency-domain dynamic properties, such as (i) phase angle, $\phi(\omega)$, that represents the gap between the stress and strain due to the time-dependency of the viscoelastic materials, (ii) storage shear modulus, $G'(\omega)$, that represents the elastic characteristics of the material and (iii) loss shear modulus, $G''(\omega)$, that corresponds to the viscous behavior of the material. The combined form of storage shear modulus and loss shear modulus results in Equation 2.1 for the phase angle, where ω is the angular frequency, in Equation 2.2 for the dynamic shear modulus, $|G^*(\omega)|$, where τ_{max} is the maximum shear stress at each cycle and γ_{max} is the applied cyclic shear strain amplitude, and in Equation 2.3 for the dynamic shear modulus, $G^*(\omega)$, where i is equal to $\sqrt{-1}$.

$$\phi(\omega) = \tan^{-1} \left[\frac{G''(\omega)}{G'(\omega)} \right] \quad (2.1)$$

$$|G^*(\omega)| = \frac{\tau_{max}}{\gamma_{max}} = \sqrt{[G'(\omega)]^2 + [G''(\omega)]^2} \quad (2.2)$$

$$G^* = G'(\omega) + iG''(\omega) \quad (2.3)$$

A dynamic frequency sweep test within the linear viscoelastic range is conducted in the dynamic shear rheometer (DSR) to define the linear viscoelastic relaxation behavior of the material. A curve fitting function for the linear viscoelastic modulus and frequency is required to determine the linear viscoelastic relaxation modulus from a test in the frequency domain. The generalized Maxwell model, typically called as Prony series, is used as a curve fitting function for the viscoelastic materials due to its capability of describing the different stages of the behavior of viscoelastic materials (S. W. Park & Kim, 2001). Prony series representation of storage and loss modulus as a function of frequency (frequency domain) was presented by Christensen (1982) and is given by Equation 2.4 and 2.5, where G_e is the equilibrium modulus, G_i is the elastic modulus, ρ_i is the relaxation time, ω is the angular frequency, and n is the number of elements of the Prony series needed to fit the analytical representation to the experimental data.

$$G'(\omega) = G_e + \sum_{i=1}^n \frac{G_i \omega^2 \rho_i^2}{\omega^2 \rho_i^2 + 1} \quad (2.4)$$

$$G''(\omega) = \sum_{i=1}^n \frac{G_i \omega \rho_i}{\omega^2 \rho_i^2 + 1} \quad (2.5)$$

The spring constants (G_i) are defined by means of the collocation method, a matching process between the analytical representation and the experimental data for a certain amount of points. Considering the Prony series parameters found by the collocation method, the static relaxation shear modulus as a function of time (time domain) can be predicted from the dynamic shear modulus as a function of frequency (frequency domain) by Equation 2.6.

$$G(t) = G_\infty + \sum_{i=1}^n G_i e^{-\frac{t}{\rho_i}} \quad (2.6)$$

The relaxation property (*m-value*) is defined by the slope of the relaxation modulus curve, in logarithm scale, and is used in the VECD approach to determine the damage evolution rate of the material. This material property can be defined by the adjustment of a power law function (Equation 2.7) in the relaxation curve predicted by the Prony series, where G_0 and G_1 are material constants, t is time, and m is the slope of the relaxation curve in the time domain.

$$G = G_0 + G_1 t^{-m} \quad (2.7)$$

2.4 VISCOELASTIC CONTINUUM DAMAGE THEORY (VECD)

Fatigue cracking is the distress mechanism most present in asphalt pavements. This phenomenon initiates as microcracks that give rise to macrocracks as a result of the crack propagation process and the coalescence of the microcracks. The asphalt mixture characterization, regarding the fatigue cracking resistance, can be based on the number of load cycles needed to take the sample to failure. However, it is important for the asphalt mixture characterization to take the effect of different loading configuration (e.g., amplitude, frequency, loading mode) into account, once that the viscoelastic properties of the asphalt concrete mixtures are dependent on loading mode and loading rate.

The viscoelastic continuum damage theory (VECD) has been used to characterize the fatigue damage of asphalt concrete mixtures, since Kim and co-workers presented evidences that the VECD theory is capable of characterizing the fatigue damage and healing of asphalt concrete mixtures independently of the loading mode (uniaxial or torsional), control mode (stress-control or strain-control), and amplitude loading (Daniel & Kim, 2002; Lee & Kim, 1998a; S. W. Park et al., 1996). The main assumptions of the VECD theory are: (i) a damaged body with a specific stiffness is equivalent to an undamaged body with reduced stiffness, and (ii) the cracks are evenly distributed throughout the damaged body.

2.4.1 Work potential theory

In order to characterize the mechanical properties of the elastic materials with growing damage, Schapery (1984, 1990) developed the work potential theory based on the principles of thermodynamic of irreversible processes. The material characterization by means of work potential theory is carried out by observations in macroscale to quantify the material changes in the microstructure using internal state variables (ISV).

In the thermodynamic theory, the changing in the elastic body structure is related to generalized forces, Q_j , and independent generalized displacements, q_j , as shown in Equation 2.8 where δq_j is the virtual displacement and $\delta W'$ is the virtual work. The physical variable q_j can be associated with strain, displacement or rotation, and Q_j to stress, force or moment.

$$\delta W' = Q_j \delta q_j \quad (2.8)$$

The strain energy function can be described as $W = W(q_j, S_m)$, where S_m ($m = 1, 2, 3, M$) indicates the change of the internal state variable, S . The thermodynamic force, f_m , is defined as

the relationship between the strain energy and the work done on a body during the damage process (Equation 2.9 and 2.10).

$$dW = \frac{\partial W}{\partial q_j} dq_j + \frac{\partial W}{\partial S_m} dS_m = Q_j dq_j - f_m dS_m \quad (2.9)$$

$$f_m = -\frac{\partial W}{\partial S_m} \quad (2.10)$$

Suppose a state function presented in Equation 2.11 and a thermodynamic force, f_m , for a damage evolution rate ($\dot{S}_m$) different from zero (Equation 2.12). By integrating Equation 2.9 for an interval t_1 - t_2 , the work that consequently changes the internal state of the material from state 1 to state 2 is represented by Equation 2.13.

$$W_s = W_s(S_m) \quad (2.11)$$

$$f_m = -\frac{\partial W}{\partial S_m} \text{ when } \dot{S}_m \neq 0 \quad (2.12)$$

$$\Delta W_T = W^{(2)} - W^{(1)} + \int_1^2 f_m dS_m \quad (2.13)$$

After integrating Equation 2.13, the work is given by Equation 2.14. Considering time $t_1=0$, the total work from $t=0$ to the current time t_2 is defined by Equation 2.15.

$$\Delta W_T = W^{(2)} - W^{(1)} + W_s^{(2)} - W_s^{(1)} \quad (2.14)$$

$$W_T = W + W_s \quad (2.15)$$

For an elastic body, the total work generated by forces Q_j is given by Equation 2.16, where $j = 1, 2, \dots, J$, and W_T is the total work for a S_m that varies with time.

$$W_T = \int Q_j dq_j \quad (2.16)$$

Schapery (1984,1990) presented the Equations 2.17 and 2.18, in order to represent the total work done on a body in terms of stress strain relationship, where σ_{ij} is the stress tensor, ε_{ij} is the strain tensor, and S_m is the internal state variable.

$$W = W(\varepsilon_{ij}, S_m) \quad (2.17)$$

$$W_T = \int \sigma_{ij} d\varepsilon_{ij} \quad (2.18)$$

The damage evolution law for an elastic media (Equation 2.19) is defined by the relation between Equations 2.10 and 2.12, in which $W_S = W_S(S_m)$ represents the dissipated energy caused by damage growth. The right-hand side of the damage evolution law refers to the force required to damage growth and the left-hand side refers to the thermodynamic force available to induce the damage growth.

$$-\frac{\partial W}{\partial S_m} = \frac{\partial W_S}{\partial S_m} \quad (2.19)$$

2.4.2 Elastic-viscoelastic correspondence principles

In order to extend the elastic continuum damage theory to characterize the mechanical behavior of viscoelastic materials, Schapery (1984,1990) makes use of the viscoelastic correspondence principles to convert physical variables in pseudo variables. This conversion is necessary to remove the effect of time-dependence of the viscoelastic materials.

The stress-strain relationship for elastic materials is described by Hooke's Law (Equation 2.20), where E is the elasticity modulus. For viscoelastic materials, the effect of time dependence must be considered for the stress-strain relationship. The stress is described by means of a convolution integral (Equation 2.21), in which τ is an increment for the time, t , and $G(t)$ is the relaxation modulus of the material.

$$\sigma = E\varepsilon \quad (2.20)$$

$$\sigma = \int_0^t G(t-\tau) \frac{d\varepsilon}{d\tau} d\tau \quad (2.21)$$

For the purpose of removing the time-dependence of the viscoelastic materials, Schapery (1984,1990) converted the stress-strain relationship for viscoelastic materials to the pseudo domain. In the pseudo domain, the viscoelastic material is equivalent to a hypothetical elastic material, where the constitutive equation for viscoelastic media (Equation 2.22) is similar to the constitutive equation for elastic media (Equation 2.20).

$$\sigma = E_R \varepsilon^R \quad (2.22)$$

However, in the pseudo domain, the variables stress and strain are not physical quantities. In this case, stress and strain are pseudo variables: pseudo stress (σ^R) and pseudo strain (ε^R).

Based on the correspondence principles $\varepsilon^R = \varepsilon$, where σ represents the time-dependent stress applied to the viscoelastic material. Schapery (1984,1990) defined pseudo strain (Equation 2.23) by the relationship between the convolution integral for physical stress (Equation 2.21) and the constitutive equation for elastic media in the pseudo domain (Equation 2.22), where, ε is the time-dependent strain of the viscoelastic material, $G(t)$ is the linear viscoelastic relaxation modulus, and E_R is the modulus for the hypothetical elastic material.

$$\varepsilon^R = \frac{1}{E_R} \int_0^t G(t-\tau) \frac{d\varepsilon}{d\tau} d\tau \quad (2.23)$$

Schapery (1990) replaced the physical variables by pseudo variables to convert the elastic models to the pseudo domain to apply them to the viscoelastic case. In Equation 2.17, the physical strain, ε , was substituted by the pseudo strain, ε^R , giving rise to the pseudo strain energy density function (Equation 2.24) The stress-pseudo strain relationship is presented by Equation 2.25, which W^R is the pseudo strain energy density.

$$W_R = W^R(\varepsilon^R, S_m) \quad (2.24)$$

$$\sigma = \frac{\partial W^R}{\partial \varepsilon^R} \quad (2.25)$$

Regarding the damage law for viscoelastic materials, it is not possible to convert the damage law for elastic media to the pseudo domain using the correspondence principles, since the viscoelastic materials are rate dependent. S.W. Park and Schapery (1997) did some considerations and presented the damage evolution law for viscoelastic materials (Equation 2.26) where $\dot{S}_m$ refers to the damage evolution rate and α_m is a material-dependent constant.

$$\dot{S}_m = \left(-\frac{\partial W^R}{\partial S_m} \right)^{\alpha_m} \quad (2.26)$$

2.4.3 Viscoelastic continuum damage

The asphalt concrete is basically a mixture of asphalt binder, coarse and fine mineral aggregate particles, filler, and air voids, and the asphalt concrete mixtures present a viscoelastic behavior due to the presence of a viscoelastic material in its composition, the asphalt binder. S. W. Park et al. (1996) proposed a uniaxial viscoelastic damage model to study the time-

dependent damage growth of the asphalt concrete with tests carried out with uniaxial loading at different strain rates. S. W. Park et al. (1996) assumed that the internal state variable (S) can represent the damage state of the material, in order to quantify the time-dependent damage growth of the material. Thus, the constitutive equation for a linear viscoelastic body with growing damage (Equation 2.27) was presented by Lee and Kim (1998b), where $C(S_m)$ represents the stiffness variation of the material attributed to the changes in the microstructure.

$$\sigma = C(S_m) \cdot \varepsilon^R \quad (2.27)$$

Replacing Equation 2.27 in the stress-pseudo strain relationship presented by Equation 2.25, the pseudo strain energy density function with time-dependent damage growth is given by Equation 2.28, where C , is a function of the damage parameter S , and the new damage evolution law for viscoelastic materials is given by Equation 2.29

$$W^R = \frac{1}{2} C(S) \cdot (\varepsilon^R)^2 \quad (2.28)$$

$$\dot{S}_m = \left(-\frac{\partial W^R}{\partial S} \right)^\alpha \quad (2.29)$$

Lee (1996) and Lee and Kim (1998b) proposed a mathematical solution for the damage evolution law based on observations made from uniaxial tensile cyclic loading tests. Lee (1996) and Lee and Kim (1998b) observed a change in the slope between the σ - ε^R cycles during the test (Figure 2.1) carried out under strain and stress controlled mode in different loading amplitudes. In order to represent these changes in the slope of the stress-pseudo strain loops, these authors proposed a new parameter, the secant pseudo stiffness (Equation 2.30) S^R , where ε_m^R is the peak pseudo strain in each stress-pseudo strain cycle and σ_m is the stress correlated to ε_m^R .

$$S^R = \frac{\sigma_m}{\varepsilon_m^R} \quad (2.30)$$

Figure 2.1 – Stress-pseudo strain hysteresis in: (a) Strain-control mode; (b) Stress-control mode

Source: Lee (1996)

Lee (1996) proposed to normalize the pseudo stiffness parameter (Equation 2.31) aiming to reduce the sample-to-sample variation, where I is the initial pseudo stiffness. Given the normalized pseudo stiffness, $C(S_m)$, the new constitutive equation for a linear viscoelastic body with growing damage is given by Equation 2.32

$$C = \frac{S^R}{I} \quad (2.31)$$

$$\sigma = IC(S_m)\varepsilon^R \quad (2.32)$$

Lee (1996) and Lee and Kim (1998b) considered the internal state variable, S_I , as a parameter to define the stiffness variation of the viscoelastic materials due to damage growth and the work function, W^R (Equation 2.33), which, $C_I(S_I)$ is a function that represents S^R .

$$W^R = \frac{I}{2} C_I(S_I) (\varepsilon_m^R)^2 \quad (2.33)$$

The material function $C_I S_I$ can be defined using experimental data and the damage evolution law (Equation 2.29), however, it is not suitable to define the material function in this way because the damage evolution law requires, a priori, the definition of $C_I S_I$. Lee and Kim, (1998b) proposed a method to overcome the characterization for $C_I S_I$, making use of the chain rule (Equation 2.34) to eliminate the S on the right-hand side of the damage evolution law. Some mathematical substitutions were done (Equation 2.35) and a numerical solution was found to determine values for the damage parameter S (Equation 2.36). Thus, the function $C_I S_I$

can be defined adjusting a power law function (Equation 2.37) to the curve C versus S , where C_{10} , C_{11} and C_{12} are the regression constants.

$$\frac{dC}{dS} = \frac{dC}{dt} \cdot \frac{dt}{dS} \quad (2.34)$$

$$\frac{dC}{dS} = \left[-\frac{I}{2} \cdot \frac{dC}{dt} \cdot (\varepsilon^R)^2 \right]^{\frac{\alpha}{1+\alpha}} \quad (2.35)$$

$$S = \sum_{i=1}^N \left[\frac{I}{2} (\varepsilon_i^R)^2 (C_{i-1} - C_i) \right]^{\frac{\alpha}{1+\alpha}} (t_i - t_{i-1})^{\frac{1}{1+\alpha}} \quad (2.36)$$

$$C_1(S_1) = C_{10} - C_{11}(S_1)^{C_{12}} \quad (2.37)$$

Regarding the constant α , it represents the speed of the crack growth in viscoelastic media or, in other words, the damage evolution rate. This constant is related to the material's creep or relaxation properties. The constant α is defined based on the characteristics of the failure zone at a crack tip. If the material's fracture energy and a failure stress are constant, α is given by Equation 2.38. If the fracture process zone size and the material's fracture energy are constant, α is calculated by Equation 2.39, in which m is the slope of the curve $\log D(t) - \log(t)$ or $\log E(t) - \log(t)$ (Schapery, 1975).

$$\alpha = 1 + \frac{1}{m} \quad (2.38)$$

$$\alpha = \frac{1}{m} \quad (2.39)$$

Lee and Kim (1998a) assessed the expressions for α for tests in controlled strain and controlled stress mode. The authors observed that Equation 2.38 is adequate for tests in controlled strain mode, and Equation 2.39 is more appropriate for tests in controlled stress mode. Considering these observations, the material's fracture energy and failure stress are constant for tests in controlled strain mode, while the material's fracture energy and the fracture process zone size are constant in controlled stress mode.

2.4.4 Fatigue life prediction model

The fatigue resistance of asphalt concrete mixtures obtained from laboratory tests is evaluated using two different approaches: phenomenological and mechanistic. The phenomenological model defines the fatigue life of the asphalt concrete by a simple fit of the fatigue life model with the time sweep test data. This model is simpler compared to the complexity of the fatigue behavior of asphalt concrete mixtures, once that this model does not take into account how the damage develops throughout the fatigue life of the mixture. On the other hand, the mechanistic model is based on mechanical and fundamental material properties and may be used for a wide range of loading and environmental conditions leading to more reliable fatigue life models.

Lee et al. (2000) proposed a mechanistic fatigue prediction model based on the viscoelastic continuum damage concepts and the work potential theory. Y.-R. Kim and Little (2005) adapted the model for torsional shear cyclic loading test without rest periods using the dissipated pseudo strain energy and pseudo stiffness. The fatigue life model is given by Equation 2.40 to 2.42, where, f is the frequency adopted for the test, S_f is the damage parameter to fatigue failure criterion, γ_0 is the strain amplitude, and C_1, C_2 are the regression constants determined by the pseudo stiffness *versus* damage parameter curve (Equation 2.37) The simplified fatigue prediction model proposed by Y.-R. Kim and Little (2005) was adopted in this research in order to assess the fatigue characterization of the FAMs.

$$N_f = A \cdot (\varepsilon^R)^{-B} \quad (2.40)$$

$$A = f \cdot \left(\frac{1}{2} I_p C_1 C_2 \right)^{-\alpha} \{1 + \alpha \cdot (1 - C_2)\}^{-1} S_f^{\{1 + \alpha(1 - C_2)\}} \quad (2.41)$$

$$B = 2\alpha \quad (2.42)$$

2.5 ASPHALT MASTIC

The asphalt concrete mixtures are comprised, in general, of asphalt binder and mineral aggregates. Although the asphalt binder is considered the element responsible for gluing the mineral particles, the asphalt mastic is the element that really performs this function. This phase of the asphalt concrete is defined as a mixture of mineral filler (aggregate particles smaller than 75 micra) and asphalt binder that involves and agglutinates the mineral aggregates. Such phase

also fills the spaces present in the mineral skeleton of the asphalt concrete, ensuring compactness, impermeability, and workability to the asphalt concrete.

The mineral filler contributes to the improvement of the pavement performance, once the presence of mineral filler in the asphalt concrete increases the stiffness increasing the resistance of the mixture to permanent deformation (Kandhal, 1981; Petersen, Plancher, & Harnsberger, 1987; Welch & Wiley, 1977). However, a stiff mastic leads to brittle or fragile mixtures, reducing the pavement performance at intermediate and low temperatures, due to the appearance of fatigue or thermal cracking (Chen & Peng, 1998).

The importance of mineral fillers in the mechanical behavior of the asphalt concrete mixtures is well known and because of that many studies related to their effect on the rheological behavior of the asphalt mastic and on the mechanical behavior of the asphalt concrete mixtures are present in the literature (Al-Suhaibani, Al-Mudaiheem, & Al-Fozan, 1992; Anderson, 1987; Anderson, Bahia, & Dongre, 1992; Cooley, Stroup-Gardinder, Brown, Hanson, & Fletcher, 1998; Harris & Stuart, 1995; Kavussi & Hicks, 1997; Shahrour & Saloukeh, 1992; Shashidhar & Romero, 1998).

Kavussi and Hicks (1997) reported that the properties of the asphalt binder can change due to the presence of the mineral filler in the mixture. This modification can occur by changes in the physical or chemical properties of the asphalt binder due to the type of mineral filler, the physical-chemical properties of the filler and the concentration of filler in the mixture. The quality of the filler can influence on the mechanical properties of the asphalt concrete mixtures such as workability (Y.-R. Kim & Little, 2004). Shashidhar and Romero (1998) draw the attention to the problem of workability due to the presence of filler in excess, once that it can affect the compaction and the performance of the asphalt concrete mixtures. Kavussi and Hicks (1997) also affirmed that the mineral filler affects the compaction characteristics, the air voids, and the stiffness of the asphalt concrete mixtures.

In a general context, the effect of mineral fillers on the properties of the asphalt concrete mixtures is related to the volumetric properties of the mineral filler or to the interaction between the asphalt binder and the mineral filler, once that this interaction is associated with the physical-chemical aspects of the asphalt mastic. Based on this hypothesis, Y.-R. Kim and Little (2004) conducted a comprehensive study of the physical-chemical aspects of several asphalt mastics by means of the sensitivity of physical-chemical mechanisms as a function of geometry, size, and surface activity of the mineral filler. They concluded that the physical-chemical aspect is associated with the adsorption intensity at the filler-asphalt interface, because a higher surface

activity contributes to the occurrence of stronger connections in the filler-asphalt interface and increase the quantity of asphalt binder needed.

The filler fraction is one of the most important elements in the asphalt concrete, although its importance sometimes does not receive attention. The filler fraction is often considered as an inert material, whose main function is to fill the voids between the particles of the coarse aggregate. Nevertheless, based on a microscopic approach of the asphalt concrete, it is visible that the largest part of the filler fraction is immersed in the asphalt binder in such a way that the asphalt binder of the asphalt concrete is not only asphalt binder but rather an asphalt mastic composed of mineral filler and asphalt binder (Anderson et al., 1992).

Microscopic analyzes of asphalt concrete by means of optical transmission microscopy images carried out during the SHRP program indicated that (i) in terms of the physical-chemical interaction between the asphalt binder and the surface of the mineral aggregate, the properties of the filler fraction should predominate, because the mineral filler is immersed in the asphalt binder, and (ii) the mineral filler is responsible for the greater portion of the specific surface generated by the mineral aggregate. The specific surface of the mineral filler can be greater than $1 \text{ m}^2/\text{g}$, while the specific surface of the particles greater than 75 microns may be of the order of a fraction of m^2/g . Due to these findings, the fine aggregate should be the main contributor to any physical-chemical interaction between the surface of the mineral aggregate and the asphalt binder (Anderson et al., 1994).

In order to understand the relation between the properties of the asphalt binder and the properties of the asphalt concrete, it is necessary to define the asphalt mastic properties. The importance of the properties of the asphalt mastic on the performance of the asphalt concrete is evidenced by the large number of studies carried out to define these properties and identify the factors that control them. Several studies indicated that physical properties of the mineral filler, such as gradation, specific surface, and shape, as well as factors related to composition, such as surface mineralogy, can be important variables. The importance of the physical-chemical interaction between the mineral filler and the asphalt binder is recognized and the dependence of the mechanical properties of the asphalt mastic on the nature of this interaction was pointed out by several studies.

The SHRP developed a set of methods to specify the mineral aggregates and the asphalt binders that should be used in the asphalt concrete design, in which the requirements for the asphalt binder and for the design of the asphalt concrete were rigorously developed. In this research, the main properties of the mineral aggregate were selected by a specialist group. The only requirement

of the Superpave specification for the mineral aggregates with a diameter smaller than 0.075 mm is the filler/asphalt ratio between 0.6 and 1.2 in weight. These values were specified to limit the stiffness provided by the mineral filler (Cooley et al., 1998).

However, to limit the filler/asphalt ratio may not be the best alternative, once that it does not allow the stiffening potential of a given asphalt binder to be evaluated. A suitable method to indicate the stiffening potential would correlate a property of the mineral filler to the stiffening potential. A laboratory test proposed by Rigden, that measures the air voids in a sample of mineral filler compacted in a dry condition, provided a good indication of the stiffening potential of a mineral filler (Cooley et al., 1998).

Regarding the interaction between filler and bitumen, Antunes, Freire, Quaresma and Micaelo (2015) and Antunes, Freire, Quaresma, and Micaelo (2016) evaluated the effect of geometric properties, physical properties, and chemical composition of the mineral filler on the filler-bitumen interaction. Concerning the filler properties, they observed a correlation between the specific surface area and the fractional voids and bitumen. The authors also observed that the chemical composition of the mineral filler does not contribute to the mastic stiffening.

Cheng et al. (2016) investigated the performance of four asphalt mastics produced with limestone, hydrated lime, fly-ash or diatomite at intermediate and high temperatures. The filler properties (density, specific surface area, particle size distribution, mineralogy component and hydrophilic coefficient) and the asphalt mastic properties (softening point, viscosity, force ductility and dynamic rheological properties) at high and intermediate temperatures were correlated by means of the grey relational analysis (GRA) method. Based on the GRA results, the specific surface area is the filler property that most influence on the asphalt mastic performance at intermediate and high temperatures. The asphalt mastic produced with diatomite presented higher values for the softening point, viscosity, deformation energy and complex modulus compared to the other three asphalt mastics.

From a sample of asphalt concrete taken from a highway, Shashidhar and Romero (1998) reported that it was possible, by evaluating the transversal section of the sample, to observe three of the elements that comprise the asphalt concrete: the mineral aggregates, the air voids, and the asphalt mastic. The distribution of the elements observed by Shashidhar and Romero (1998) highlights the importance of the asphalt mastic in the workability and performance of the asphalt concrete. A typically dense asphalt concrete can contain for examples up to 5 % of the particles passing sieve #200 and up to 5 % of asphalt binder, both percentages being calculated in relation to the weight of the mixture. This relationship results

in filler/asphalt ratio of 34 and 66 in volume, assuming that the filler mixes with all the asphalt binder present in the mixture. Nevertheless, the filler/asphalt ratio may be higher, once that the asphalt binder that coats the coarse aggregate cannot mix with the filler.

For the filler/asphalt ratio of 34 and 66, the mineral filler would be suspended and the stiffening of the asphalt binder with the presence of mineral filler would be the result of the filling voids and the physical-chemical interactions between asphalt binder and filler (Anderson & Goetz, 1973). This hypothesis would be in contrast to the purpose of the coarse aggregate particles in the asphalt concrete, once that the contact between the aggregate particles plays an important role in the mechanical properties of the asphalt concrete.

Robati, Carter and Perraton (2015) developed a conceptual method capable of defining the optimum filler amount for the asphalt concrete, in order to study the filler stiffening effect on asphalt mastic for microsurfacing. The proposed model is able to predict the mastic stiffness ($|G^*|$) as a function of the filler concentration based on a qualitative relationship between the model parameter (b or stiffening rate) and filler properties as Ridgen voids (RV), effective filler size (D10), pH, and methylene blue value (MBV). The authors validated the model for asphalt mastic with different properties and suggested that the model can be used to predict the optimum filler concentration for cold asphalt concrete mixtures and HMA.

Y.-R. Kim et al. (2003b) mention that the asphalt concrete performance can be enhanced if the asphalt mastic is designed to increase the resistances to fatigue and fracture. Bahia et al. (1999) and Smith and Hesp (2000) reported that the fatigue damage is strongly related to the characteristics of the asphalt binder, along with the properties of the mineral filler and the interaction between asphalt binder and mineral filler. The mineral filler contributes to the increase of fatigue life in tests conducted in controlled strain mode, even with the increase in the stiffness (Y.-R. Kim et al., 2003b). The authors observed that this increase in the fatigue life is due to the lower damage evolution rate and the higher capacity of the mixture to accumulate total damage, using the mechanistic fatigue prediction model based on the viscoelastic continuum damage theory.

Regarding oxidation and stiffening, the mineral filler affects the aging of the asphalt binder by means of two mechanisms. The filler can accelerate the oxidation if it works as a catalyst. In turn, the filler is capable of reducing the aging due to oxidation for being an obstacle for the oxygen reaction. However, Gubler, Liu, Anderson and Partl (1999) observed only the catalyst effect regarding the asphalt mastic stiffness during the aging process.

The effect of the type of mineral fillers in the asphalt mastic was evaluated by Anderson et al. (1994). The asphalt mastic produced with 25-32 vol % limestone, gravel, sandstone and greywacke fillers were submitted to long-term aging in the PAV. The authors reported that it was not possible to observe any measurable difference between the effects of the mineral fillers on asphalt aging. However, S.-C. Huang and Zeng (2007) aged asphalt mastics produced with 20 wt% limestone and granite in the PAV for 100-2000 hours at 60 °C, and observed that both mineral fillers reduced the long-term aging effect in the asphalt mastic.

Wu and Airey (2011) evaluated the effect of different mineral fillers in asphalt mastics aged in the TFOT by means of DSR tests and FTIR tests. The asphalt mastics were produced with 40 vol% limestone (basic filler) or gristone (acidic filler). After the aging process, the asphalt mastics presented lower ageing indices (1.5-1.9) compared to the neat bitumen (2.3), and the lower index of 1.5 was obtained for the asphalt mastic with limestone. The reason for this result is the combination of a catalytic effect of the mineral filler and the adsorption of the lighter components of the bitumen in the mineral porosity, resulting in the adsorption of polar fractions from the asphalt to the filler surface. Besides, the authors observed that the asphalt binder recovered from the asphalt mastic produced with limestone presented more oxidation components than the one produce with gristone at the same aging level. It can be concluded that the basic filler can catalyze much more the asphalt oxidation.

Faxina, Fabbri and Soares (2009) aged the asphalt mastics produced with 15, 30 and 45 vol% of basalt filler in the RTFOT. The aging index at higher temperature significantly changes from the asphalt mastic produced with 30 and 45 vol% compared to the neat asphalt binder. This result shows that the increase in the amount of mineral filler in the asphalt mastic composition influences the performance asphalt mastic in the short-term aged condition.

Another study regarding to the effect of the amount of mineral filler in the asphalt mastic was conducted by Abutalib, Fini, Aflaki and Abu-Lebdeh (2015). The authors aged the asphalt mastic produced with different percentage of silica fume (2, 4 and 8 wt%) and asphalt binder PG 64-22 in the RTFOT, in order to evaluate the effectiveness of silica fume to reduce the oxidative aging of the asphalt binders. Based on the rotational viscosity and complex shear modulus of the asphalt mastics, they observed that the silica fume significantly reduced the aging index of the asphalt binder. They also observed that the increase of the percentage of silica fume in the composition of the asphalt mastic reduced the temperature susceptibility. Abutalib et al. (2015) pointed out that the effectiveness of the silica fume in the reduction of

the oxidative aging of the asphalt binder can be related to the high polarity of the silica fume, once that it has a high surface area and present a low degree of agglomeration.

Lesueur, Teixeira, Lázaro, Andaluz and Ruiz (2016) studied the effect of several mineral fillers (limestone, hydrated lime, granite filler, calcic lime, fine calcic lime, Portland cement and hydraulic lime) to reduce the aging of the asphalt binder. They proposed a new procedure to evaluate the aging of the asphalt binder based on the PAV procedure and the ring ball softening test. In the proposed procedure, the asphalt mastic is produced with 20 wt% of mineral filler and aged in the PAV for 5 hours to simulated the RTFOT aging followed of 20 hours of PAV to simulate the RTFOT+PAV aging. The authors used the PAV to simulate both the short-term and long-term aging due to the problems related to the measurement of the viscosity when mineral filler is added to the asphalt binder. The variation in the R&B softening point parameter after and before aging was adopted to evaluate the effect of different mineral fillers with aging level. The results obtained from this method showed that hydrated lime is more efficient in reduce the asphalt aging compared to the active fillers such as Portland cement and hydraulic lime. Other mineral fillers such as granite and limestone did not reduce the stiffness of the asphalt binder with the aging level.

3 STUDY OF FAM DESIGN METHODS

The main objective of this chapter is to present a preliminary study carried out during this research regarding the applicability of some FAM design methods present in the literature for the FAMs prepared with modified asphalt binders. This chapter discusses about the limitations in the replication of those methods when modified asphalt binders are used, and the viability of using the specific surface concept to estimate the FAM binder content. This chapter is divided in five sections. The first section is a brief introduction about the design methods available in the literature review, and used in this preliminary study to define the binder content of the FAMs prepared with modified binders. The second section presents the materials used to prepare the FAMs. The third section describes the design methods used in this preliminary study to define the binder contents for the FAMs prepared with modified binders. The fourth section shows the results and findings obtained by using these design methods, and the fifth section presents the conclusions on the applicability of these design method for the FAMs prepared with modified binders.

3.1 INTRODUCTION

Cracking is generally thought of as a phenomenon that develops from a micro to a macro scale and because of that the fine portion of the asphalt concrete can be used as a representative scale for the development of this phenomenon in the asphalt concrete. Taking this hypothesis into account, some researchers (Kim 2003; Zollinger 2005; Castelo Branco 2008) started to study the fatigue characteristics of the FAM, assuming that they are directly associated with the fatigue behavior of the asphalt concrete. FAM is defined as a portion of the asphalt concrete composed of fine aggregates, filler, binder and air voids that represents a scale between asphalt mastic and asphalt concrete.

The studies with FAM have been getting prominence since a good agreement for the properties between the FAM and asphalt concrete was reported by researchers (Arambula et al. 2007; Caro et al. 2008; Underwood, Kim 2011; Motamed et al. 2012; Coutinho 2012; Im et al. 2015; Gudipudi, Underwood 2015; Nabizadeh 2015; Haghshenas; 2016). This matrix presents an internal structure that is more homogenous than the one presented by the asphalt concrete (Masad et al 2006). Another advantage of working with FAM is the reduced size of the samples: FAM samples generally have about 12 mm in diameter and 45 to 50 mm in height. This might

represent a considerable reduction in material consumption and laboratorial work compared to the amount of material and time needed to prepare asphalt concrete specimens.

In spite of the growing number of investigations in this area, there is no consensus between the researchers about a proper design method that can be applied to most materials used to produce asphalt concrete mixtures and that could represent the FAM fraction within the asphalt concrete. The air voids content that best represents the FAM is not well known and, because of that, the methods developed to determine the binder content of the fine aggregate matrix tend to be empirical, and based on the binder content obtained in the asphalt concrete design. Kim (2003) started first adopting a fixed value of 8 % for the binder content, which represents an asphalt film thickness of 10 microns. After that, Castelo Branco (2008) proposed a procedure to define the binder content based on the assumption that the FAM binder content is equal to the binder content needed to cover all of the aggregate particles, such as coarse aggregate, fine aggregate, and filler. Karki (2010) adopted the same assumption presented by Kim (2003) and proposed calculations based on a film thickness of 12 microns. Other researchers suggested empirical methods: Coutinho et al. (2011) determined the FAM binder content using the solvent extraction binder method and Sousa et al. (2013) used the ignition method.

This subject becomes more complex when one thinks of a way to determine the binder content for a FAM prepared with a modified asphalt binder. The first attempt in addressing this challenging issue is to apply the existing methods in order to check their applicability to FAMs prepared with modified asphalt binders. In this research, one neat asphalt cement (AC) and three modified ones (AC+PPA – polyphosphoric acid, AC+SBS – styrene-butadiene-styrene copolymer, and AC+rubber) were submitted to some methods available in the literature to determine the FAM binder content: Castelo Branco (2008), Coutinho et al. (2011) adapted by Freire (2015) and Sousa et al. (2013).

In view of the shortcomings observed during the application of the existing FAM design methods to modified asphalt binders, a method that determines the optimum binder content of the FAM produced with modified binders, based on the specific surface concept and the optimum binder content for the asphalt concrete was evaluated. In order to represent the fine aggregate matrix present in the asphalt concrete produced with a certain modified asphalt binder, was considered the natural proportionality between the FAM binder content and the binder content of the asphalt concrete produced with that same modified binder. This

assumption was made considering the idea behind of the study with fine aggregate matrix, which is to represent the fine portion of the asphalt concrete.

The binder contents of the FAMs produced with modified binder was obtained by multiplying the reference binder content (binder content of the FAM produced with the neat binder) by a ratio specific for each modified asphalt binder. This ratio was calculated by dividing the binder content obtained in the design of the asphalt concrete produced with each modified asphalt binder by the binder content of the asphalt concrete produced with the conventional asphalt binder. This procedure is simpler and free from some limitations associated with experimental methods used to determine the FAM binder content, like those that will be discussed in this chapter.

3.2 MATERIALS AND TEST PROCEDURES

One source of basalt rock and four asphalt binders, one neat and three modified ones, were used to produce the FAM samples. The modifier used were: (i) a mesh #30 crumb rubber obtained from the tread layer of passenger vehicle tires, (ii) the Kraton D1101 linear triblock SBS copolymer, presenting a polystyrene content of 31 % and (iii) the Innovalt E200 PPA provided by Innophos. The modifier contents were chosen aiming to shift the high-temperature PG from 64 (neat binder) to 76: 1.2 % of PPA, 4.5 % of SBS copolymer, and 14 % of crumb-rubber. A 722D Fisatom low-shear mixer was used to prepare the AC+PPA and a L4R Silverson high-shear mixer was used to produce the AC+SBS and the AC+rubber.

As far as aggregate gradation is concerned, the main assumption in studies with FAM is that it represents the fine portion of the aggregate gradation of the asphalt concrete. For this reason, the material passing sieve #10 was used to produce the FAM samples. This sieve was chosen because the sieve #16 (commonly used to represent the FAM in international studies) does not make part of the sieve series of Brazilians standards for asphalt concrete mixtures. There are also evidences (Freire et al. 2014) that the fatigue characteristics of the samples made with particles passing sieve #10 and #16 are not affected by aggregate size. In other words, this means that both aggregate sizes can be used to represent the FAM. By adopting this particle size, the ratio between the aggregate size and sample diameter is 1:6, which is higher than the minimum of 1:3 recommended by Kim et al. (2004).

The percentage of aggregates passing the sieves below sieve #10 is determined by Equation 3.1, where #ii represents the sieves below sieve #10. Figure 3.1 shows the aggregate gradations of the asphalt concrete and the corresponding FAM. The asphalt concrete used here

is a typical dense-graded hot mix asphalt (HMA) for road construction in Brazil. The mixing and compaction temperatures were established according to the AASHTO TP4 and ASTM D 4402-02M-15 procedures. Measurements of rotational viscosity were carried out using a Brookfield viscometer model DV II + PRO with spindle 21. The mixing and compaction temperatures, respectively, are 152 and 140 °C for the neat binder, 164 and 154 °C for the AC+PPA, 180 and 169 °C for the AC+SBS, and 193 and 187 °C for the AC+rubber.

$$\frac{\text{Mass of aggregate passing sieve \#ii in full mixture}}{\text{Mass of aggregate passing sieve \#10 in full mixture}} \times 100\% \quad (3.1)$$

Figure 3.1 – Aggregate gradation of the HMA and the FAM

3.3 DETERMINATION OF THE FAM BINDER CONTENT

The first step in this study was to replicate the FAM design procedures developed by Castelo Branco (2008), Coutinho et al. (2011) – later adapted by Freire (2015), and Sousa et al. (2013), in order to answer three key questions: (i) are they able to yield equal or at least comparable results?, (ii) are they applicable to modified asphalt binders?, and (iii) are the binder contents obtained in these methods proportional to the ones obtained in the asphalt concrete design?

Castelo Branco (2008) determined the FAM asphalt content based on the following two assumptions: (i) the FAM binder content is equal to the one presented by the fine aggregate matrix of the asphalt concrete, and (ii) the quantity of mineral aggregate smaller than 1.18 mm

in the FAM is proportional to the one present in the asphalt concrete. In turn, Coutinho et al. (2011) and Sousa et al. (2013) suggested empirical methods. In order to define the FAM binder content, Coutinho et al. (2011) adopted the solvent extraction binder method (AASHTO T164) and Sousa et al. (2013) adopted the ignition method (AASHTO T 308). Both methods calculate the FAM binder content taking into account only the fine portion of the mixture passing the sieve #10 (for Coutinho et al. 2011) or #16 (for Sousa et al. 2013), regardless of the amount of fine aggregate matrix adhered to the coarse aggregate. Later, Freire (2015) proposed a correction in the calculations presented by Coutinho et al. (2011), in order to include the fine matrix adhered to the coarse aggregate particles in the calculations.

3.3.1 Method Proposed by Castelo Branco (2008)

The determination of the FAM binder content according to the method proposed by Castelo Branco (2008) must follow the steps below:

- a) obtain information about the HMA: mass of full mixture (W_{HMA}), gradation, percent mass of aggregates passing sieve #16 ($\%pass\#16$), binder content ($\%P_{b,HMA}$) and mass of asphalt (W_b) – this last item is obtained by applying Equation 3.2;
- b) calculate the mass of aggregates ($W_{agg, FAM}$) of the HMA passing sieve #16 (1.18 mm) (Equation 3.3) and build the aggregate gradation curve for the FAM keeping the same proportions of the full HMA for each fraction passing sieve #16;
- c) adopt the total mass (W_{SGC}) to be used to produce the samples with 90 mm in height and 150 mm in diameter in the SGC;
- d) calculate the mass of each aggregate fraction used to produce the FAM samples ($W_{agg,MAF}$);
- e) calculate the binder content present in the FAM ($\%P_{b,FAM}$) and the mass of binder for the FAM samples ($W_{b,FAM}$) (Equation 3.4 and 3.5)

$$W_b = W_{HMA} \cdot \%P_{b,HMA} \quad (3.2)$$

$$W_{agg,FAM} = \%pass\#16 \cdot W_{HMA} \quad (3.3)$$

$$\%P_{b,FAM} = \frac{W_b}{W_{agg,FAM} + W_b} \quad (3.4)$$

$$W_{b,FAM} = W_{SGC} \cdot \% P_{b,FAM} \quad (3.5)$$

As mentioned earlier, sieve #16 is not part of the Brazilian sieve series and because of that the calculations were done using sieve #10 in place of sieve #16.

3.3.2 Method proposed by Coutinho et al. (2011) and later adapted by Freire (2015)

In order to obtain the FAM binder content using the method proposed by Coutinho et al. (2011), the following steps must be run with the loose HMA mixture:

- a) separation of 1,000 g of loose HMA in two fractions using the sieve #10 (2.00 mm): material retained in the sieve #10 (coarse aggregate covered by mastic and fine aggregate covered by asphalt and adhered to the coarse particles), W_c , and (ii) material passing sieve #10 (fine aggregates covered by asphalt), W_f ;
- b) binder extraction of the two portions obtained in the previous step; obtention of the total mass retained in sieve #10 (W_{ca}), the mass of asphalt in the fraction retained in sieve #10 ($W_{cb} = W_c - W_{ca}$), the total mass passing sieve #10 (W_{fa}) and the mass of asphalt in the fraction passing sieve #10 ($W_{fb} = W_f - W_{fa}$);
- c) fractioning of the mass of aggregates retained in sieve #10 in order to obtain two portions: (i) mass of coarse aggregate (W_{cac}) and (ii) mass of fine aggregate adhered to coarse aggregate (W_{caf}).

The binder content present in the material passing sieve #10 (C_{FAM}) is obtained by Equation 3.6:

$$C_{FAM} = \frac{W_{fb}}{W_f} \quad (3.6)$$

A critical aspect in this procedure is the disregard of the fraction of FAM adhered to the coarse aggregates, however, Freire (2015) proposed a correction in the formula presented by Coutinho et al. (2011) to obtain the FAM binder content taking into account the fraction of FAM adhered to the coarse aggregates. In the conception of this formula, Freire (2015) assumed that the binder content of the FAM adhered to the coarse aggregates is equal to the binder content of the FAM passing sieve #10. The corrected FAM binder content is calculated by Equation 3.7.

$$C_{FAM} = \frac{W_{fb} + W_{cbf}}{W_f + W_{caf} + W_{cbf}} \quad (3.7)$$

3.3.3 Method proposed by Sousa et al. (2013)

The procedure is comprised of the following steps:

- a) three portions of loose HMA are prepared - the minimum amount depends on the nominal maximum aggregate size (NMAS) of the mineral aggregate (according to AASHTO T209): 4,000 g for NMAS of 37.5 mm, 2,500 g for NMAS of 19.0 mm or 25 mm, and 1,500 g for NMAS lower than 12.5 mm;
- b) the three samples are aged for 2 hours at 135 ± 5 °C, according to AASHTO T209; in the sequence, the loose samples are taken from the oven and allowed to cool for 30 min; the mixture particles are separated by hand before the mass gets totally cooled;
- c) mechanical sieving is used to screen the samples in sieves #4, #8 and #16; stainless steel balls of 9.5 mm in diameter are recommended to facilitate the separation of the particles; in this study, for practical purposes, sieves #4, #8, and #16 were replaced, respectively, by sieves #3/8", #4, and #10 in order to adapt the sieve intervals to sieve #10 once that sieve #16 is not part of the Brazilian standard sieve series;
- d) after fractioning, the material is separated into the following groups: (i) material retained in sieve #3/8"; (ii) material passing sieve #3/8" and retained in sieve #4; (iii) material passing sieve #4 and retained in sieve #10; and (iv) material passing sieve #10; after that, each group of material is dried at 110 °C;
- e) in the sequence, each group of material is weighted in order to register the mass of the pan (W_p) and the mass of the pair pan+sample (W_{Mi}); the containers are taken to the ignition oven at 427 °C for asphalt extraction; after extraction, the mass of aggregate for each group is determined, in which W_{Ai} is the mass of the pan with the material after the asphalt extraction process

Equation 3.8 is used to calculate the binder content of each group. The FAM binder content is the one calculated for group 4 (material passing sieve #10).

$$P_{bi} = \frac{W_{Mi} - W_{Ai}}{W_{Mi} - W_p} \cdot \% , \text{ where } i = 1 \text{ to } 4 \quad (3.8)$$

3.3.4 Determination of the FAM binder content by means of the specific surface of the mineral aggregate

After the reproduction of the design methods proposed by Castelo Branco (2008), Coutinho et al. (2011) adapted by Freire (2015), and Sousa et al. (2013) for the materials used in this study, five issues of concern related to the determination of the FAM binder content came up: (i) excessively high binder contents, (ii) no proportionality between the FAM binder contents and the HMA binder contents when modified asphalt binders were used, (iii) influence of particulate materials present in the composition of the modified asphalt binders, like SBS copolymer or crumb rubber, in the calculations; (iv) inefficiency of the extraction method for modified asphalt binders and (v) inefficiency of the fractionation method for modified binders, because of the difficulty in separating mixture particles by hand. These shortcomings raised concerns about the applicability of these procedures for the materials studied here. In order to get over these issues, an alternative FAM design method was tested, following the procedure developed by Duriez (Arrambide and Duriez, 1959) to estimate the AC binder content and based on the richness modulus “K” and the surface area or specific surface (Ss).

The specific surface coefficient related to each sieve interval developed by Duriez (Arrambide and Duriez, 1959) was adapted to (i) the sieve set adopted in this study, (ii) the FAM gradation (particle sizes smaller than 2.00 mm), and (iii) the aggregate density used in this study. The specific surface coefficient for each sieve interval is calculated by Equation 3.9, where S is the specific surface coefficient (m^2/kg), A is the particle area (m^2), V is the particle volume (m^3), and ρ is the weighted average bulk specific density of fine aggregates and filler (g/cm^3).

$$S = \frac{A}{V \cdot \rho} \quad (3.9)$$

Assuming the shape of the aggregate particles as a perfect cube, area and volume can be calculated according to Equation 3.10 and 3.11, where “ a ” is the face of the cube (m). The diagonal of the cube (Equation 3.12) is defined by the average of the nominal maximum aggregate diameter for each sieve interval used to produce the FAM. Equation 3.13 describes the specific surface of a basalt aggregate with $\rho_{\text{real}} = 2.957$, where S_{SFAM} is the specific surface

of the aggregates of the FAM (m^2/kg), $P_{2.00} - P_{0.42}$ is the percent of particles between 2.00 mm and 0.42 mm, $P_{0.42} - P_{0.18}$ is the percent of particles between 0.42 mm and 0.18 mm, $P_{0.18} - P_{0.075}$ is the percent of particles between 0.18 mm and 0.075 mm, and $P_{0.075}$ is the percent of particles smaller than 0.075 mm.

The FAM asphalt content can be calculated by Equation 3.14, where $P_{b, \text{FAM}}$ is the FAM binder content for the total weight of the mixture, S_{FAM} as calculated by Equation 3.13, and K is the richness modulus. According to Arrambide and Duriez (1957), the K value for a dense mixture is 3.75 and for a mixture with high binder content is 4.5. Based on this, it was assumed that the interval for the K value between 3.75 and 4.5 is acceptable for FAMs.

$$A = 6a^2 \quad (3.10)$$

$$V = a^3 \quad (3.11)$$

$$d = a\sqrt{3} \quad (3.12)$$

$$S_{\text{FAM}} = \frac{2.90 (P_{2.00} - P_{0.42}) + 11.71(P_{0.42} - P_{0.18}) + 27.56(P_{0.18} - P_{0.075}) + 135(P_{0.075})}{100} \quad (3.13)$$

$$P_{b, \text{FAM}} = \frac{100K\sqrt[5]{S_{\text{FAM}}}}{100 + (K\sqrt[5]{S_{\text{FAM}}})} \quad (3.14)$$

Aggregate absorption is another important property that must be included in the calculations. Fine aggregate absorption is obtained by means of the procedure ASTM C128-15. The FAM binder content is obtained by Equation 3.15, where $P_{b, \text{final, FAM}}$ is the FAM binder content, $P_{b, \text{FAM}}$ is the binder content according to Arrambide and Duriez (1957), and $\%A_{\text{abs}}$ is the fine aggregate absorption (%).

$$P_{b, \text{final, FAM}} = P_{b, \text{FAM}} \times (1 + \%A_{\text{abs}}) \quad (3.15)$$

The binder content for the FAMs prepared with the modified asphalt binders was determined following two steps: (i) the binder content for the FAM produced with the neat asphalt binder was calculated using the specific surface method, and (ii) the binder content calculated in Equation 3.15 was multiplied by the ratios between the binder contents of the AC prepared with the modified asphalt binders and the one prepared with the conventional binder.

3.3.5 Preparation of the FAM samples

Specimens with 100 mm in diameter were compacted in the SGC, with a pressure of 600 ± 18 kPa and a gyration angle of $1.25 \pm 0.02^\circ$. Both ends of the specimens were sawed, aiming to obtain a more homogeneous air voids distribution. The criterion to stop the compaction was a number of gyrations of 100, the same used for AC. The FAM samples were extracted using a diamond drill coupled to a drilling machine.

3.4 RESULTS AND FINDINGS

3.4.1 Study of the FAM Design Methods

In order to check the applicability of some procedures available in the literature to define the optimum binder content of the FAMs evaluated here, the methods proposed by Castelo Branco (2008), Coutinho et al. (2011) adapted by Freire (2015), and Sousa et al. (2013) were carried out. In parallel, the procedure based on the specific surface concept was also performed. Figure 3.2 presents the binder contents for the HMA and for the FAMs produced with basalt and the four asphalt binders. The results obtained for the Coutinho's method corresponds to only one test. The results obtained for the Sousa's method correspond to only one test for the FAMs prepared with the neat binder and the AC+PPA. At this stage, it was noticed that the results obtained by the specific surface method for the FAMs prepared with the neat binder and the AC+PPA matched the Sousa's method. Because of that, it was decided not to replicate the Coutinho's method. The main reason for that is that the Coutinho's method yielded results much lower than those obtained by the other two methods. For the FAMs prepared with the AC+rubber and the AC+SBS, the variability between two replicates carried out by the same operator was 6.9 and 4.8 %, respectively. For the FAM prepared with the neat binder and using the Sousa's method, two operators carried out the procedure in order to check the variability among different operators. In the following subsections, a discussion about the main shortcomings in each of the assessed methods is presented.

Figure 3.2 – Binder contents of the HMA and of the FAMs according to some methods available in the literature

3.4.2 Method Proposed by Castelo Branco (2008)

The values in Figure 3.2 indicate that the highest binder contents for the FAMs were obtained using the procedure proposed by Castelo Branco (2008). In order to check the adequacy of the binder contents obtained by means of this method, the FAM produced with the neat asphalt binder was compacted in the SGC. The compaction was carried out with no difficulties, but, on the other hand, it was not possible to extract the cylindrical FAM samples from the SGC specimen. The FAM samples broke during the extraction and it is believed that this happened because of the excess of asphalt binder. In spite of the use of water for refrigeration during the extraction process, the asphalt binder melted due to the overheating caused by friction between the diamond drill and the sample. The difficulties observed during the extraction of the samples produced with the materials studied here cast some doubts on the effectiveness of the method as a good tool to determine the binder content for the fine portion of the HMA. Nevertheless, it is worthy to mention that this does not mean that this method would not work for any kind of material or should never be used.

3.4.3 Method Proposed by Coutinho et al. (2011) and Adapted by Freire (2015)

The method proposed by Coutinho et al. (2011) and adapted by Freire (2015) resulted in the lowest binder contents for the FAMs, compared to the other methods, with values ranging from 6.1 to 6.4 %. The FAM produced with the neat asphalt binder was compacted in the SGC, in order to check the adequacy of the binder contents obtained by means of this method. During

the mixing process, it was observed that the aggregate particles were not completely covered by asphalt. This low binder content had reflection on the compacted sample, resulting in an inadequate densification of the sample (a very porous mixture was obtained, revealing high air voids). This is believed to be the result of the use of an amount of binder that was insufficient to cover the aggregate particles perfectly.

Table 3.1 – Calculations to obtain the FAM binder content according to the method proposed by Coutinho et al. (2011) and adapted by Freire (2015) and some additional information

row	item	neat	AC+PPA	AC+SBS	AC+rubber
1	Binder contents of the HMA (%) ^a	4.4	4.6	4.9	5.5
2	Mass of material passing sieve #10 before extraction (g)	143.9	64.6	87.1	194.0
3	Mass of material passing sieve #10 after extraction (g)	134.4	60.2	81.5	181.8
4	Mass of binder covering the material passing sieve #10 (g) [2-3]	9.5	4.4	5.6	12.2
5	Asphalt binder (%) (4/2)	6.6	6.8	6.4	6.3
6	Mass of material retained in sieve #10 before extraction (g)	1,398.0	1,117.4	1,093.6	985.9
7	Mass of material retained in sieve #10 after extraction (g)	1,350.5	1,067.8	1,049.0	954.7
8	Mass of material passing sieve #10 adhered to the coarse aggregate (g)	368.7	338.2	315.1	208.2
9	Mass of binder covering the fine material adhered to the coarse aggregate (g) (5*8)	24.33	23.04	20.26	13.09
10	FAM binder content (%) [(4+9)/(3+4+8+9)]	6.3	6.4	6.1	6.1
11	Percentage of material smaller than 2.00 mm after sieving [2/6]	10.3	5.8	8.0	19.7
12	Percentage of modifier in the modified asphalt binders	na	1.2	4.5	14.0
13	Percentage of asphalt in the modified asphalt binders [100% - row 12]	na	98.8	95.5	86.0
14	Binder content of the HMA discounting the amount of modifier [row 1 – (0.01*row 12*row 1)]	4.4	4.5	4.7	4.7

^abinder contents obtained for a 4 % target value for air voids

The calculations are presented in Table 3.1. Some problems were found when applying this method to the modified binders. The first is related to the FAM produced with the asphalt-rubber binder: it was not possible to extract 100 % of the fine aggregate matrix adhered to the coarse aggregate particles. This is clearly due to the difficulty in diluting the modified binder in kerosene. Figure 3.3 (a) shows the final aspect of some coarse aggregate particles after the extraction process – the dark areas correspond to regions covered by mastic. Residual mastic was also observed covering the coarse aggregates of the mixture compounded with AC+SBS, but in a lower amount when compared with the area covered by mastic for the mixture compounded with the AC+rubber. No mastic covering the aggregates was observed for the mixtures prepared with the neat binder and the AC+PPA. For purpose of comparison,

Figure 3.3 (b) shows some coarse aggregates obtained from the mixture prepared with the AC+PPA after extraction, where it is clearly visible that the particles are completely washed out.

Figure 3.3 – (a) Mastic covering the aggregate after extraction with kerosene for the mixture compounded with the AC+rubber, and (b) particles of the mixture compounded with the AC+PPA with no mastic on the top

It is possible to infer that the use of a modified binder with particulate materials, like SBS copolymer and crumb rubber, can make this method unfeasible for this sort of materials in particular. It is believed that the accumulation of mastic in the surface of the coarse aggregates, as a result of the inefficiency of the extraction process, resulted in a mass of aggregate that is higher than the real one. Because the aggregate mass is higher, the resulting binder mass is lower and, consequently, lower binder contents are obtained. These results are completely opposite to the tendency of increasing binder content for the modified asphalt binders obtained in the HMA designs and, because of this, it is possible to infer that the extraction process was the main cause of the inefficiency of this method when applied specifically to modified asphalt binders, like the AC+SBS and the AC+rubber.

The second problem associated with the use of the procedure proposed by Coutinho et al. (2011) lays on the percentage of material with particle sizes lower than 2.00 mm obtained after sieving. Looking at row 11 of Table 3.1, it is possible to notice that the percentage of material passing sieve #10 varies expressively. It is believed that this happened because of the agglutination capacity of each asphalt binder. Data in Row 14 show that the effective binder content of each mixture design is quite similar. Taking the agglutinating capacity of the pure binder as reference, one can see that the percentage of material passing sieve #10 is slightly lower for the HMA produced with the AC+PPA and the AC+SBS. This happened because the amount of fine particles adhered to the coarse aggregates is higher for the HMA prepared with the AC+PPA and the AC+SBS. This might indicate that these binders present a higher capacity

of agglutinating the finest particles in such a way that they form lumps larger than the sieve opening. The opposite might have occurred with the HMA prepared with the AC+rubber: the agglutinating capacity is supposed to be lower than the one imparted by the AC+PPA and the AC+SBS due to the nature of the interaction between crumb rubber and binder: crumb rubber swells during the processing of the asphalt binder without any reactions that could represent some gain in terms of agglutinating capacity. This problem was solved with the correction in the calculations, proposed by Freire (2015), in order to consider the mass of fine aggregates adhered to the coarse aggregates.

A third difficulty encountered when using the method proposed by Coutinho et al. (2011) and adapted by Freire (2015) is related to the binder contents: this procedure was not able to differentiate the binder contents of the FAMs produced with different modified binders, as it is expected when taking into account the HMA binder contents. The binder contents ranged from 6.1 to 6.4 % for the FAMs produced with the modified binders, while the binder contents for the HMA produced with the same materials varied from 4.4 to 5.5 %. If the hypothesis that the FAM represents the fine matrix of the full mixture is true, then the binder content of the fine matrix of the HMA should be directly proportional to the binder content of the full HMA. It can be easily concluded that this method is not able to estimate binder contents proportional to those obtained in the HMA design. In other words, this method is not able to take account of the effect of the type of asphalt binder on the binder content of the fine matrix of the HMA.

Another aspect that stands out from the data presented in Table 3.1 is the fact that the binder content for the FAM produced with the conventional binder (6.3 %) resulted higher than the binder contents obtained for two out the three FAMs produced with modified asphalt binders, i. e., AC+SBS (6.1 %) and AC+rubber (6.1 %). Additionally, it also draws one attention the fact that the binder content for the FAM produced with the asphalt-rubber binder resulted equivalent to the one obtained for the AC+SBS. The latter observation is absolutely opposite to what is expected when determining the binder content for mixtures prepared with asphalt-rubber binders, i. e., the binder contents for such materials are generally 1 % (or more) higher than the binder contents for HMA produced with non-modified asphalt binders (see row 1). Even when comparing the binder contents for HMA prepared with asphalt binders modified with SBS copolymer and asphalt-rubber binders, it is natural to expect slightly higher binder contents for the HMA prepared with asphalt-rubber binders (Pilati, 2008; Onofre, Castelo Branco, Soares, & Faxina, 2013; Domingos, 2017).

This extended discussion is intended to go deep into the results but it is also very important in terms of highlighting shortcomings related to the application of this method particularly to modified asphalt binders. As previously mentioned for the method proposed by Castelo Branco (2008), it is not meant that this method would not work for any kind of modified asphalt binder or should never be used.

3.4.4 Method Proposed by Sousa et al. (2013)

A muffle furnace (EDG, model 3P-S) was used in substitution for the ignition oven used by Sousa et al. (2013) and the calcination of the asphalt binder was carried out at 500 °C. In this procedure, the calculation of the FAM binder content takes into account only the material whose particle sizes are smaller than 1.18 mm (sieve #16) discounting any fine aggregate particles glued to the coarse aggregate particles. Because of this, it was investigated the particle size distribution of the fine aggregate particles glued to the coarse portion, in order to check if differences could be found between the gradation of the fine portion passing sieve #10 (adapted for the standard sieve series in Brazil) and the fine portion glued to the coarse portion. If these two gradations were different, in the case, for example, of one being finer than the other, one portion would need more asphalt to cover the particles than the other and then the disregard of the fine portion glued to the coarse aggregates could lead to a higher or lower FAM binder content.

As can be seen in Figure 3.4, the fine aggregates glued to the coarse portion follows the same distribution of the fine portion of the HMA and this was observed for the four asphalt binders. In other words, the aggregate gradation of the fine portion passing sieve #10 is not different from the aggregate gradation of the fine portion glued to the coarse aggregate to an extent that it could affect the calculations to obtain the FAM binder content. Because of this, it is possible to conclude that the disregard of the fine material glued to the coarse aggregates does not interfere in the calculations of the FAM binder contents for the asphalt binders used here, in particular the modified ones.

The method proposed by Sousa et al. (2013) is an experimental procedure and, because of this, it was necessary to check the variability of the binder content values when different operators run the method. The mixture tested in this experiment considering two operators was the reference mixture made of basalt and neat asphalt. For the operator A, the FAM binder content was 7.6 % and for the operator B it was 7.3 %, resulting in a variability of 4.0 %. This level of variability is supposed to be related to the quantity of material with particle sizes smaller

than 2.00 mm used to calculate the FAM binder content: an equal amount of loose asphalt concrete was given to both operators and the quantity of fine aggregate after sieving for operator A was 110.54 g and for operator B was 189.37 g. Based on these results, it can be concluded that the method is reproducible.

For the FAMs prepared with the modified binders, the procedure proposed by Sousa et al. (2013) resulted in a binder content of 8.0 % for the FAM prepared with the AC+PPA and 7.8 % for the FAM prepared with the AC+SBS. Assuming that the FAM represents the fine matrix of the full mixture and that the binder content of the fine matrix of the HMA should be directly proportional to the binder content of the HMA, it can be said that these results are in contrast with those obtained for the HMA design, where the binder content of the mixture prepared with the AC+PPA (4.7 %) is lower than the one for the mixture prepared with the AC+SBS (5.0 %). The binder content of the mixture prepared with the AC+rubber was 9.8 %, which can be considered very high, once that most of the FAM samples broke during extraction. It was observed that the rupture of the samples during extraction was related to the use of an excessively high binder content. Problems in the extraction of samples from SGC samples with excessively high binder contents were also reported previously during the extraction of samples prepared according to the procedure proposed by Castelo Branco (2008).

Another complementary experiment was run in order to check if the modified asphalt binders could have contributed with some particulate material that could interfere in the calculations of the FAM binder contents. This was done because it is widely known that the determination of the binder content of an AC prepared with an asphalt binder modified with particulate materials, like asphalt-rubber, is a very hard task. Residuals of these particulate materials can be mixed with the mineral aggregates, affecting directly the calculation of the binder content.

One hundred grams of each asphalt binder were put in the muffle furnace to determine the mass of the residuals after calcination. The following percentages of residuals were found: 0.03 % for the neat binder, 0.14 % for the AC+PPA, 0.07 % for the AC+SBS, and 2.30 % for the AC+rubber. The masses of the residuals were discounted from the mass after extraction, once that this value should include only the mass of the mineral aggregates. After the calculations, the corrected binder content for the neat binder did not change. On the other hand, it changed from 8.0 to 7.9 % for the AC+PPA, from 7.8 % to 7.7 % for the AC+SBS, and from 9.8 to 9.5 % for the AC+rubber. These variations in the binder content for the AC+PPA and for the AC+SBS could be considered insignificant, but, on the other hand, the variation for the

AC+rubber might be an issue of concern. Considering that the residuals from the asphalt binders modified with particulate materials are able to interfere in the final calculations of the FAM binder content, it is recommended that a complementary experiment, like the one ran here, should be performed in order to discount the mass of the residuals and obtain a corrected FAM binder content.

Figure 3.4 – Aggregate gradation for the HMA, the FAM, and the fines glued to the coarse portion

By comparing the FAM binder contents provided by the method proposed by Sousa et al (2013) with the binder contents of the HMA, it is possible to conclude that the method is able to yield FAM binder contents that are proportional to the ones observed for the

HMA, except for the FAM produced with the AC+SBS. In order to check the results, the test was replicated but the results of the two runs were exactly the same, confirming the FAM binder content originally determined. The hypothesis for this lack of correspondence is some aspect specifically related to the nature of the asphalt binder and not to the method. On the other hand, it is also possible to say that the method was not able to produce a FAM binder content proportional to the one found for the HMA when an asphalt binder produced with SBS copolymer was used.

3.4.5 Procedure based on the specific surface of the mineral aggregate

The specific surface coefficient for each sieve interval was calculated assuming: (i) the shape of the aggregate particles as a perfect cube; (ii) the diagonal of the cube for each sieve interval as the average of the nominal maximum aggregate diameter of each sieve interval, and (iii) the weighted average bulk specific density of fine aggregates and filler (ρ). The specific surface coefficients (S) shown in Table 3.2 were obtained using Equation 3.9, 3.10, 3.11, and 3.12. For the portion of particle sizes smaller than 0.075 mm, the coefficient 135 was adopted based on the recommendation by Arrambide and Duriez (1957), once that the calculated value (93.71) is much lower than the one recommended by them. This value (93.71) was calculated with basis on the assumption that all particles passing sieve #200 have an equivalent diameter of 75 microns. This is obviously not true, and because of that, the original coefficient presented by Arrambide and Duriez (1975) was adopted. The percentage of mineral aggregate presented in Table 3.2 for each sieve interval was calculated using Equation 3.1, where the quantity of mineral aggregate is defined with basis on the proportion of material with particle sizes smaller than 2.00 mm in the full mixture. Therefore, for a basalt with a SS_{FAM} of 29.75 m²/kg, an absorption coefficient of 0.6 %, and adopting a richness modulus (K) of 4 (K varies from 3.75 for a dense mixture to 4.5 for a mixture with high binder content), the binder content calculated for the FAM prepared with the neat binder is 7.4 %. If the spherical shape for the aggregate particles is considered, the calculated binder content is 7.2 %, what shows that the assumption of a cubic or spherical shape for the particles leads to similar results.

A serious matter of concern regarding the application of the specific surface method to modified asphalt binders is related to the fact that this method was outlined with basis on, and for, unmodified binders only. At this point, it is important to remember the reader that, as mentioned earlier, the binder content for the FAMs prepared with the modified asphalt binders was determined following two steps: (i) the binder content for the FAM produced with the neat

asphalt binder was calculated using the specific surface method, and (ii) the binder content calculated in Equation 3.15 was multiplied by the ratios between the binder contents of the HMA prepared with the modified asphalt binders and the one prepared with the conventional binder. This procedure was outlined with basis on the hypothesis that the FAM represents the fine matrix of the full mixture and that the binder content of the fine matrix of the HMA should be directly proportional to the binder content of the HMA.

Table 3.2 – Specific surface coefficients and the percentage of mineral aggregate for each sieve interval

	2 to 0.42 mm	0.42 to 0.18 mm	0.18 to 0.075 mm	Smaller than 0.075 mm
P			2.957	
d (cm)	1.21E-01	3.00E-02	1.28E-02	3.75E-03
A (cm ²)	2.93E-02	1.80E-03	3.25E-04	2.81E-05
V (cm ³)	3.41E-04	5.20E-06	3.99E-07	1.01E-08
S (m ² /kg)	2.90	11.71	27.56	135
P (%)	100	47	28	17

By applying this procedure, the following results were obtained: for the HMA, the ratios between binder contents are 1.06 (4.66/4.37) for the AC+PPA, 1.13 for the AC+SBS, and 1.26 for the AC+rubber. By applying these ratios to the FAMs, starting with a binder content of 7.35 % for the FAM prepared with the neat asphalt, the resulting binder contents for the FAMs produced with modified asphalt binder are: 7.8 % (AC+PPA), 8.3 % (AC+SBS), and 9.3 % (AC+rubber).

3.4.6 Air voids from samples produced using the FAM binder content obtained by means of the proposed procedure

The distribution of air voids of the four FAMs cored from SGC specimens is illustrated in Figure 3.5. The proposed method resulted in air voids ranging from 1.8 % to 4.6 %. These values are acceptable and can be considered representative of the air voids present in the fine portion of an HMA. A research conducted by Underwood and Kim (2012), by means of computer tomography images of HMA, concluded that the FAM contains from 40 to 70 % of the air voids of a full HMA. Taking such range in account and the conventional target air voids for HMA of 4 %, it is assumed that the FAM air voids could range from 1.6 to 2.8 %. For a target air voids of 7 %, the FAM air voids could range from 2.8 to 4.9 %.

The air voids distribution shows no evidence of edge effects due to the compaction of the samples prepared with the AC, the AC+SBS and the AC+rubber. It is easily seen that the air voids at the edges and at the center are almost the same. The specimen prepared with the

AC+PPA shows areas with different air voids, but, this air voids distribution within the specimen is more related to heterogeneity of the samples than to edge effects.

Figure 3.5 – Air voids distribution of the FAM samples extracted from the SGC specimens for the four asphalt binders

The absence of clear evidences of edge effects can be explained by the criterion used to determine the moment to stop the compaction process. For the compaction of the FAM samples in the gyratory compactor, it was assumed that the number of gyration should be kept the same used in the compaction of the HMA, i.e., 100 gyrations. In the studies conducted by Zollinger (2005) and Castelo Branco (2008), the height or the density of the SGC specimens

were used as the criterion to suspend of the compaction. In their studies, Zollinger (2005) and Castelo Branco (2008) noticed the influence of the compaction in the distribution of air voids in the FAMs. Castelo Branco (2008) recommended the separation of the FAM samples in groups A (inner concentric zone), B (intermediate) and C (outer zone), without indicating the magnitude of the air voids for each zone.

3.4.7 Remarks on the determination of the FAM binder content by means of the procedure based on the specific surface method

The equivalent results obtained by the application of the specific surface method and the method of Sousa et al. (2013) to the FAMs produced with the neat binder [7.3 % for the specific surface method and 7.4 % for the method of Sousa et al. (2013)] and with the AC+PPA (8.0 and 7.8 %) can be interpreted as evidences that the specific surface method was validated by means of the method presented by Sousa et al. (2013). These two binders have as a common characteristic the absence of particulate materials and the data obtained during the reproduction of the procedure proposed by Sousa et al. (2013) proved that these binders did not influence the calculations. Because similar results were obtained by employing both methods, the ratios derived from the HMA binder contents could be applied either in conjunction with the results obtained in the specific surface method or in conjunction with the results obtained from the method by Sousa et al. (2013). Nevertheless, caution should be exercised when looking at these equivalent results, once that both methods present limitations.

The method by Sousa et al. (2013), as any other empirical method, is prone to repeatability and reproducibility issues. As discussed earlier, the procedure proposed by Sousa et al. (2013) was replicated by two different operators and, specifically in this case, the results varied by only 4 %, what can be considered excellent for a procedure relatively complex in terms of execution like this one. The rationale behind this method is very sound and evidences were shown here that it works very well for asphalt binders, either pure or modified, except when particulate materials, like crumb rubber, are used. For such a case, an additional test was recommended, in order to adapt the calculations to this sort of material. Additional tests employing other asphalt binders, either neat or modified, should be performed in order to confirm the general applicability of this method or to specify the modified asphalt binders to which the method is not applicable.

As far as the specific surface method is concerned, it is important to keep in mind that the calculation of the specific surface by means of specific surface factors associated to certain

particle sizes are based on the assumption that the resulting area is equal to an average area of cubes or spheres with dimensions equivalent to the average size opening of two adjacent sieves (Wang & Frost, 2002). The application of such procedure yields the lowest superficial area among all the possible shapes of a particle and, because of that, according to Wang and Frost (2002), this method is not able to take into account, in an appropriate manner, the effects of shape, roughness and texture of the particles. In a research conducted with particles ranging between 3/8 and n. 4 (9.51 and 4.76 mm), Wang and Frost (2002) observed that the specific surface and the sphericity (the ratio between the surface area of a particle and the surface area of a smooth sphere with the same volume) present a wide variation among individual particles within the same range size and that the specific surface of aggregates is much higher (84 %) than spheres of equivalent size. But this conclusion should be seen with caution, once only coarse aggregates were evaluated.

The complexity associated to the determination of the specific surface increases with the reduction of the particle size and, because of that, it is extremely difficult to measure with precision the superficial area of fillers. In a recent research, Cepuritis, Gargoczi, Ferraris, Jacobsen and Sorensen (2017) evaluated fillers (particles sizes ranging from 3 to 300 microns) from 10 types of rocks, covering a wide mineralogy range, and concluded that the error in the calculations, when one assumes sphericity of the particles, ranges from 20 to 30 % only. Those authors recommended that the specific surface estimated from the particle size distribution, assuming sphericity of the particles, should be adjusted upward by 20 % for particles smaller than about 20 microns of equivalent size and 30 % for particles larger than about 20 microns of equivalent size. Cepuritis, Wigum, Garboczi, Mortsell and Jacobsen (2014) have shown that about 90 % of the specific surface of the filler is concentrated in the range of particles smaller than 20 microns. In turn, Cepuritis et al. (2017) showed that for filler particles with particles size passing 125 μm or 63 μm sieves about 50 % of the specific surface is concentrated on particles with spherical dimension smaller than approximately 5 microns.

The discussion presented earlier gives an idea of the complexity behind the estimation of the specific surface of mineral aggregates, but, on the other hand, it is important to keep in mind that any method used to estimate the specific surface of mineral particles will be prone to error. According to Cepuritis et al. (2014), different techniques used to characterize the particle size of mineral fillers (Blaine, BET, laser diffraction, sedimentation and others) can easily present superficial areas that differ by up to a factor of ten. Because of the inherent difficulty of measuring the superficial area of very small particles and the wide variability of results

associated to different techniques, the use of the specific surface as a method to estimate the FAM binder content is an issue that deserves much more research. At this point, it is also important to mention that the objective of this preliminary study is not to present the specific surface method as an alternative method to estimate the FAM binder content. It was used here only as an academic exercise and, coincidentally or not, the results obtained by means of this method matched the ones obtained by employing the method proposed by Sousa et al. (2013) for some of the materials tested here.

3.5 CONCLUSIONS

The first objective of this preliminary study was to check if the methods available in the literature to determine the binder content of fine aggregate matrices could be employed to determine the binder content of fine aggregate matrices produced with modified asphalt binders. During the development of the study, some shortcomings were identified in the replication of those methods for the asphalt binders modified with the SBS copolymer and the crumb rubber. Such shortcomings led the authors to develop a procedure capable of determining the binder content for FAMs produced with modified asphalt binders.

The proposed procedure depends only on two main pieces of information: (i) the binder content of a FAM produced with neat binder, obtained either by the method proposed by Sousa et al. (2013) or by the method based on the specific surface concept, and (ii) the binder contents obtained from the design of HMA prepared with the neat and modified binders. The binder content for the FAMs prepared with the modified asphalt binders was determined according to the following procedure: the binder content for the FAM produced with the neat asphalt binder was multiplied by the ratios between the binder contents of the HMA prepared with the modified asphalt binders and the one prepared with the conventional binder. This procedure was outlined with basis on the hypothesis that the FAM represents the fine matrix of the full mixture and that the binder content of the fine matrix of the HMA should be directly proportional to the binder content of the HMA. The idea behind the proposed procedure is to make the determination of the binder content of FAMs produced with modified binders easy and free from the shortcomings observed when empirical methods based on mixture fractionation and binder extraction or calcination are used.

The evidences of the efficiency and applicability of this procedure are: (i) it was possible to determine FAM binder contents that resulted in reasonable air voids for the FAM samples (between 1.8 and 4.6 %); (ii) it was possible to extract the FAM samples from the SGC

specimens easily, once that the obtained binder contents are neither too high, as those obtained when the procedure proposed by Castelo Branco (2008) was used, nor too low, as those obtained when the procedure proposed by Coutinho et al. (2011) adapted by Freire (2015) was used; and (iii) it is possible to eliminate some shortcomings, like those reported here, associated with the use of modified asphalt binders, in general, and mainly those produced with particulate materials, like asphalt-rubber.

Finally, it is important to mention a caveat regarding the application of the methods proposed by Castelo Branco (2008), Coutinho et al. (2011) adapted by Freire (2015) and Sousa et al. (2013) to modified asphalt binders: some difficulties found during the application of these methods to the HMA prepared with some modified asphalt binders were mentioned but it is not meant that these methods are not efficient or that they should not be used with other modified asphalt binders. What stands out from the discussion presented here is the importance of checking if the modified asphalt binder in use can influence or not the calculations.

4 MATERIALS AND METHOD

The objective of this chapter is to describe with details (i) the materials and the procedures used to produce the FAM and the asphalt mastic, (ii) the aging simulation for each scale in order to evaluate the aging effect in the materials, (iii) the test procedures chosen to assess the linear viscoelastic and damage properties of the FAM and the asphalt mastics, and (iv) the analysis method used to treat the data from the frequency, time and amplitude sweep tests.

4.1 MINERAL AGGREGATES

The mineral aggregate used to produce the FAM samples is a basalt rock obtained from Bandeirantes Quarry, located in São Carlos, São Paulo. The mineral aggregate characterization was carried out as per the standard procedures from DNIT (Departamento Nacional de Infraestrutura de Transportes – National Department of Transportation Infrastructure) and ASTM (American Society for Testing and Materials): (i) gradation (DNER-ME 083/98); (ii) absorption and specific gravity of the fine aggregate (ASTM C128-15) and specific gravity of filler (DNER-ME 084/95). These characteristics of the mineral aggregates are presented in Table 4.1.

Table 4.1 – Mineral aggregate characteristics

Properties	Results
Absorption	0.6 %
Adhesion	Unsatisfactory
Specific gravity	2.957

As far as aggregate gradation is concerned, the main assumption in studies with FAM is that it represents the fine portion of the aggregate gradation of the HMA. In this study was considered suitable to produce FAM samples with fine aggregate particles smaller than 2.00 mm (passing sieve #10) based on the studies presented in section 1.1.2 (nominal maximum aggregate size for the FAM).

In order to establish the FAM gradation distribution, a dense curve positioned in the center of the range C of the DNIT specification (DNIT 031/2004-ES) was chosen. This dense curve was adopted because it is a typical mixture used for the road construction in Brazil. The percentage of aggregates passing the sieves below sieve #10 is determined by Equation 4.1

where #ii represents the sieves below sieve #10. Table 4.2 and Figure 4.1 show the FAM and HMA gradation distribution.

$$\frac{\text{Mass of aggregate passing sieve \#ii in full mixture}}{\text{Mass of aggregate passing sieve \#10 in full mixture}} \times 100\% \quad (4.1)$$

Table 4.2 – Mineral aggregate proportions for the FAM and HMA

Sieve number	Opening size (mm)	FAM	HMA
		Percentage by mass passing (%)	
3/4"	19.1	–	100
1/2"	12.7	–	90
3/8"	9.52	–	80
n° 4	4.76	–	58
n° 10	2.00	100	36
n° 40	0.42	47	17
n° 80	0.18	28	10
n° 200	0.075	17	6

Figure 4.1 – Gradation distribution for the FAM and HMA

4.2 ASPHALT BINDERS

Four asphalt binders were used to produce the FAMs: one unmodified (PG 64-XX provided by Replan/Petrobras) and three modified. The modified binders were produced in the

Road Laboratory of the São Carlos School of Engineering (EESC). The modifiers used to produce the three modified asphalt binder are presented below:

- (i) polyphosphoric acid (PPA): the Innovalt E200 PPA provided by Innophos;
- (ii) styrene-butadiene-styrene copolymer (SBS): the Kraton D1101 linear triblock SBS copolymer, presenting a polystyrene content of 31 % provided by Betunel Indústria e Comércio Ltda.
- (iii) crumb rubber: a mesh #30 crumb rubber obtained from the tread layer of passenger vehicle tires provided by Ecija Comércio Exportação e Importação de Produtos Ltda.;

The modifier contents were chosen aiming to shift the high-temperature PG from 64 (neat binder) to 76: 1.2 % of PPA, 4.5 % of SBS copolymer, and 14 % of crumb-rubber. A 722D Fisatom low-shear mixer was used to prepare the AC + PPA and a L4R Silverson high-shear mixer was used to produce the AC + SBS and the AC + rubber.

The mixing and compaction temperatures for the four asphalt binders were defined by tests done in the Brookfield viscometer model DVII-PRO. The test was performed with spindle n°21 and followed the procedures described in the standard ASTM D 4402M-15. Table 4.3 presents the parameters used during the Brookfield test to measure the material viscosity and Table 4.4 presents the mixing and compaction temperatures for each asphalt binder.

Table 4.3 – Parameter used in the viscosity test

Temperature (°C)	Rotation (rpm)	Shear rate (Seg-1)
135	20	19
143	40	37
150	60	56
163	80	74
177	100	93

*The torque percentage during the test were between 10 % to 98 % as defined by ASTM D 4402-02M-15.

Table 4.4 – Mixing and compaction temperatures

Asphalt binder	Mixing (°C)	Compaction (°C)
AC + neat	152	140
AC + PPA	164	154
AC + SBS	180	169
AC + rubber	193	187

4.3 FAM MIXTURES

4.3.1 FAM design method and preparation of the mixtures

The binder contents used to produce the FAM samples were determined according to the procedure presented in Chapter 3. For the FAM produced with the neat binder, the binder content is 7.4 %, for the AC+PPA the binder content is 7.8 %, for the AC+SBS the binder content is 7.7 %, and for the AC+ rubber the binder content is 9.3 %. The FAM mixtures were prepared using the mixing and compaction temperatures presented in Table 4.4, and the temperature for the aggregates was 10 °C higher than the ones adopted for the binders.

4.3.2 Aging of the FAM mixtures

The loose FAM mixture was aged instead of aging the binder separately in the rolling thin-film oven (RTFOT) and in the pressurized aging vessel (PAV), as recommend by Arega et al. (2013), since the binder aging can change in the presence of the mineral aggregate. The short-term aging of the FAMs was carried out according to the procedure presented in AASHTO R30. The loose FAM mixtures were conditioned in an oven at 135 °C during 4 hours before compaction. During the short-term aging procedure, the loose mixture was stirred every sixty minutes to ensure uniform conditioning.

For the long-term aging, the loose FAM mixtures were placed in trays (Figure 4.2) and conditioned in a ventilated oven at 60 °C. This temperature was chosen once that it has been used by other researchers in order to simulate the long-term aging of FAMs (Arega et al., 2013; Li et al., 2015; Tong et al., 2015; Cucalon et al., 2017). The loose FAM mixtures were conditioned in the ventilated oven for 30 and 60 days before compaction.

Figure 4.2 – Fabricated trays for long-term condition of FAM mixtures

4.3.3 Compaction method

After the aging process, FAM specimens of 100 mm in diameter were compacted in the SGC, with a pressure of 600 ± 18 kPa and a gyration angle of $1.25 \pm 0.02^\circ$ (Figure 1.3), according to the procedure presented by Zollinger (2005). Both ends of the specimens were sawed, aiming to obtain a more homogeneous air voids distribution. This is an important step, since Masad et al. (2002) reported the presence of large air void content at the top and the bottom of SGC specimens observed in X-ray computed tomography images.

The criterion to stop the compaction was a number of gyrations equal to 100, the same used for asphalt concrete mixtures. According to Masad et al. (1999) a higher number of gyrations can generate regions within the specimen with lower air voids, resulting in the border effect (higher air voids content in the boarder and lower air voids content in the center of the specimen). The FAM samples were extracted from the SGC specimens (Figure 4.4) by means of a diamond drill coupled to a drilling machine.

Figure 4.3 – SGC Servopac

Figure 4.4 – FAM samples extracted from SGC specimens

4.3.4 Sample preparation

The preparation of the sample before running the tests is an important step of the experiment. The first step was to sand the top and bottom of the FAM samples in order to avoid the effect of eccentricity. Eccentricity may result in the application of additional stress or strain

that is not originated from the commanded torsional loading. After the sanding process, two metal caps were glued to the FAM sample ends using an epoxy-based glue. The cure time is 24 hours as recommended by the manufacturer of the glue. At the end of the cure time, the samples glued to the metal caps were attached to the clamp of the equipment and submitted to the conditioning process (Figure 4.6). The samples were conditioned for one hour at 25 °C.

4.4 TESTS IN THE DSR

The tests with the FAM samples were carried out in a dynamic shear rheometer model MCR-302 DSR from Anton Paar (Figure 4.5). Two tests were run in order to obtain the linear viscoelastic (LVE) properties of the materials: an amplitude sweep, to define the LVE range for each material, and a fingerprint test, to define the damage evolution rate parameter (α) for each sample. A time sweep test was adopted to assess the damage properties of the FAMs, as pseudo stiffness (C) and damage accumulation (S). These tests protocols and the procedure of analysis will be described in detail in the next sections.

Figure 4.5 – DSR model MCR-302 DSR

Figure 4.6 – FAM samples attached to the clamps

4.4.1 Determination of the linear viscoelastic range of the samples

The first information that needs to be obtained for each material is its linear viscoelastic range. In order to obtain such range, stress sweeps were performed, from 5 to 450 kPa, at 25 °C and 1 Hz, as illustrated in Figure 4.7.

Figure 4.7 – Depicts of LVE range test

Such stress values were obtained for use in the fingerprint test. The linear viscoelastic range is the range of stresses under which the materials would undergo a reduction up to 10 % of their initial stiffness. Some tests were necessary to define the minimum stress level that should be used for the fingerprint test. It was observed that 15 kPa would be enough to generate good data based in the coefficients of variation of the read points in each stress level. The specimens used here were discarded after the tests. An example for the FAM prepared with the unmodified asphalt binder and aged in long-term (30 days) is given in Figure 4.8. It can be seen that a drop of 10 % of the initial $|G^*|$ ($9.69E8 \times 0.9 = 8.72E8$) is achieved when a stress level is higher than 100 kPa. Table 4.5 presents the minimum stress level (LVE_{minimum}), capable of producing reliable data in terms of the resolution of the equipment, and the LVE_{maximum} , correspondent to a drop of 10 % of the initial $|G^*|$.

Figure 4.8 – Determination of the LVE range for the FAM prepared with the unmodified asphalt binder and aged in long-term (30 days)

Table 4.5 – LVE range for the FAM samples

Aging	FAM	LVE Range (kPa)	
		LVE _{minimum}	LVE _{maximum}
Short term	Neat binder	15	100
	AC + PPA	15	100
	AC + SBS	15	50
	AC + rubber	15	100
Long term (30 days)	Neat binder	15	100
	AC + PPA	15	150
	AC + SBS	15	150
	AC + rubber	15	200
Long term (60 days)	Neat binder	15	100
	AC + PPA	15	150
	AC + SBS	15	150
	AC + rubber	15	250

4.4.2 Fingerprint tests – linear viscoelastic properties

In the second step of the test, a second specimen was employed to perform the fingerprint test. The objective of the fingerprint is to obtain values of $|G^*|$ and δ of the materials, at different frequencies, in order to calculate the parameter m (viscoelastic property of the material). The slope of the relaxation modulus curve (m) is defined by the response of the material during the loading period and it is used to calculate the damage evolution rate parameter (α). The test must be performed at a stress level within the LVE range of each material, in order to guarantee that no damage is induced in the sample. The stress of 15 kPa was used in these tests and it was chosen due to the aforementioned reasons. Special care was

taken in order to avoid the induction of damage to the samples at this step, once that the same sample is used posteriorly in the damage test.

In order to minimize the level of damage induced to the sample during the fingerprint test, the following measures were taken: (i) adoption of a reduced number of frequencies; (ii) introduction of a rest period of 5 minutes between successive frequencies; and (iii) adoption of a minimum number of loading applications at each frequency. Preliminary tests indicated that frequencies between 30 and 0.05 Hz were enough to obtain good adjustments of the Prony series and the Laplace transform, both employed in the interconversion from frequency to time domain. The following frequencies, in Hz, were used in the fingerprint: 30, 26, 22, 18, 14, 10, 6, 4, 2, 1, 0.5, 0.2, 0.1, and 0.05 and three loading cycles of 15 kPa were applied in each frequency.

The next step was the prediction of the relaxation modulus values ($G(t)$) using the data from the frequency sweep, in order to obtain the parameter m , that represents the slope of the relaxation curve. For each frequency, the storage modulus (G') was calculated according to Equation 4.2.

$$G'(\omega) = |G^*(\omega)| \cdot \cos \delta(\omega) \quad (4.2)$$

Prony series (Equation 4.3) representation of storage modulus as a function of frequency (Christensen, 1982), was fitted to the experimental data, G' versus angular frequency (ω) values, because of its capability of describing the different stages of the behavior of a viscoelastic material (S. W. Park & Kim, 2001). Figure 4.9 depicts an example of a four-series Prony series adjusted to the G' data of a FAM sample, where G_e is the equilibrium modulus, G_i is the elastic modulus of the spring of the generalized Maxwell model, ρ_i is the relaxation time, ω is the angular frequency and n is the number of elements of the Prony series.

$$G'(\omega) = G_e + \sum_{i=1}^n \frac{G_i \omega^2 \rho_i^2}{\omega^2 \rho_i^2 + 1} \quad (4.3)$$

Figure 4.9 – Fitting of a four-series Prony series to G' versus ω data

After the determination of the constants G_e , G_i and ρ_i for each element of the Prony series, a generalized Maxwell model (or Wiechert model) was used to predict $G(t)$ according to Equation 4.4, and the curve $G(t)_{predicted}$ versus time is built (Figure 4.10). A power law function (Equation 4.5) is then used to fit the G vs. *time* data in order to define the material constants G_0 , G_1 and relaxation rate (m).

$$G(t) = G_e + \sum_{i=1}^n G_i e^{\frac{-t}{\rho_i}} \quad (4.4)$$

$$G = G_0 + G_1 \cdot t^{-m} \quad (4.5)$$

Figure 4.10 – Curve $G(t)_{predicted}$ versus time and adjust of the power law model

The damage evolution rate, α , is calculated with basis on the m value obtained from the fitting of the power law model. Schapery (1990) and S. W. Park et al. (1996) recommended to calculate α using Equation 4.6, for materials with constant fracture energy and constant fracture stress, and Equation 4.7, for materials with constant fracture energy and fracture process zone size. Researchers have been following the same approach and using Equation 4.6 for tests in controlled strain mode and Equation 4.7 for tests in controlled stress mode (Daniel & Kim, 2002; Karki, 2014). In this study, the damage tests were carried out in controlled stress mode and because of that the damage evolution rate was calculated by Equation 4.7

$$\alpha = 1 + \frac{1}{m} \quad (4.6)$$

$$\alpha = \frac{1}{m} \quad (4.7)$$

4.4.3 Damage tests

Initially was considered the possibility of adopting the linear amplitude sweep (LAS) test for the FAM samples since this test as known as an accelerate damage test. However, the implementation of the LAS test for the FAM samples tested in the DSR was not possible due to the limitation of the equipment regarding to the maximum level of torque. Freire et al. (2015) reported that was necessary to increase the number of loading cycle for each level of strain amplitude in order to cause damage of the sample, resulting in an increase of the test duration. Even with this modification and applying the maximum level of torque in the FAM samples, Freire et al. (2015) did not achieve the failure stage of the FAM mixtures.

Therefore, the procedure used in the damage test follows the same rationale of a conventional fatigue test, i.e., a cyclic and reversal load is continuously applied to the sample up to a certain level of reduction in the stiffness of the material or its failure. It is in practice a conventional time sweep test. This test was carried out in controlled stress mode instead of controlled strain due to the torque limitation of the DSR aforementioned. The same limitation for the controlled strain mode test was observed by Kanaan et al. (2014) due to the high stiffness of the FAM samples produced with RAS.

The tension applied to the specimens was calculated with basis on the results of the stress sweep test according to the following criterion: the average $|G^*|$ values at each stress level is divided by the average $|G^*|$ at the tension used in the fingerprint ($|G^*|_{Ive}$) and the tension that

yields a relationship $|G^*|/|G^*|_{lve}$ of 0.9 is adopted. By following this procedure, it is possible to guarantee that the applied tension is going to generate an initial damage to the samples lower than 10 %, i.e., the initial C values of the samples will not be lower than 0.9. Other tests were carried out at higher stress level (300 to 400 kPa) in order to verify the superposition of the curves C vs. S and to reduce the test duration. Differently from what was done by Karki (2014), the damage test was conducted without the intercalation of rest periods, i.e., the effect of healing on the damage accumulation suffered by the materials was not evaluated. The suppression of such rest periods was due to the operational difficulties discussed below.

The procedure adopted in the execution of this experiment is the result of a series of adaptations done in the procedure proposed by Karki (2014). The main difficulties associated to the reproduction of the original procedure proposed by Karki (2014) were the long duration of the tests and the extremely high volume of data recorded by the computer, along with the operation difficulties of the DSR during the attempts to implement the rest periods in a specific level of integrity. In an attempt to reduce the duration of the tests, the frequency was reduced from 10 Hz, as used by Karki (2014) in this dissertation, to 1 Hz, since that at lower frequencies the stiffness of the material is lower. In a fatigue test run in stress control, the lower the stiffness the lower the number of cycles to take the material to rupture or to reach a certain level of damage. Adjustments to the acquisition data rate (1 point each 30 second) allowed the register of data along the total duration of the test, without occurrence of interruptions of the software as observed during the first tests. With the removal of the rest periods from the procedure, operational problems were no longer observed and the duration of the tests was reduced.

4.5 PROCEDURE OF ANALYSIS

4.5.1 Damage analysis

The accumulated damage in the sample was defined based on the damage model derived using the Schapery's correspondence principles, the work potential theory and the rate-type damage evolution law. With basis on the $|G^*|$ values for each loading cycle, the values of the pseudo stiffness, C_k , were calculated by Equation 4.8, where I is the sample-to-sample variation in the initial stiffness and $|G^*|_{lve}$ is the complex modulus obtained in the fingerprint test at 1 Hz. The parameter I is a mathematical artifice to force the pseudo stiffness to be equal to 100 % when damage is zero, in order to build C vs. S curves with a starting point for integrity of 100 % or, in other words, without damage.

$$C_k = \frac{|G_k^*|}{I \cdot |G^*|_{LVE}} \quad (4.8)$$

The correction parameter I is needed because of three reasons: (i) inherent variability of the material, i. e., two measurements at the same conditions in the same sample but at different moments can differ slightly, (ii) loading history, i.e., the loading applied to the material during the fingerprint test can impose long-term effects in the sample, and (ii) damage accumulated by the sample during the fingerprint test, i. e., although the fingerprint test is run at stress levels within the linear viscoelastic range of the material, a low tensile stress can damage the material if the number of cycles is high.

In order to avoid the effect of the equipment resolution reading the displacement during the test, the C values were sorted from highest to lowest. This was done because resolution problems in the DSR are able to generate C values at cycle k that are higher than at cycle $k-1$ (when it should be lower once that the material is losing integrity), resulting in problems in the worksheet used to calculate the S values.

The accumulate damage (S) for the N number of load/strain cycles was calculated based on the relationship among energy, stress and damage evolution rate in the pseudoelastic domain. The discrete form for this relationship is present in Equation 4.9, where $S_{u,0}$ is the internal state variable at the beginning of load cycles (in this study, it was assumed that no damage was induced to the sample before starting the test), and Δt_k is the difference of time between loading cycles.

$$S = \sum_{i=1}^N \left[\frac{I}{2} (\varepsilon_i^R)^2 (C_{i-1} - C_i) \right]^{\frac{\alpha}{1+\alpha}} (t_i - t_{i-1})^{\frac{1}{1+\alpha}} \quad (4.9)$$

4.5.2 Prediction of fatigue life

The final product of the procedure of analysis proposed by Karki (2014), and adopted in this study, are the characteristic curves of the FAMs. Such curves are independent of the loading conditions and because of that they are considered real material properties. Once that the simple comparison among characteristic curves is not possible, the procedure used by Karki (2014) was adopted in this study. The objective of this procedure is to build a fatigue model, based on the C vs. S curves of each material, and predict the number of load applications (N_f) that is able to generate a certain damage level associated with a certain level of reduction in the integrity

of the material, taking into account different strain levels in the pavement. In other words, this procedure allows one to compare materials in terms of the number of cycles needed to generate a certain level of reduction of its integrity, considering different strain levels in the pavement. If the number of load repetitions needed to generate a reduction of stiffness of for example 0.75 is higher for the material A than for material B, this means that the material A presents higher resistance to damage accumulation, at a certain strain level in the pavement.

In order to perform such analysis, the first step is to fit a power law model (Equation 4.10) to the curve C vs. S of the material to define the coefficients C_0 , C_1 and C_2 .

$$C = C_0 - C_1 S_u^{C_2} \quad (4.10)$$

The next step it to choose a certain level of reduction in pseudo stiffness, as for example 50 % or $C = 0.50$, and obtain the correspondent S_u value, directly from the C vs. S curve or using a power model adjusted to the data. Based on these values, the coefficients $A_{u,d}$ and B_u of the mechanistic fatigue model (Equation 4.11) is calculated, where $A_{u,d}$ is calculated using Equation 4.12 and B_u is obtained using Equation 4.13. The fatigue model will allow to estimate the different numbers of load application to reach a certain level of integrity as a function of the different strain levels in the pavement. In this study was adopted 50 % of reduction in pseudo stiffness as a failure criterion. It was not possible to observe the superposition of the characteristic curves (curve C vs. S) for the different stress levels, and because of that it was necessary to build an average fatigue life curve based on the results for the FAMs tested at the low stress level and the ones tested at the high strain level. The averaged N_f curve was built based on the averaged the linear dynamic shear modulus ($|G^*|_{lve}$), the averaged damage accumulation rate (α), and the average for the coefficients C_1 and C_2 of the power law model of the two curves.

$$N_{u,d} = A_{u,d} \cdot (\epsilon^R)^{-B_u} \quad (4.11)$$

$$A_{u,d} = f \cdot \left(\frac{1}{2} C_1 C_2 \right)^{-\alpha} \{1 + \alpha \cdot (1 - C_2)\}^{-1} S_{u,d}^{\{1 + \alpha \cdot (1 - C_2)\}} \quad (4.12)$$

$$B_u = 2\alpha \quad (4.13)$$

4.6 ASPHALT MASTICS

The rheological characterization of asphalt mastic is getting important because of the contribution of mastic about the mechanistic behavior of asphalt concrete mixtures. In general, an asphalt concrete with higher percentage of mineral filler can lead to a difficult compaction and an excessive stiffness, reducing the fatigue cracking and thermal cracking resistance of the asphalt concrete. The rheological characterization of mastics evaluates the stiffness level induced, for example, due to the increase in the f/a rate and the effect of different types of mineral aggregate. The rheological evaluation of the asphalt mastics is based on concepts and in laboratorial practices used in the rheological characterization of asphalt binders. The extend of asphalt binder characterization to the asphalt mastic characterization is possible assuming mastic as a modified asphalt binder. However, it is important to keep in mind, in reality, that the mastic has a distinct role in the mechanistic behavior of the asphalt concrete compared to the modified asphalt binder. The mastic is a mixture of asphalt and filler, and represent a microscale of the asphalt concrete. This microscale has a significant effect in the mechanical behavior of the asphalt concrete mixtures related to rutting and cracking.

In this study the asphalt mastics were characterize in order to compare the fatigue life of the FAM with the fatigue damage tolerance index (a_f) of the asphalt mastic and investigate the possible correlations between the two scales, once that these two scales have similar microstructure.

4.6.1 Production of the asphalt mastics

The asphalt mastics evaluated in this study were produced with rock basalt provided by Bandeirantes Quarry and four asphalt binders used for the FAM characterization. Four different f/a ratios (0.00, 0.15, 0.30 and 0.45), in volume, were adopted to produce the asphalt mastics. The f/a ratios were chosen in order to cover a large range of f/a ratios used for the production of asphalt surface layer. For the preparation of mastics, the asphalt binder and the filler were heated in the mixing temperatures presented in Table 4.4.

Table 4.7 are related to a mass of asphalt mastic of 400 g and for the respective relative densities presented in Table 4.6. The relative density for the filler was defined as per the standard ASTM C128-15, and for the asphalt binders as per standard ASTM D70-09e1.

Table 4.6 – Relative density for the filler and asphalt binders

Materials	Relative density (g/cm ³)
Filler	2.769
Neat binder	1.002
AC+PPA	1.002
AC+SBS	1.003
AC+Rubber	1.017

Table 4.7 – Filler/asphalt ratios of the asphalt mastics, in volume

Asphalt binder	f/a ratio	0.00	0.15	0.30	0.45
Neat binder	filler (g)	0.00	117.22	181.31	221.71
	asphalt (g)	400.00	282.78	218.69	178.29
AC+PPA	filler (g)	0.00	117.17	181.25	221.65
	asphalt (g)	400.00	282.83	218.75	178.35
AC+SBS	filler (g)	0.00	117.16	181.23	221.64
	asphalt (g)	400.00	282.84	218.77	178.36
AC+rubber	filler (g)	0.00	115.97	179.81	220.22
	asphalt (g)	400.00	284.03	220.19	179.78

In this study, the f/a ratios are presented in volume. In mass, this three relationship corresponds, respective, to 0.41, 0.82 and 1.23, for an asphalt binder PG 64-XX with relative density of 1.04 and a rock basalt filler with relative density of 2.850. Take into account the range of material passing sieve #200, by the specification DNIT 031/2006, from 2 % to 10 %, the f/a ratio in mass would be 1.09 for a typical asphalt concrete with 6 % of filler and an optimum binder content of 5.5 %. The f/a ratio in volume used in this study is among the values adopted for the typical asphalt concrete mixtures. The same is observed for the design method Superpave for asphalt concrete, the range of f/a ratio, in mass, is from 0.6 to 1.2, and it is among the values for f/a ratio adopted for this study.

4.6.2 Aging Mastic

The asphalt binders were aged in short and long-term in order to study the effect of aging in the rheological properties of the asphalt mastics. These properties can be correlated to the rheological properties of the FAM and the mechanical properties of the asphalt concrete, once the mastic is a part of the aforementioned scales. The four asphalt binders were conditioned to the rolling thin-film oven (RTFOT) test to simulate the short-term aging as per ASTM D2872-

12e1. In sequence, the residue from RTFOT were aged in the pressurized aging vessel (PAV) to simulate the long-term aging as per ASTM D6521-13.

4.6.3 DSR test

The rheological characterization of the asphalt mastics was carried out in the dynamic shear rheometer (DSR) model MCR-302 DSR from Anton Paar, from samples aged at short and long-term, due to the difficult in the sample preparation for the other tests, as softening point, penetration, ductility, and the bending beam rheometer (BBR). In order to compare the fatigue models for the FAMs with the fatigue models for the asphalt mastics, only the LAS test at 25 °C was performed in the asphalt mastics.

4.6.4 Linear amplitude sweep test (LAS)

The LAS test was proposed by Johnson (2010) as an accelerated fatigue test for asphalt binders. The test is carried out in the DSR for the unaged, short and/or long-term aged samples. The sample is tested using a parallel plate geometry of 8 mm with distance of 2 mm between the plates. The test is divided by two steps: (1) a frequency sweep from 0.1 to 30 Hz at 0.1 % of strain to define the linear viscoelastic properties, and (2) an amplitude sweep in controlled strain mode from 0.1 % to 30 % at 10 Hz until the failure sample. The loading sequence consist of an interval of 10 seconds at one constant deformation amplitude, and each interval is followed by another interval with higher deformation amplitude, as shown in Figure 4.11.

Figure 4.11 – Increment deformation in the LAS test

Source: Adapted from Johnson (2010).

The results from the rheological characterization of the asphalt binder in the linear viscoelastic region and of the strain amplitude sweep are used to adjust a fatigue model based

on the VECD concepts. For the asphalt binder characterization, the model is derived from the relationship between an applied load and the fatigue life of the material (Figure 4.12). Asphalt concrete mixtures and asphalt binders presented a good correlation between the applied load and the fatigue life (N_f) according to the Equation 4.14, where the parameters A and B are material characteristic and $\gamma_{\max}$ is the maximum deformation in the pavement.

$$N_f = A(\gamma_{\max})^{-B} \quad (4.14)$$

The parameter A and B is calculated by Equation 4.15 e 4.16, in which f is the frequency (10 Hz), S_f is the accumulated damage in the sample at the failure in the amplitude interval with deformation of 1.0 %, k is defined by Equation 4.17, and α is the inclination of the curve in log-log of the storage modulus ($|G^*|. \cos \delta$) versus frequency, calculated by Equation 4.18.

$$B = 2\alpha \quad (4.15)$$

$$A = \frac{f(S_f)^k}{k(\pi C_1 C_2)^\alpha} \quad (4.16)$$

$$k = 1 + (1 - C_2)\alpha \quad (4.17)$$

$$\alpha = \frac{1}{m} \quad (4.18)$$

Figure 4.12 – Fatigue model

Source: Adapted from Johnson (2010).

The coefficients C_0 , C_1 e C_2 can be defined by linearizing a power law model (Figure 4.13) adjusted to the curve $|G^*|$ vs. $S(t)$ (Equation 4.19), where the $S(t)$ is the accumulated damage in the sample, calculated by Equation 4.20, in which the γ_i is the shear deformation, and C is the pseudo stiffness (Equation 4.21) at any time t .

$$C(t) = C_0 - C_1(S)^{C_2} \quad (4.19)$$

$$S(t) = \sum_{i=1}^N \left[\pi(\gamma_i)^2 (C_{i-1} - C_i) \right]^{\frac{\alpha}{1+\alpha}} (t_i - t_{i-1})^{\frac{1}{1+\alpha}} \quad (4.20)$$

$$C(t) = \frac{G^*(t)}{G^*_{initial}} \quad (4.21)$$

Figure 4.13 – Curve pseudo stiffness versus damage accumulation

The adequate failure criterion of fatigue failure to asphalt concrete and asphalt binders is a topic in discussion. The traditional criterion more accepted by researchers is the reduction of initial $|G^*|$ in 50 %. Johnson (2010) observed that 35 % reduction of $|G^*|$ sen δ value presented an acceptable correlation between the results from the time sweep tests and LAS. Based on this observation Johnson (2010) proposed to calculate the values for $S(t)$ by Equation 4.22:

$$S_f = 0,35 \left(\frac{C_0}{C_1} \right)^{\frac{1}{C_2}} \quad (4.22)$$

Martins (2014) proposed a failure criterion based on the minimum point for the da/dN vs. a (crack length) curve or the peak of the shear stress vs. strain curve. However, for the materials evaluated in this study, it was observed that the minimum point for the da/dN vs. a curve did not match the peak of the shear torque curve [Figure 4.14 (a)]. The failure criterion adopted in this study is the peak for the curve of shear stress and/or oscillation torque vs. a . It is assumed that the peak of the shear stress curve is the maximum stress level necessary to fail the sample, and as shown in Figure 4.14 (b) the maximum point for these curves coincides. Based on this assumption, the values for S can be calculated by Equation 4.23, in which C_0 , C_1 , and C_2 are the coefficients defined by the adjustment of a power law model to the curve C vs. S , and C_f is the value for the pseudo stiffness at the failure of the sample.

Figure 4.14 – Comparison between the oscillation torque and da/dN curve (a), and oscillation torque curve and oscillation stress curve

$$S_f = \left(\frac{C_0 - C_f}{C_1} \right)^{\frac{1}{C_2}} \quad (4.23)$$

With the modification proposed by Hintz (2012), the test was renamed as modified LAS. The difference between the two test procedures is the format of the strain amplitude sequence (Figure 4.15). The loading sequence proposed by Hintz (2012) adopted the same cycle number (test time) and the same levels for the strain amplitudes proposed by Johnson (2010). The modification proposed by Hintz (2012) were incorporated to the AASHTO standard project (AASHTO TP 101-12-UL). Recently, was published the standard AASHTO TP 101-14, which one adopted the changed in the loading sequence proposed by Hintz (2012).

Figure 4.15 – Increment deformation in the modified LAS test

Source: Adapted from Hintz (2012).

5 ASPHALT BINDERS AND ASPHALT MASTICS

The objective of this chapter is to present the results of the linear amplitude sweep (LAS) tests for the four asphalt evaluated in this research, and for the asphalt mastics produced with these four asphalt binders. Four filler/asphalt ratios were used in the preparation of the samples: 0.00, 0.15, 0.30 and 0.45 (in volume). The asphalt binder, represented by the $f/a = 0.00$, and three asphalt mastics ($f/a = 0.15$, 0.30 and 0.45) were submitted to short- and long-term aging, according to the protocols prescribed by the Superpave specification, and only the short- and long-term aged samples were submitted to the LAS tests. The results were analyzed by means of the viscoelastic continuum damage (VECD) theory with the estimation of the parameters of the fatigue model ($N_f = A \cdot \gamma^{-B}$), and by means of the determination of the fatigue damage tolerance index (a_f). The chapter was separated in four items, in order to show results related to the effects of the filler/asphalt ratio, aging, and type of asphalt on the parameters of the fatigue model, along with the fatigue curves obtained from such models.

5.1 EFFECT OF THE FILLER/ASPHALT RATIO

5.1.1 Parameters A and B of the fatigue model

Johnson (2010) proposed a model, $N_f = A \cdot \gamma^{-B}$, that is able to predict the fatigue behavior of the materials under different strain levels by means of the LAS test. In this model, the N_f represents the fatigue life, i.e. the number of axle-load repetitions that takes the material to failure, and γ is the shear strain applied. The parameter A is dependent on the variation of the material integrity as a function of damage accumulation and on the initial dynamic modulus (no damage in the material). The A values are higher when the material keeps higher integrity, measured by means of the $|G^*|$ values. For a fast drop of the $|G^*|$ values, the parameter A will be lower. The coefficient A is determined by means of the adjustment of the model expressed in Equation 4.10 to the C vs. S curve of the material. The failure point was determined by the peak of the curve for shear stress and/or oscillation torque vs. a , once that the maximum point for these curves coincides. The exponent B is related to the asphalt binder sensibility to the strain level. For higher values of the exponent B, the slope of the fatigue curve increases, indicating that the material is more sensitive to variations in the strain levels in the pavement (NUÑEZ, 2013; PAMPLONA, 2013). The exponent B corresponds to the double of the alpha values and because of that it expresses directly the damage evolution rate of the material.

The objective of this section is to show the effect of the filler/asphalt ratio on the parameters A and B of the fatigue model. Table 5.1 and Figure 5.1 show the values for the parameters A and B of the fatigue models for the asphalt mastics produced with the neat binder as a function of the f/a ratio and aging level. Following this same pattern, Table 5.2 and Figure 5.2, Table 5.3 and Figure 5.3, and Table 5.4 and Figure 5.4 show the values for the coefficients A and B of the fatigue models for the asphalt mastics produced with the AC+PPA, the AC+SBS, and the AC+rubber, respectively.

Table 5.1 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the neat binder as a function of the f/a ratio and aging level

Aging level	f/a ratio	A	Relationship	B	Relationship
RTFOT	0.00	2.41E+05	1.00	2.75	1.00
	0.15	1.90E+05	0.79	2.67	0.97
	0.30	1.43E+05	0.59	2.67	0.97
	0.45	1.01E+05	0.42	2.76	1.00
PAV	0.00	5.35E+05	1.00	3.28	1.00
	0.15	4.46E+05	0.83	3.23	0.99
	0.30	2.15E+05	0.40	3.33	1.02
	0.45	1.27E+05	0.24	3.44	1.05

The results in Table 5.1 shows that the increase of the f/a ratio decreases the A values and affects the B values only slightly. This means that the increase of the amount of filler reduces the integrity of the materials, what implies that the materials will crack after the application of a lower number of axle load repetitions, compared to the neat binder or an asphalt mastic with a lower f/a ratio. Similar B values for all f/a ratios imply that the materials will not change significantly their rate of damage accumulation because of the incorporation of higher amounts of mineral filler. Such patterns were observed for both the short- and long-term aged samples, what shows that the increase in the level of severity of the aging did not affect the pattern of effect of the f/a ratio on A and B values.

The same tendency for the effect of the f/a ratio on the A values was observed for the mastics prepared with the AC+PPA, the AC+SBS and the AC+rubber, regardless of the aging intensity. Regarding the B values, only the mastics prepared with the AC+PPA showed some reduction in the damage accumulation rate, i. e., only the mastics prepared with the AC+PPA had their rate of damage accumulation reduced with the addition of increasing amounts of mineral filler. This is valid for the mastics aged both in short- and long term. The other mastics

showed slight reductions of B with increasing f/a ratios for the materials aged in short-term and the effect of increasing f/a ratios was almost null for the mastic aged in long-term.

Figure 5.1 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the neat binder as a function of the f/a ratio

Table 5.2 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+PPA as a function of the f/a ratio and aging level

Aging level	f/a ratio	A	Relationship	B	Relationship
RTFOT	0.00	2.14E+06	1.00	3.58	1.00
	0.15	8.13E+05	0.38	3.19	0.89
	0.30	2.86E+05	0.13	3.03	0.85
	0.45	2.10E+05	0.10	3.03	0.85
PAV	0.00	4.26E+06	1.00	4.28	1.00
	0.15	1.76E+06	0.41	3.93	0.92
	0.30	7.08E+05	0.17	3.82	0.89
	0.45	2.92E+05	0.07	3.96	0.92

Figure 5.2 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+PPA as a function of the f/a ratio and aging level

Table 5.3 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+SBS as a function of the f/a ratio and aging level

Aging level	f/a ratio	A	Relationship	B	Relationship
RTFOT	0.00	6.48E+05	1.00	3.24	1.00
	0.15	4.51E+05	0.69	3.00	0.92
	0.30	2.75E+05	0.42	3.03	0.93
	0.45	1.66E+05	0.26	3.04	0.94
PAV	0.00	1.29E+06	1.00	3.70	1.00
	0.15	7.58E+05	0.59	3.65	0.99
	0.30	4.70E+05	0.37	3.79	1.02
	0.45	3.03E+05	0.24	3.77	1.02

Figure 5.3 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+SBS as a function of the f/a ratio and aging level

Table 5.4 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+rubber as a function of the f/a ratio and aging level

Aging level	f/a ratio	A	Relationship	B	Relationship
RTFOT	0.00	2.80E+06	1.00	3.34	1.00
	0.15	1.37E+06	0.49	3.23	0.97
	0.30	4.11E+05	0.15	3.21	0.96
	0.45	1.53E+05	0.05	3.16	0.95
PAV	0.00	5.64E+06	1.00	3.59	1.00
	0.15	4.53E+06	0.80	3.70	1.03
	0.30	1.64E+06	0.29	3.84	1.07
	0.45	5.22E+05	0.09	3.88	1.08

Figure 5.4 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+RUBBER as a function of the f/a ratio and aging level

5.1.2 Fatigue damage tolerance index (a_f)

The objective of this section is to show the effect of the filler/asphalt ratio on the fatigue damage tolerance index (a_f). Table 5.5 shows the a_f values for the asphalt mastics as a function of the f/a ratio and aging level, and Table 5.6 shows the relationships between the a_f values for the asphalt mastics produced with the neat and modified binders in relation to the neat and modified binders ($f/a = 0.00$). Figure 5.5 shows a comparison of the a_f values for the mastics aged in short-term and in long-term. The results in Table 5.5 show that the increase in the f/a ratio increases the fatigue damage tolerance index, indicating that the mastics present a higher tolerance to fatigue damage in the extent that the f/a ratio increases. Such increase is evident for both aging levels.

Table 5.5 – A_f values for the asphalt mastics as a function of the f/a ratio and aging level

Aging level	f/a ratio	Neat binder	AC +PPA	AC+SBS	AC+rubber
RTFOT	0.00	0.78	0.95	0.87	0.96
	0.15	0.88	0.99	1.00	1.05
	0.30	1.04	1.06	1.12	1.12
	0.45	1.09	1.16	1.18	1.14
PAV	0.00	0.87	0.90	0.90	1.04
	0.15	0.99	1.04	1.01	1.16
	0.30	1.01	1.11	1.08	1.24
	0.45	1.08	1.16	1.21	1.25

Table 5.6 – Relationships between the a_f values for the asphalt mastics produced with $f/a = 0.15, 0.30$ e 0.45 in relation to the asphalt binder ($f/a = 0.00$)

Aging level	f/a ratio	Neat binder	AC +PPA	AC+SBS	AC+rubber
RTFOT	0.00	1.00	1.00	1.00	1.00
	0.15	1.13	1.05	1.15	1.09
	0.30	1.34	1.12	1.29	1.17
	0.45	1.41	1.22	1.35	1.19
PAV	0.00	1.00	1.00	1.00	1.00
	0.15	1.13	1.15	1.12	1.12
	0.30	1.16	1.23	1.20	1.20
	0.45	1.25	1.28	1.35	1.21

Figure 5.5 – A_f values for the asphalt mastics aged in short- and long-term

5.2 EFFECT OF THE AGING LEVEL

5.2.1 Parameter A and B of the fatigue model

The objective of this section is to show the effect of the aging level on the parameters A and B of the fatigue model. Table 5.7 and Figure 5.6 show the values for the parameters A and B of the fatigue models for the asphalt mastics produced with the neat binder as a function of

the aging level and the f/a ratio. Following this same pattern, Table 5.8 and Figure 5.7, Table 5.9 and Figure 5.8, and Table 5.10 and Figure 5.9 show the values for the coefficients A and B of the fatigue models for the asphalt mastics produced with the AC+PPA, the AC+SBS, and the AC+rubber, respectively.

Table 5.7 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the neat binder as a function of the aging level and the f/a ratio

Parameter	f/a ratio	RTFOT	PAV	PAV/RTFOT
A	0.00	2.41E+05	5.35E+05	2.22
	0.15	1.90E+05	4.46E+05	2.34
	0.30	1.43E+05	2.15E+05	1.50
	0.45	1.01E+05	1.27E+05	1.27
B	0.00	2.75	3.28	1.19
	0.15	2.67	3.23	1.21
	0.30	2.67	3.33	1.25
	0.45	2.76	3.44	1.25

Figure 5.6 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the neat binder as a function of the aging level and the f/a ratio

The results for the mastics prepared with the neat binder show that the increase in the aging level, from short-term to long-term, is capable of increasing the A values proportionally. This means that the mastics have an increase in their integrity because of aging in long-term. Such increase in integrity reduces in the extent that the f/a ratio increases. In relation to the B values, aging increases the rate of damage accumulation and the f/a ratio increases it slightly.

Similarly to what was observed for the mastics prepared with the neat binder, the results for the mastics prepared with the AC+PPA and the AC+SBS show that the increase in the aging

level, from short-term to long-term, is capable of increasing the A values proportionally. Such increase in integrity reduces in the extent that the f/a ratio increases. Similarly to what was observed for the mastics prepared with the neat binder, aging increases the rate of damage accumulation of the mastics prepared with the AC+PPA and the AC+SBS, and the f/a ratio increases it slightly.

Table 5.8 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+PPA as a function of the aging level and the f/a ratio

Parameter	f/a ratio	RTFOT	PAV	PAV/RTFOT
A	0.00	2.14E+06	4.26E+06	1.99
	0.15	8.13E+05	1.76E+06	2.16
	0.30	2.86E+05	7.08E+05	2.48
	0.45	2.10E+05	2.92E+05	1.39
B	0.00	3.58	4.28	1.20
	0.15	3.19	3.93	1.23
	0.30	3.03	3.82	1.26
	0.45	3.03	3.96	1.31

Figure 5.7 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+PPA as a function of the aging level and f/a ratio

Table 5.9 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+SBS as a function of the aging level and the f/a ratio

Parameter	f/a ratio	RTFOT	PAV	PAV/RTFOT
A	0.00	6.48E+05	1.29E+06	1.98
	0.15	4.51E+05	7.58E+05	1.68
	0.30	2.75E+05	4.70E+05	1.71
	0.45	1.66E+05	3.03E+05	1.83
B	0.00	3.24	3.70	1.14
	0.15	3.00	3.65	1.22
	0.30	3.03	3.79	1.25
	0.45	3.04	3.77	1.24

Figure 5.8 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+SBS as a function of the aging level and the f/a ratio

Table 5.10 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+rubber as a function of the aging level and the f/a ratio

Parameter	f/a ratio	RTFOT	PAV	PAV/RTFOT
A	0.00	2.80E+06	5.64E+06	2.01
	0.15	1.37E+06	4.53E+06	3.30
	0.30	4.11E+05	1.64E+06	3.99
	0.45	1.53E+05	5.22E+05	3.42
B	0.00	3.34	3.59	1.08
	0.15	3.23	3.70	1.14
	0.30	3.21	3.84	1.19
	0.45	3.16	3.88	1.23

Figure 5.9 – Coefficients A and B of the fatigue model for the asphalt mastics produced with the AC+rubber as a function of the aging level and the f/a ratio

Similarly to what was observed for the mastics prepared with the neat binder, the AC+PPA and the AC+SBS, the results for the mastics prepared with the AC+rubber also show that the increase in the aging level, from short-term to long-term, is capable of increasing the A values proportionally. But differently from what was observed for the mastics prepared with those three binders, the increase in integrity increases with the f/a ratio. Similarly to what was observed for the mastics prepared with the neat binder, the AC+PPA and the AC+SBS, aging increases the rate of damage accumulation and the f/a ratio increases it slightly.

5.2.2 Fatigue damage tolerance index (a_f)

The objective of this section is to show the effect of the aging level on the fatigue damage tolerance ratio (a_f). Table 5.11 shows the a_f values for the asphalt mastics produced with the neat binder, the AC+PPA, the AC+SBS and the AC+rubber, as a function of the aging level and the f/a ratio, and the relationships between the a_f values for the PAV- and RTFOT-aged materials. Figure 5.10 shows a comparison of the a_f values for the mastics prepared with the neat binder, the AC+PPA, the AC+SBS and the AC+rubber, and aged in short- and long-term.

The results show that the increase of the aging level from short-term to long-term does not affect significantly the fatigue damage tolerance indices for the mastics prepared with the neat binder, the AC+PPA and the AC+SBS. On the other hand, a slight increase of a_f values is observed for the mastics prepared with the AC+rubber after the long-term aging. This implies that mastics prepared with the AC+rubber have a higher tolerance to fatigue damage after long-term aging.

Table 5.11 – A_f values for the asphalt mastics as a function of the aging level and the f/a ratio for the asphalt mastics, and the relationships between the a_f values for the PAV- and RTFOT-aged materials

Material	f/a ratio	RTFOT	PAV	PAV/RTFOT
Neat binder	0.00	0.78	0.87	1.12
	0.15	0.88	0.99	1.12
	0.30	1.04	1.01	0.97
	0.45	1.09	1.08	0.99
AC+PPA	0.00	0.95	0.90	0.95
	0.15	0.99	1.04	1.05
	0.30	1.06	1.11	1.04
	0.45	1.16	1.16	1.00
AC+SBS	0.00	0.87	0.90	1.03
	0.15	1.00	1.01	1.01
	0.30	1.12	1.08	0.96
	0.45	1.18	1.21	1.03
AC+rubber	0.00	0.96	1.04	1.08
	0.15	1.05	1.16	1.11
	0.30	1.12	1.24	1.11
	0.45	1.14	1.25	1.10

Figure 5.10 – A_f values for the asphalt mastics as a function of the aging level and the f/a ratio

5.3 EFFECT OF THE TYPE OF ASPHALT BINDER

5.3.1 Parameter A and B of the fatigue model

The objective of this section is to show the effect of the type of asphalt binder on the parameters A and B of the fatigue model. Table 5.12 shows the values for the parameters A and B of the fatigue models for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.00$. Table 5.12 also shows the relationships between the parameters for the modified binders divided by the parameters for the neat binder. Figure 5.11 depicts the parameters A and B of the fatigue models for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.00$. Following this same pattern, Table 5.13 and Figure 5.12, Table 5.14 and Figure 5.13, and Table 5.15 and Figure 5.14 show the values for the coefficients A and B of the fatigue models for the filler/asphalt ratios of 0.15, 0.30 and 0.45, respectively. The overall tendency is the increase of the A and B values of the mastics with the use of modified binders in comparison to the mastics prepared with the neat binder, regardless of the f/a ratio. This means that the mastics present higher integrity and higher rate of damage accumulation, compared to the mastics prepared with the neat binder. The mastics prepared with the AC+rubber presented the highest increase of A values and the mastics prepared with the AC+SBS presented the lowest increase of A values, compared to mastics prepared with neat binder. In relation to B, the mastics prepared with the AC+PPA showed the highest increase and the mastics prepared with the AC+SBS showed the lowest increase, compared to mastics prepared with neat binder.

Table 5.12 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.00$, and the relationships between the parameters for the modified binders divided by the parameters for the neat binder

Aging level	Asphalt binder	A	Relationship	B	Relationship
RTFOT	Neat binder	2,41E+05	1,00	2,75	1,00
	AC +PPA	2,14E+06	8,88	3,58	1,30
	AC+SBS	6,48E+05	2,69	3,24	1,18
	AC+rubber	2,80E+06	11,61	3,34	1,21
PAV	Neat binder	5,35E+05	1,00	3,28	1,00
	AC +PPA	4,26E+06	7,97	4,28	1,31
	AC+SBS	1,29E+06	2,40	3,70	1,13
	AC+rubber	5,64E+06	10,55	3,59	1,10

Figure 5.11 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.00$

Table 5.13 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.15$, and the relationships between the parameters for the modified binders divided by the parameters for the neat binder

Aging level	Asphalt binder	A	Relationship	B	Relationship
RTFOT	Neat binder	1.90E+05	1.00	2.67	1.00
	AC +PPA	8.13E+05	4.27	3.19	1.20
	AC+SBS	4.51E+05	2.37	3.00	1.13
	AC+rubber	1.37E+06	7.21	3.23	1.21
PAV	Neat binder	4.46E+05	1.00	3.23	1.00
	AC +PPA	1.76E+06	3.94	3.93	1.22
	AC+SBS	7.58E+05	1.70	3.65	1.13
	AC+rubber	4.53E+06	10.17	3.70	1.15

Figure 5.12 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.15$

Table 5.14 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.30$, and the relationships between the parameters for the modified binders divided by the parameters for the neat binder

Aging level	Asphalt binder	A	Relationship	B	Relationship
RTFOT	Neat binder	1.43E+05	1.00	2.67	1.00
	AC +PPA	2.86E+05	1.99	3.03	1.14
	AC+SBS	2.75E+05	1.92	3.03	1.13
	AC+rubber	4.11E+05	2.87	3.21	1.20
PAV	Neat binder	2.15E+05	1.00	3.33	1.00
	AC +PPA	7.08E+05	3.30	3.82	1.15
	AC+SBS	4.70E+05	2.19	3.79	1.14
	AC+rubber	1.64E+06	7.65	3.84	1.15

Figure 5.13 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.30$

Table 5.15 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.45$, and the relationships between the parameters for the modified binders divided by the parameters for the neat binder

Aging level	Asphalt binder	A	Relationship	B	Relationship
RTFOT	Neat binder	1.01E+05	1.00	2.76	1.00
	AC +PPA	2.10E+05	2.09	3.03	1.10
	AC+SBS	1.66E+05	1.65	3.04	1.10
	AC+rubber	1.53E+05	1.52	3.16	1.15
PAV	Neat binder	1.27E+05	1.00	3.44	1.00
	AC +PPA	2.92E+05	2.29	3.96	1.15
	AC+SBS	3.03E+05	2.38	3.77	1.10
	AC+rubber	5.22E+05	4.09	3.88	1.13

Figure 5.14 – Coefficients A and B of the fatigue model for the asphalt mastics as a function of the type of asphalt binder and aging level for $f/a=0.45$

5.3.2 Fatigue damage tolerance index (a_f)

The objective of this section is to show the effect of the type of asphalt binder on the fatigue damage tolerance ratio (a_f). Table 5.16 shows the a_f values for the asphalt mastics as a function of the type of asphalt binder, aging level and f/a ratio. Table 5.17 shows relationships between the a_f values of the mastics produced with the modified binders divided by the a_f values of the mastics produced with the neat binder as a function of the aging level and the f/a ratios. Figure 5.15 shows a comparison of the a_f values for the asphalt mastics as a function of the type of asphalt binder, aging level and f/a ratio. The use of modified binders in the preparation of the mastics resulted in increase of the fatigue damage tolerance index, what means that the use of modified binders tends to increase the fatigue life of the materials. The mastics prepared with the AC+rubber presented the highest increase of the a_f values and the ones prepared with the AC+SBS presented the lowest increase of the a_f values, compared to the mastics prepared with the neat binder.

Table 5.16 – A_f values for the asphalt mastics as a function of the type of asphalt binder, aging level and f/a ratio

Aging level	Asphalt binder	$f/a = 0.00$	$f/a = 0.15$	$f/a = 0.30$	$f/a = 0.45$
RTFOT	Neat binder	0.78	0.88	1.04	1.09
	AC +PPA	0.95	0.99	1.06	1.16
	AC+SBS	0.87	1.00	1.12	1.18
	AC+rubber	0.96	1.05	1.12	1.14
PAV	Neat binder	0.87	0.99	1.01	1.08
	AC +PPA	0.90	1.04	1.11	1.16
	AC+SBS	0.90	1.01	1.08	1.21
	AC+rubber	1.04	1.16	1.24	1.25

Table 5.17 – Relationships between the a_f values of the mastics produced with the modified binders divided by the a_f values of the mastic produced with the neat binder as a function of the aging level and the f/a ratios

Aging level	Asphalt binder	$f/a = 0.00$	$f/a = 0.15$	$f/a = 0.30$	$f/a = 0.45$
RTFOT	Neat binder	1.00	1.00	1.00	1.00
	AC +PPA	1.22	1.12	1.02	1.06
	AC+SBS	1.12	1.13	1.08	1.08
	AC+rubber	1.23	1.19	1.08	1.04
PAV	Neat binder	1.00	1.00	1.00	1.00
	AC +PPA	1.04	1.05	1.10	1.07
	AC+SBS	1.03	1.02	1.07	1.12
	AC+rubber	1.19	1.18	1.23	1.15

Figure 5.15 – Comparison of the a_f values for the asphalt mastics as a function of the type of asphalt binder, aging level and f/a ratio

5.4 FATIGUE CURVES

5.4.1 Effect of filler/asphalt ratio

The objective of this section is to show the effect of the filler/asphalt ratio on the fatigue life curves of the asphalt mastics Table 5.18 presents the fatigue models for the asphalt binder and asphalt mastics as a function of the type of asphalt binder, aging level and f/a ratio.

Figure 5.16 shows the fatigue curves as a function of the f/a ratio for the asphalt mastics produced with the neat binder aged in short- and long-term. Following this same pattern, Figure 5.17 to Figure 5.19 illustrate the fatigue curves for the mastics produced with the AC+PPA, the AC+SBS, and the AC+rubber, respectively. The overall effect of the increasing amount of mineral filler is noticed as the shift of the fatigue curves down, what represents a reduction in the fatigue life of the materials for the same strain level. This happened because, as mentioned before, the increase of the f/a ratio is capable of reducing the A values and increasing the B values.

Table 5.18 – Fatigue model for the asphalt mastics as a function of the type of asphalt binder, aging level and f/a ratio

Aging level	f/a ratio	AC NEAT	AC+PPA	AC+SBS	AC+rubber
RTFOT	0.00	$N_f = 241,204 \cdot \gamma^{2.75}$	$N_f = 2,142,275 \cdot \gamma^{3.58}$	$N_f = 648,437 \cdot \gamma^{3.24}$	$N_f = 2,800,734 \cdot \gamma^{3.34}$
	0.15	$N_f = 190,487 \cdot \gamma^{2.67}$	$N_f = 812,634 \cdot \gamma^{3.19}$	$N_f = 450,565 \cdot \gamma^{3.00}$	$N_f = 1,372,784 \cdot \gamma^{3.23}$
	0.30	$N_f = 143,398 \cdot \gamma^{2.67}$	$N_f = 286,018 \cdot \gamma^{3.03}$	$N_f = 274,913 \cdot \gamma^{3.03}$	$N_f = 411,083 \cdot \gamma^{3.21}$
	0.45	$N_f = 100,606 \cdot \gamma^{2.67}$	$N_f = 210,163 \cdot \gamma^{3.03}$	$N_f = 165,715 \cdot \gamma^{3.04}$	$N_f = 152,756 \cdot \gamma^{3.16}$
PAV	0.00	$N_f = 534,513 \cdot \gamma^{3.28}$	$N_f = 4,257,515 \cdot \gamma^{4.28}$	$N_f = 1,285,340 \cdot \gamma^{3.70}$	$N_f = 5,641,517 \cdot \gamma^{3.59}$
	0.15	$N_f = 445,779 \cdot \gamma^{3.23}$	$N_f = 1,755,224 \cdot \gamma^{3.98}$	$N_f = 757,680 \cdot \gamma^{3.65}$	$N_f = 4,533,393 \cdot \gamma^{3.70}$
	0.30	$N_f = 214,585 \cdot \gamma^{3.33}$	$N_f = 707,968 \cdot \gamma^{3.82}$	$N_f = 469,618 \cdot \gamma^{3.79}$	$N_f = 1,641,142 \cdot \gamma^{3.84}$
	0.45	$N_f = 127,428 \cdot \gamma^{3.44}$	$N_f = 292,217 \cdot \gamma^{3.96}$	$N_f = 303,047 \cdot \gamma^{3.77}$	$N_f = 521,784 \cdot \gamma^{3.88}$

Figure 5.16 – Comparison of the fatigue curves as a function of f/a ratio for the mastics produced with the neat binder aged in short- and long-term

Figure 5.17 – Comparison of the fatigue curves as a function of f/a ratio for the mastics produced with the AC+PPA aged in short- and long-term

Figure 5.18 – Comparison of the fatigue curves as a function of f/a ratio for the mastics produced with the AC+SBS aged in short- and long-term

Figure 5.19 – Comparison of the fatigue curves as a function of f/a ratio for the mastics produced with the AC+rubber aged in short- and long-term

5.4.2 Effect of the aging level

The objective of this section is to show the effect of the aging level on the fatigue life curves of the asphalt mastics. Figure 5.20 shows the fatigue curves as a function of the aging level for the mastics produced with the neat binder for the f/a ratio equal to 0.00, 0.15, 0.30 and 0.45. Following this same pattern, Figure 5.21 to Figure 5.23 depicts the fatigue curves as function of aging level for the mastics produced with the AC+PPA, the AC+SBS, and the AC+rubber, respectively. As mentioned before, the long-term aging is capable of increasing the A and B values compared to the short-term aging, in such a way that the fatigue curves initiate at higher N_f values but the ratio of decrease of N_f with the increase of the strain is higher.

Figure 5.20 – Comparison of the fatigue curves as a function of aging level for the mastic produced with the neat binder for the f/a ratio equal to 0.00, 0.15, 0.30 and 0.45

Figure 5.21 – Comparison of the fatigue curves as a function of aging level for the mastics produced with the AC+PPA for the f/a ratio equal to 0.00, 0.15, 0.30 and 0.45

Figure 5.22 – Comparison of the fatigue curves as a function of aging level for the mastics produced with the AC+SBS for the f/a ratio equal to 0.00, 0.15, 0.30 and 0.45

Figure 5.23 – Comparison of the fatigue curves as a function of aging level for the mastics produced with the AC+rubber for the f/a ratio equal to 0.00, 0.15, 0.30 and 0.45

5.4.3 Effect of the type of asphalt binder

The objective of this section is to show the effect of the modified asphalt binders on the fatigue life curves of the asphalt mastics. Figure 5.24 shows the fatigue curves for the mastics with f/a ratio of 0.00 aged in short- and long-term. Following this same pattern, Figure 5.25 to Figure 5.27 illustrate the fatigue life curves for the f/a ratio of 0.15, 0.30 and 0.45, respectively. The effects of the presence of the modified binders vary with the f/a ratio and the only way of evaluating which material presents the highest fatigue life is by means of the rank order carried out in the next section.

Figure 5.24 – Comparison of the fatigue curves as a function of the type of asphalt binder for mastic with $f/a=0.00$ and short- and long-term aging

Figure 5.25 – Comparison of the fatigue curves as a function of the type of asphalt binder for mastic with $f/a=0.15$ and short- and long-term aging

Figure 5.26 – Comparison of the fatigue curves as a function of the type of asphalt binder for mastic with $f/a=0.30$ and short- and long-term aging

Figure 5.27 – Comparison of the fatigue curves as a function of the type of asphalt binder for mastic with $f/a=0.45$ and short- and long-term aging

5.5 RANK ORDER BASED ON THE N_F VALUES

The objective of this section is to order the mastics produced with different asphalt binders in relation to the number of axle-load repetitions that takes the material to failure, taking the effects of the f/a ratio and aging into account. Two strain levels were adopted in this analysis, i. e., 2 and 20 %, once that the materials tend to present different responses to low and high strains. This rank order consists in the ascription of a numerical value, between 1 and 4, referring to the classification of the material in a rank of the results of all materials. The numeration was ascribed from the best to the worse materials, in such a way that the best results received lower values and the worse ones received the highest. The best results represent the materials whose number of axle load repetitions is higher.

The materials were first ranked separately, according to the aging level (short and long-term) and strain level (2 and 20 %). Posteriorly, they were ranked according to the aging level (short and long-term) but considering the average position for the two strain levels. And they were finally ranked according to the global effect of aging, considering the average position for the two aging levels. Figure 5.28 shows the rank order of the asphalt mastics for the two strain levels, 2 % and 20 %, and short-term aging, and Figure 5.29 shows the rank order of the asphalt mastics for the two strain levels and long-term aging. Figure 5.30 presents the rank order for each aging level, where the results represent the average rank order for the two strain levels.

Figure 5.31 presents the final rank order, and in this case, the results represent the average rank order for the two strain levels and the two aging levels. In this rank order, the asphalt binder ($f/a = 0.00$) was subtracted from the calculation, once that it is another scale. A specific rank order for the asphalt binder will be presented in the sequence.

Figure 5.28 – Rank order of the asphalt mastics for the two strain levels (2 % and 20 %) and short-term aging

The mastics prepared with the AC+PPA and aged in short-term presented the highest fatigue life at 2 % strain level and the mastics prepared with the neat binder presented the lowest ones. However, at 20 % strain level, the mastics prepared the neat binder presented the highest fatigue life and the mastics prepared with the AC+SBS presented the lowest one.

Figure 5.29 – Rank order of the asphalt mastics for the two strain levels (2 % and 20 %) and long-term aging

A different picture is seen when the materials are aged in long-term. The mastics prepared with the AC+rubber presented the highest fatigue life at 2 % strain level and the mastics

prepared with the neat binder presented the lowest ones. At 20 % strain level, the mastics prepared the AC+rubber also presented the highest fatigue life and the mastics prepared with the AC+SBS presented the lowest one.

When the rank orders done at both strain levels are combined, the mastics prepared with the AC+PPA presented the highest fatigue lives and the mastics prepared with the AC+SBS presented the lowest ones, when the materials are aged in short-term. For the long-term aging, the mastics prepared with the AC+rubber presented the highest fatigue lives and the mastics prepared with the AC+SBS presented the lowest ones. When the rank orders done at both aging levels are combined, a final rank order is obtained. The mastics prepared with the AC+rubber occupy the first position, with the highest fatigue life, and the mastics prepared with the AC+SBS occupy the fourth, with the lowest fatigue life.

Figure 5.30 – Rank order of the asphalt mastics for short- and long-term aging

Figure 5.31 – Final rank order for the asphalt mastics

Figure 5.32 shows the rank order of the asphalt binders for the two strain levels, 2 % and 20 %, and short-term aging, and Figure 5.33 shows the rank order of the asphalt binders for the two strain levels and long-term aging. Figure 5.34 presents the rank order for each aging level, where the results represent the average rank order for the two strain levels. Figure 5.35 presents the final rank order, and in this case, the results represent the average rank order for the two strain levels and the two aging levels.

Figure 5.32 – Rank order of the RTFOT-aged asphalt binders for the two strain levels (2 % and 20 %)

The neat binder aged in short-term presented the highest fatigue life at 2 % strain level and the AC+rubber presented the lowest ones. However, at 20 % strain level, the AC+PPA presented the highest fatigue life and the AC+SBS presented the lowest one. A different picture is seen when the materials are aged in long-term. The AC+rubber presented the highest fatigue life at 2 % strain level and the neat binder presented the lowest ones. At 20 % strain level, the AC+rubber also presented the highest fatigue life and the AC+PPA presented the lowest one.

Figure 5.33 – Rank order of the PAV-aged asphalt binders for the two strain levels (2 % and 20 %)

When the rank orders done at both strain levels are combined, the neat binder presented the highest fatigue life and the AC+rubber presented the lowest ones, when the materials are aged in both short- and long-term. When the rank orders done at both aging levels are combined, a final rank order is obtained. The AC+rubber occupy the first position, with the highest fatigue life, and the AC+SBS occupy the fourth, with the lowest fatigue life.

Figure 5.34 – Rank order of the asphalt binders for short- and long-term aging

Figure 5.35 – Final rank order for the asphalt binders

6 FINE AGGREGATE MATRICES

The objective of this chapter is to present the results of the time sweep tests under controlled stress mode carried out with the fine aggregate matrices (FAM) produced with the four asphalt binders studied in this research (neat AC, AC+PPA, AC+SBS and AC+rubber). The FAM samples were submitted to short- and long-term aging in order to evaluate the effect of aging on the damage properties of the materials. The results were analyzed by means of the viscoelastic continuum damage (VECD) theory with the estimation of the parameters of the fatigue model $N_f = A \cdot \gamma^{-B}$. The chapter was divided in five sections, in order to show results related to the linear viscoelastic properties, relaxation properties and damage evolution rate, characteristic curves (C vs. S), fatigue models and estimates of the number of axle load repetitions to failure (N_f) based on the fatigue model, and rank order of the materials.

6.1 LINEAR VISCOELASTIC PROPERTIES

Table 6.1 presents the linear viscoelastic properties (LVE) of the materials, including $|G^*|$, phase angle and strain, as a function of the aging level. The LVE properties of the materials were obtained by means of a frequency sweep from 30 Hz to 0.05 Hz at 15 kPa and 25 °C. The air voids of the samples and the binder content for each FAM are also presented for reference.

Table 6.1 – Viscoelastic properties of the materials

Aging level	Materials	Sample	% binder	Air voids (%)	$ G^* $ (Pa)	$ G^* $ (Pa)	CV	δ (°)	δ (°)	γ (μstrain)
Short-term	neat binder	1	7.4	4.8	7.51E+08	8.04E+08	25	42	40	20
		2		4.7	1.03E+09			38		15
		3		4.9	6.31E+08			40		24
	AC+PPA	1	7.8	3.3	1.20E+09	1.02E+09	0.12	37	38	13
		2		3.5	9.31E+08			39		16
		3		3.0	9.77E+08			39		15
		4		3.7	9.53E+08			35		16
	AC+SBS	1	7.7	2.0	9.15E+08	1.01E+09	0.19	36	37	16
		2		2.1	1.28E+09			36		12
		3		1.9	8.40E+08			39		18
		4		1.8	9.94E+08			35		15
	AC+rubber	1	9.3	2.9	6.82E+08	5.74E+08	0.28	35	33	22
		2		2.9	3.93E+08			30		38
		3		3.0	6.48E+08			34		22
30 days	neat binder	1	7.4	3.4	9.47E+08	9.09E+08	0.19	40	40	16
		2		3.4	1.06E+09			40		14
		3		3.4	7.19E+08			40		21

Aging level	Materials	Sample	% binder	Air voids (%)	G* (Pa)	G* (Pa)	CV	δ (°)	δ (°)	γ (μ strain)
60 days	AC+PPA	1		2.6	1.35E+09			36		11
		2	7.8	2.6	1.22E+09	1.22E+09	0.11	35	36	12
		3		2.6	1.09E+09			37		14
	AC+SBS	1		1.4	9.30E+08			39		16
		2	7.7	1.4	1.10E+09	1.05E+09	0.10	36	37	14
		3		1.4	1.11E+09			37		14
	AC+rubber	1		2.6	1.15E+09			29		13
		2	9.3	2.6	1.15E+09	1.29E+09	0.19	30	29	13
		3		2.5	1.57E+09			27		10
	neat binder	1		3.6	1.11E+09			39		14
		2	7.4	3.7	1.08E+09	1.06E+09	0.06	39	40	14
		3		3.7	9.96E+08			42		15
	AC+PPA	1		2.5	1.11E+09			37		13
		2	7.8	2.6	1.14E+09	1.15E+09	0.04	35	37	13
		3		2.4	1.20E+09			38		13
	AC+SBS	1		2.0	1.18E+09			33		13
		2	7.7	2.0	8.03E+08	1.05E+09	0.20	33	33	19
		3		2.1	1.17E+09			34		13
	AC+rubber	1		3.1	1.66E+09	2.24E+09	0.36	26	25	9
		2	9.3	3.0	2.81E+09			24		5

Figure 6.1 to Figure 6.3 show graphical comparisons of the results of $|G^*|$ of the samples aged in short-term, 30 days and 60 days, respectively. It is noteworthy that similar values for $|G^*|$ were obtained for the minority of the materials, as in the case of the FAMs prepared with the AC+PPA in short-term, the FAMs prepared with the AC+SBS and the AC+rubber in 30 days, and the FAMs prepared with the neat binder and the AC+PPA in 60 days.

Figure 6.1 – Comparison of $|G^*|$ (Pa) of the samples aged in short-term

Figure 6.2 – Comparison of $|G^*|$ (Pa) of the samples aged in 30 days Figure 6.3 – Comparison of $|G^*|$ (Pa) of the samples aged in 60 days

Figure 6.4 shows a comparison of the average $|G^*|$ values for the FAMs produced with the four asphalt binders as a function of the aging level. Only the FAMs prepared with the neat binder and the AC+rubber presented increase in the $|G^*|$ values with the aging level. Aging affected the $|G^*|$ values slightly for the FAM prepared with the neat binder and affected the $|G^*|$ values expensively for the FAMs prepared with the AC+rubber. This would be expected for the FAMs prepared with all binders, but those produced with the AC+PPA and the AC+SBS presented unexpected results for $|G^*|$. The FAMs produced with the AC+SBS draws one's attention, once that the $|G^*|$ values for the samples in the three aging levels are identical. It is also noteworthy that the FAMs prepared with neat binder, AC+SBS and AC+PPA show similar $|G^*|$ values, indicating that there is no clear effect of the stiffness of the asphalt binder on the stiffness of the FAM.

Figure 6.4 – Comparison of the average $|G^*|$ values for the FAMs produced with the four asphalt binders as a function of the aging level

Figure 6.5 shows a comparison of the average δ values for the FAMs produced with the four asphalt binders as a function of the aging level. The FAMs prepared with modified binders presented lower values for the phase angle (δ) compared to the FAMs prepared with neat binder. This reduction in the phase angle values is expected, once that the modifiers increase the elastic response of the asphalt binders. This reduction was more significant for the FAMs prepared with the AC+rubber (8 degrees between extremes). Regarding the aging effect, the FAMs prepared with the neat binder presented the same δ values for the three aging level, showing that the elastic response of these materials was not affected by the aging. For the FAMs prepared with the AC+PPA and the AC+SBS, the phase angles resulted similar regardless of the aging level.

Figure 6.5 – Comparison of the average δ values for the FAMs produced with the four asphalt binders as a function of the aging level

6.2 RELAXATION PROPERTIES AND DAMAGE EVOLUTION RATE

Table 6.2 presents the slope of the relaxation curves and the damage evolution rate ($1/m$) of the materials, as a function of the aging level. The air voids of the samples are presented again for reference.

Table 6.2 – Relaxations properties and damage evolution rate of the materials

Aging level	Materials	Sample	% binder	Air voids (%)	m	m (average)	α	α (average)
Short-term	neat binder	1	7.4	4.8	0.50	0.47	2.00	2.15
		2		4.7	0.45		2.24	
		3		4.9	0.45		2.20	
	AC+PPA	1	7.8	3.3	0.43	0.43	2.33	2.34
		2		3.5	0.44		2.27	
		3		3	0.44		2.25	
		4		3.7	0.39		2.52	
	AC+SBS	1	7.7	2	0.42	0.44	2.37	2.27
		2		2.1	0.49		2.03	
		3		1.9	0.45		2.23	
		4		1.8	0.41		2.46	
	AC+rubber	1	9.3	2.9	0.40	0.38	2.47	2.62
		2		2.9	0.35		2.87	
		3		3	0.40		2.53	
30 days	neat binder	1	7.4	3.4	0.49	0.47	2.04	2.12
		2		3.4	0.47		2.12	
		3		3.4	0.45		2.19	
	AC+PPA	1	7.8	2.6	0.42	0.41	2.37	2.43
		2		2.6	0.39		2.57	
		3		2.6	0.43		2.34	
	AC+SBS	1	7.7	1.4	0.46	0.43	2.20	2.31
		2		1.4	0.42		2.38	
		3		1.4	0.42		2.36	
	AC+rubber	1	9.3	2.6	0.36	0.33	2.81	3.03
		2		2.6	0.33		2.99	
		3		2.5	0.30		3.30	
60 days	neat binder	1	7.4	3.6	0.46	0.47	2.17	2.15
		2		3.7	0.45		2.22	
		3		3.7	0.49		2.05	
	AC+PPA	1	7.8	2.5	0.44	0.42	2.29	2.37
		2		2.6	0.40		2.51	
		3		2.4	0.43		2.31	
	AC+SBS	1	7.7	2	0.37	0.39	2.67	2.55
		2		2	0.41		2.43	
		3		2.1	0.39		2.55	
	AC+rubber	1	9.3	3.1	0.45	0.45	2.23	2.24
		2		3.0	0.45		2.24	

Figure 6.6 to Figure 6.8 show graphical comparisons of the results of the m values of the samples aged in short-term, 30 days and 60 days, respectively. It is notable that the m values between the replicates were similar for most of the FAMs. Figure 6.9 shows a comparison of the average m values for the FAMs produced with the four asphalt binders as a function of the aging level.

Figure 6.6 – Comparison of the m values of the samples aged in short-term

Figure 6.7 – Comparison of the m values of the samples aged in 30 days

Figure 6.8 – Comparison of the m values of the samples aged in 60 days Figure 6.9 – Comparison of the average m values of the materials as a function of the aging level

As shown in Figure 6.9, the m values for the FAMs prepared with neat binder and AC+PPA are not affected by the aging level. The effect of aging in the relaxation property is more pronounced for the FAMs prepared with the AC+SBS, where the m values reduce with the aging level. For the FAMs prepared with the AC+rubber no clear trend was observed for the effect of the extended aging. It seems that the m values for the FAMs prepared with the modified binders are lower than those obtained for the FAMs prepared with the neat binder. This means that the FAMs prepared with the modified binders present a lower relaxation rate and as a consequence these materials will present a higher rate of damage accumulation.

Figure 6.10 to Figure 6.12 show graphical comparisons of the results of the α values of the samples aged in short-term, 30 days and 60 days, respectively. Figure 6.13 compares the

average α values of the materials according to the aging level. As mentioned before in relation to the m values, the α values are independent of the aging level, for the FAMs prepared with the neat binder and the AC+PPA. The effect of aging on the damage accumulation rate is more pronounced for the FAMs prepared with the AC+SBS, once that the α values for the FAMs aged in long-term at 60 days are significantly higher compared with the FAMs aged in short- and long-term at 30 days. For the FAM prepared with the AC+rubber, no clear trend was observed regarding the effect of the aging level. Regarding the modifiers, seems that the FAMs prepared with the modified materials present higher α values compared to the FAMs prepared with the neat binder.

Figure 6.10 – Comparison of the α values of the samples aged in short-term

Figure 6.11 – Comparison of the α values of the samples aged in 30 days

Figure 6.12 – Comparison of the α values of the samples aged in 60 days Figure 6.13 – Comparison of the α values of the materials as a function of the aging level

6.3 CHARACTERISTIC CURVES

In this section, the characteristic curves for each material tested at low and high stress levels are presented. The FAMs samples were tested using low stresses in order to generate an initial damage to the samples lower than 10 %, i.e., the initial C values of the samples will not be lower than 0.9. Other tests were carried out at higher stress levels (300 to 400 kPa) in order to verify the superposition of the curves C vs. S and to reduce the test duration.

It is visible that the characteristic curves for the different stress levels did not overlap. In order to try to obtain curves with similar shapes, new characteristic curves were obtained from the samples tested at high stresses and the average of the characteristic curves was calculated. These average curves were built using the average values for the linear viscoelastic properties

($|G^*|_{lve}$ and α) of the samples prepared with the same materials and tested in the same loading condition. This artifice of calculating the characteristic curve of each material with the average of the linear viscoelastic properties was adopted in order to reduce the effect of variability among samples and obtain a unique characteristic curve for the same material.

Figure 6.14 to Figure 6.17 depict the C vs. S curves for the FAMs aged in short-term, including the individual results and the average of the curves C vs. S . The legends of the curves C vs. S present information related to (i) the aging levels, which are represented by the notations ST for short-term, LT 30D for long-term at 30 days, and LT 60D for long term at 60 days, (ii) the identification of the samples as shown in Table 6.1 and Table 6.2, (iii) the linear viscoelastic properties, $|G^*|_{lve}$ and α (a), of each sample and the average of these properties for the average curves C vs. S , and (iv) the stress level applied to the sample to damage it (t).

Figure 6.14 – Curves C vs. S and the average curves C vs. S for the FAMs prepared with the neat binder and aged in short-term

Figure 6.15 – Curves C vs. S and the average curves C vs. S for the FAMs prepared with the AC+PPA and aged in short-term

Figure 6.16 – Curves C vs. S and the average curves C vs. S for the FAMs prepared with the AC+SBS and aged in short-term

Figure 6.17 – Curves C vs. S and the average curves C vs. S for the FAMs prepared with the AC+rubber and aged in short-term

Based on the curves C vs. S presented in Figure 6.14 to Figure 6.17, it is possible to conclude that is not appropriate to test the FAMs samples at low stresses, once that is not possible to observe the superposition of the curves C vs. S for different stress levels. For most cases, it is possible to observe the superposition of the curves C vs. S with the average of the linear viscoelastic properties, with the exception of the FAMs prepared with the neat binder and the AC+rubber. However, the fatigue curves for the FAMs prepared with the neat binder and the AC+rubber overlapped, as will be shown in the next section.

Figure 6.18 to Figure 6.21 present the C vs. S curves for the FAMs aged in long-term for 30 days, including the individual results and the average of the C vs. S curves.

Figure 6.18 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 30 days, prepared with the neat binder

Figure 6.19 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 30 days, prepared with the AC+PPA

Figure 6.20 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 30 days, prepared with the AC+SBS

Figure 6.21 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 30 days, prepared with the AC+rubber

Based on the curves C vs. S presented in Figure 6.18 to Figure 6.21, it is possible to conclude that it is not appropriate to test the FAM samples at low stresses, once that it is not possible to observe the superposition of curves C vs. S for different stress levels. For all the cases, it is possible to observe the superposition of the curves C vs. S with the average of the linear viscoelastic properties. It is important to point out that the curves C vs. S for the FAMs produced with neat binder and AC+SBS overlapped even before the calculation of the average of the linear viscoelastic properties. Figure 6.22 to Figure 6.25 show the C vs. S curves for the FAMs aged in long-term for 60 days, including the individual results and the average of the C vs. S curves.

Figure 6.22 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 60 days, prepared with the neat binder

Figure 6.23 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 60 days, prepared with the AC+PPA

Figure 6.24 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 60 days, prepared with the AC+SBS

Figure 6.25 – Curves C vs. S and the average of C vs. S curves for the FAMs aged in long-term for 60 days, prepared with the AC+rubber

Figure 6.22 to Figure 6.25 show the superposition of the C vs. S curves with the average of the linear viscoelastic properties for all the materials. The superposition was also observed for the FAMs samples aged in long-term at 30 days. Figure 6.26 depicts comparisons of the average of C vs. S curves of the FAMs produced with the four asphalt binders and aged in short-term, 30 days and 60 days.

Figure 6.26 – Average of C vs. S curves of the FAMs produced with the four asphalt binders and aged in (a) short-term, (b) long-term for 30 days, and (c) long-term for 60 days

Figure 6.26 shows that the FAMs prepared with modified binders are able to accumulate more damage than the FAM prepared with the neat binder for all the aging conditions. The FAMs produced with the AC+PPA and AC+SBS presented similar average C vs. S curves in all the aging conditions. The FAMs prepared with the AC+rubber stands out in most of the aging conditions, showing more capacity to accumulate damage. The results for the material aged in long-term at 60 days is an exception, once that it presented an average C vs. S curve

similar to that obtained for the FAM prepared with neat binder. Figure 6.27 shows the effects of aging on the FAMs produced with the neat binder, AC+PPA, AC+SBS and AC+rubber.

Figure 6.27 – Effect of aging on the FAMs produced with the (a) neat binder, (b) AC+PPA, (c) AC+SBS, and (d) AC+rubber

The effect of aging is not clear in the average characteristics curves for the FAMs prepared with the neat binder and the AC+rubber. The aging effect is clearly visible only for the FAMs prepared with the AC+PPA and the AC+SBS, which presented a greater capacity to accumulate damage to the extent that the aging becomes more severe.

6.4 FATIGUE MODELS

Table 6.3 presents the average values for the parameters A and B of the fatigue models and the average values for the damage accumulation parameter (S) assuming a reduction of

50 % on the pseudo stiffness for the FAMs. This table also presents the relationships of the parameters for the FAMs produced with the modified binders divided by the parameters for the FAMs prepared with the neat binder. The fatigue models presented in this dissertation were adjusted assuming that failure occurs for a reduction of 50 % on the pseudo stiffness. Table 6.4 presents the fatigue models for the FAMs produced with the four asphalt binders according to the aging level.

Table 6.3 – Parameters A and B of the fatigue models

Aging level	Materials	A average	Relationship	B average	Relationship	S _{50 %} average	Relationship
Short-term	neat binder	1.92E+30	1.00	4.44	1.00	7.77E+08	1.00
	AC+PPA	3.81E+32	1.98E+02	4.76	1.07	1.20E+09	1.54
	AC+SBS	1.23E+32	6.42E+01	4.69	1.06	1.13E+09	1.45
	AC+rubber	3.50E+35	1.82E+05	5.40	1.21	1.19E+09	1.53
30 days	neat binder	6.02E+29	1.00	4.31	1.00	8.24E+08	1.00
	AC+PPA	2.95E+33	4.89E+03	4.91	1.14	1.38E+09	1.67
	AC+SBS	2.82E+32	4.68E+02	4.74	1.10	1.23E+09	1.49
	AC+rubber	1.33E+42	2.21E+12	6.29	1.46	3.65E+09	4.43
60 days	neat binder	3.45E+29	1.00	4.27	1.00	8.05E+08	1.00
	AC+PPA	8.86E+32	2.57E+03	4.82	1.13	1.35E+09	1.67
	AC+SBS	3.32E+33	9.64E+03	4.97	1.16	1.20E+09	1.49
	AC+rubber	6.20E+29	1.80E+00	4.47	1.05	5.90E+08	0.73

Table 6.4 – Final fatigue models

Aging level	Asphalt binder	Fatigue models
Short-term	neat	$1.92E+30.\gamma^{-4.44}$
	AC+PPA	$3.81E+32.\gamma^{-4.76}$
	AC+SBS	$1.23E+32.\gamma^{-4.69}$
	AC+rubber	$3.50E+35.\gamma^{-5.40}$
30 days	neat	$6.02E+29.\gamma^{-4.31}$
	AC+PPA	$2.95E+33.\gamma^{-4.91}$
	AC+SBS	$2.82E+32.\gamma^{-4.74}$
	AC+rubber	$1.33E+42.\gamma^{-6.29}$
60 days	neat	$3.45E+29.\gamma^{-4.27}$
	AC+PPA	$8.86E+32.\gamma^{-4.82}$
	AC+SBS	$3.32E+33.\gamma^{-4.97}$
	AC+rubber	$6.20E+29.\gamma^{-4.47}$

The results show that the parameter A increases when modified binders are used, but the effect of longer aging times is not clear. Regarding the parameter B, the use of modified binders

yields FAMs with slightly higher rates of damage accumulation, once that slightly higher B values are observed. The FAMs prepared with the AC+rubber and aged in short-term and 30 days present relatively high increases in B , but after 60 days the B value for this material is similar to the one obtained for the FAM produced with the neat binder. With respect to the damage accumulation parameter (S), it follows the same trend presented for the A parameter, i.e., the use of modifier binders increases the capacity of the FAM to accumulate damage under loading. The S values for the materials did not change significantly with the aging level, with the exception of the FAM prepared with the AC+rubber. Such material presented a significantly reduction in the capacity of accumulating damage with the extended aging, showing its high sensitivity to aging.

Figure 6.28 presents the fatigue life of the FAMs prepared with the neat binder, the AC+PPA, the AC+SBS and the AC+rubber, aged in short-term. The fatigue lives are presented in two ways, (i) the fatigue life for the linear viscoelastic properties ($|G^*|_{lve}$ and α) of each sample and (ii) the fatigue life for the average of $|G^*|_{lve}$ and α of the samples tested and prepared with each material.

Figure 6.29 and Figure 6.30 follow the same pattern for the long-term aging at 30 and 60 days, respectively. Figure 6.28 shows that the average fatigue curves overlapped for most materials. For the FAMs prepared with the AC+rubber, it can be notice that the average fatigue curves of the samples are similar. This means that to compare the fatigue behavior of the FAMs with basis on the C vs. S curves using the average linear viscoelastic properties is a good solution.

Figure 6.28 – Fatigue curves and average fatigue curves of the FAMs produced with the (a) neat binder, (b) AC+PPA, (c) AC+SBS, and (d) AC+rubber, aged in short-term

Figure 6.29 – Fatigue curves and average fatigue curves of the FAMs produced with the (a) neat binder, (b) AC+PPA, (c) AC+SBS, and (d) AC+rubber, aged in long-term for 30 days

Figure 6.30 – Fatigue curves and average fatigue curves of the FAMs produced with the (a) neat binder, (b) AC+PPA, (c) AC+SBS, and (d) AC+rubber, aged in long-term for 60 days

For the long-term aging at 30 and 60 days, the average fatigue lives for all of the FAMs overlapped. This superposition of the average fatigue lives shows that the calculation of the C vs. S curves based on the average of the linear viscoelastic properties results in similar fatigue lives for a specific material. Because of that, it is possible to compare the fatigue performance of the FAMs using the average fatigue lives. Figure 6.31 to Figure 6.33 show a comparison of the average fatigue curves of the FAMs produced with the four asphalt binders after short-term aging, 30 days and 60 days, respectively.

Figure 6.31 shows that the use of modified binders enhance the fatigue life of the FAMs. For the short-term aging, the FAMs prepared with the AC+PPA, the AC+SBS, and the AC+rubber present fatigue lives greater than the FAM produced with the neat binder. Regarding

the FAMs prepared with the modified binders, the FAM produced with the AC+rubber presents the highest fatigue life, once that the A value for the FAM produced with the AC+rubber is the highest one for the short-term aging condition. It is important to point out that the fatigue life of the FAMs prepared with the modified binders are similar to the one obtained for the FAM prepared with the neat binder at high strain levels. This behavior for high strain levels, e.g., 10 % of strain, is associated to the increase of the damage evolution rate (α) of the FAM produced with the modified binders. It is important to point out that such aging level may not be representative of the conditions under which fatigue cracking occurs in real pavements - where severe aging makes the mixtures more prone to cracking.

Figure 6.31 – Average fatigue curves of the FAMs produced with the four asphalt binders and aged in short-term

Figure 6.32 shows the fatigue curves for materials aged after 30 days, what can be considered a sort of long-term aging. All the FAMs produced with modified binders present fatigue life greater than the FAM produced with the neat binder, which is the same trend observed for the FAM samples aged in short-term. Concerning the FAMs produced with modified binders, the FAM produced with the AC+rubber results in higher fatigue life, followed by the FAM produced with the AC+PPA and by the FAM produced with the AC+SBS. The fatigue lives for the FAMs prepared with the AC+PPA and AC+SBS are equivalent, once that the values of the A and B parameters are similar for the two materials, as shown in Table 6.3. With respect to the fatigue life of the FAMs prepared with the modified binders at high strain levels, these FAMs showed lower fatigue life compared to the FAM prepared with the neat binder. This same behavior for high strains was also observed for the FAM prepared with the modified binders aged in short-term.

Figure 6.32 – Average fatigue curves of the FAMs produced with the four asphalt binders and aged in 30 days

Figure 6.33 depicts the fatigue behavior of FAMs aged in a condition of greater severity, compared to 30 days aging. The FAMs produced with the AC+SBS and the AC+PPA present very similar fatigue curves and both are slightly above the one obtained for the FAM produced with the neat binder. The FAM produced with the AC+rubber presented a behavior completely different from the ones observed at other aging levels, once that its fatigue curve is below the one obtained for the FAM produced with the neat binder. This behavior is due to the low capacity of the material to accumulate damage for a 50 % reduction of the pseudo stiffness compared to the other materials, as shown in Table 6.3. This may suggest that this material is very sensitive to long-term aging, although its behavior when aged in short-term and long-term at 30 days resulted superior to the other FAMs.

Figure 6.33 – Average fatigue curves of the FAMs produced with the four asphalt binders and aged in 60 days

Figure 6.34 presents a comparison of the average fatigue curves of the FAMs produced with the neat binder, AC+PPA, AC+SBS and AC+rubber as a function of the aging level. The fatigue curves of the FAMs diminish when the materials are subjected to higher aging levels. The FAM produced with the neat binder seems to be an exception, once that the fatigue lives resulted similar, showing a small effect of extended aging. The great sensitivity of the FAM produced with the AC+rubber to extended aging, as mentioned before, is also clear in Figure 6.34, where the fatigue curve for 60 days aging is below the others and very far from them.

Figure 6.34 – Average fatigue curves for the FAMs produced with the (a) neat binder, (b) AC+PPA, (c) AC+SBS and (d) AC+rubber as a function of the aging level

6.5 RANK ORDER BASED ON THE N_F VALUES

The objective of this section is to order the FAMs produced with different asphalt binders in relation to the number of axle-load repetitions that takes the material to failure, taking the

effect of aging into account. Two strain levels were adopted in this analysis, i. e., 0.1 and 10 %, once that the materials tend to present different responses to low and high strains. This rank order consists in the ascription of a numerical value, between 1 and 4, referring to the classification of the material in a rank of the results of all materials. The numeration was ascribed from the best to the worse materials, in such a way that the best results received the lowest values and the worse ones received the highest. The best results represent the materials whose number of axle load repetitions is higher.

The materials were first ranked separately, according to the aging level (short, 30 days, and 60 days) and strain level (0.1 and 10 %). Posteriorly, they were ranked according to the aging level (short-term, 30 days, and 60 days) but considering the average position for the two strain levels. They were finally ranked according to the global effect of aging, considering the average position for the three aging levels.

Figure 6.35 to Figure 6.37 show the rank order of the FAMs for the two strain levels, 0.1 % and 10 %, and aged in short-term, 30 days, and 60 days, respectively. Figure 6.38 to Figure 6.40 presents the rank order for the FAMs aged in short-term, 30 days, and 60 days, respectively, where the results represent the average rank order for the two strain levels. Figure 6.41 presents the final rank order, and in this case, the results represent the average rank order for the two strain levels and the three aging levels.

Figure 6.35 – Rank order of the FAMs for the two strain levels (0.1 % and 10 %) and short-term aging

Figure 6.36 – Rank order of the FAMs for the two strain levels (0.1 % and 10 %) and 30-days aging

Figure 6.37 – Rank order of the FAMs for the two strain levels (0.1 % and 10 %) and 60-days aging

Figure 6.38 – Rank order of the FAMs for short-term aging

Figure 6.39 – Rank order of the FAMs for 30-days aging

Figure 6.40 – Rank order of the FAMs for 60-days aging

Figure 6.41 – Final rank order for the FAMs

The rank orders specific for each strain level (0.1 % and 10 %) as function of aging level show that the FAM produced with the AC+rubber presents a good fatigue behavior when aged in short-term and 30 days and the worst behavior when the material is subjected to long-term aging (60 days). The behavior of the FAM produced with the neat binder deserves attention, once that its fatigue life for the long-term aging are higher than the ones obtained for the FAMs produced with the modified binders at high strains. When the rank order for the two strain levels are combined, the FAMs produced with the AC+rubber and the AC+SBS presented the highest fatigue lives for the short- and the long-term aging at 60 days, respectively. It is important to point out that all the materials presented the same rank order of 2.5 for the long-term aging of 30 days. When the rank order for the two strain levels and the three aging levels are combined, the FAM produced with the AC+SBS obtained the best fatigue behavior and the FAM produced with the neat binder obtained the worst fatigue behavior. Such final results are consistent, once that it is expected that modified binders are able to improve the fatigue behavior of the asphalt concrete mixtures, as compared to neat binder.

7 CORRELATIONS BETWEEN SCALES

The objective of this chapter is to evaluate the correlations among (i) the linear viscoelastic properties, such as $|G^|_{lve}$ and α with the fatigue characteristics (N_f) of the FAMs at 0.1 and 10 % of strain; and (ii) the fatigue characteristics of the FAMs with the fatigue characteristics of the asphalt binders and the asphalt mastics.*

The correlations among these properties were evaluated by means of the Pearson correlation coefficient, a statistic coefficient used to show the linear association between two variables, in which the value $r = 1$ means a perfect positive correlation and the value $r = -1$ means a perfect negative correlation. Table 7.1 presents the correlations between the results for $|G^*|_{lve}$ and α , and the correlation of the $|G^*|_{lve}$ and α with N_f at 0.1 % and N_f at 10 % of strain.

Table 7.1 – Correlations between the linear viscoelastic properties with the fatigue characteristics for the FAMs

Properties	r
$ G^* _{lve}$ vs. α	-0.02
$ G^* _{lve}$ vs. N_f at 0.1 % strain	0.05
$ G^* _{lve}$ vs. N_f at 10 % strain	-0.65
α vs. N_f at 0.1 % strain	+0.85
α vs. N_f at 10 % strain	+0.11

Table 7.1 shows good correlations (only between the $|G^*|_{lve}$ and N_f at 10 % and between the α values and the N_f at 10 %. The other correlations resulted very poor. A correlation of -0.65 was obtained between $|G^*|_{lve}$ and N_f at 10 %, what means that higher fatigue lives are associated to lower stiffness – but this is valid only for high strains. A correlation of +0.85 was obtained between the α values and the N_f at 10 %, which means that higher fatigue lives are associated to higher damage evolution rates – but this is valid only for low strains. Table 7.2 to Table 7.5 show the correlations between the A and B values of the FAMs with the A and B values of the asphalt binder and asphalt mastics, as a function of the respective aging levels.

Table 7.2 – Correlations between the A and B values of FAMs and binders

		aging condition	binder		
			RTFOT	PAV	PAV
FAM	A	short-term	0.74		
		30 days		0.75	
		60 days			-0.38
	B	short-term	0.52		
		30 days		0.09	
		60 days			0.70

Table 7.3 – Correlations between the A and B values of FAMs and mastics (f/a = 0.15)

		aging condition	mastic f/a = 0.15		
			RTFOT	PAV	PAV
FAM	A	short-term	0.87		
		30 days		0.95	
		60 days			-0.43
	B	short-term	0.79		
		30 days		0.44	
		60 days			0.71

Table 7.4 – Correlations between the A and B values of FAMs and mastics (f/a = 0.30)

		aging condition	mastic f/a = 0.30		
			RTFOT	PAV	PAV
FAM	A	short-term	0.81		
		30 days		0.95	
		60 days			-0.34
	B	short-term	0.87		
		30 days		0.64	
		60 days			0.71

Table 7.5 – Correlations between the A and B values of FAMs and mastics (f/a = 0.45)

		aging condition	mastic f/a = 0.45		
			RTFOT	PAV	PAV
FAM	A	short-term	-0.07		
		30 days		0.87	
		60 days			-0.06
	B	short-term	0.86		
		30 days		0.60	
		60 days			0.63

The A and B values obtained for the asphalt binders and the asphalt mastics aged in short-term in the RTFO correlated well with the A and B values obtained for the FAMs aged in short-term (r values ranged from 0.52 to 0.87, except for one correlation equals to 0.07) and the A and B values obtained for the asphalt binders and asphalt mastics aged in long-term in the PAV correlated better with the A and B values obtained for the FAMs aged in 30 days (r values ranged from 0.44 to 0.95), except for one correlation equal to 0.09, than with the A and B values for the FAMs aged in 60 days (r values ranged from 0.34 to 0.71), except for one correlation equal to 0.06. Table 7.6 to Table 7.9 show the correlations between the N_f values of the FAMs at 0.1 % and 10 % strain with the a_f values of the asphalt binder and asphalt mastics, as a function of the respective aging levels.

Table 7.6 – Correlations between the N_f values of the FAMs and the a_f values of the asphalt binders

N_f	aging condition	a_f - binder		
		RTFOT	PAV	PAV
FAM	0.1 %	short-term	0.55	
		30 days	0.98	
		60 days		0.43
	10 %	short-term	0.60	
		30 days	0.96	
		60 days		0.81

Table 7.7 – Correlations between the N_f values of the FAMs and the a_f values of the asphalt mastics for $f/a=0.15$

N_f	aging condition	a_f - mastic $f/a=0.15$		
		RTFOT	PAV	PAV
FAM	0.1 %	short-term	0.65	
		30 days	0.97	
		60 days		-0.46
	10 %	short-term	0.70	
		30 days	0.71	
		60 days		-0.98

Table 7.8 – Correlations between the N_f values of the FAMs and the a_f values of the asphalt mastics for $f/a=0.30$

	N_f	aging condition	a_f - mastic $f/a=0.30$		
			RTFOT	PAV	PAV
FAM	0.1 %	short-term	0.56		
		30 days		0.91	
		60 days			-0.27
	10 %	short-term	0.61		
		30 days		0.84	
		60 days			-1.00

Table 7.9 – Correlations between the N_f values of the FAMs and the a_f values of the asphalt mastics for $f/a=0.45$

	N_f	aging condition	a_f - mastic $f/a=0.45$		
			RTFOT	PAV	PAV
FAM	0.1 %	short-term	0.01		
		30 days		0.70	
		60 days			0.21
	10 %	short-term	0.09		
		30 days		-0.78	
		60 days			-0.36

The a_f values obtained for the asphalt binders and the asphalt mastics aged in short-term in the RTFOT correlated well with the N_f values at 0.1 and 10 % strain obtained for the FAMs aged in short-term (r values ranged from 0.55 to 0.70, except for correlations equal to 0.01 and 0.09 for the asphalt mastic $f/a=0.45$) and the a_f values obtained for the asphalt binders and asphalt mastics aged in long-term in the PAV correlated better with the N_f values at 0.1 and 10 % strain obtained for the FAMs aged in 30 days (r values ranged from 0.70 to 0.98) than with the N_f values at 0.1 and 10 % strain for the FAMs aged in 60 days (r values ranged from 0.27 to 0.81), except for one correlation equal to 1.00 and another one equal to 0.98).

Table 7.10 shows the final position for the three scales: asphalt binder, asphalt mastic and FAM. No coincidence was observed among the three scales. Coincidences were observed only between the asphalt binder and asphalt mastic for the asphalt modified with crumb-rubber and SBS, which occupied the first and the last position in the rank order, respectively. The AC+PPA presented an intermediate position. The neat binder loses position when the scale approaches the full mixture scale.

Table 7.10 – Final rank order for the three scales

	Neat binder	AC+PPA	AC+SBS	AC+rubber
Asphalt binder	2	3	4	1
Asphalt mastic	3	2	4	1
FAM	4	2	1	3

8 CONCLUSIONS

The objective of this dissertation is to check the hypotheses that: (i) the use of modified asphalt binder can enhance the fatigue properties of the FAMs, and (ii) that severe aging acts to compromise the fatigue behavior of the FAMs. The study is grounded on the hypothesis defended by some researchers that the fatigue cracking starts in discontinuities present in the full asphalt concrete mixtures, such as air voids and microcracks, and develops over time under the application of reversible loading. Such microcracks, according to those researchers, develop in two circumstances: (i) after adhesive failure, when the crack occurs in the interface aggregate-mortar, and/or (ii) after cohesive failure, when the crack develops within the mortar or FAM. Based on such interpretation of the cracking phenomenon in asphalt concrete mixtures, it is plausible to use the FAMs to estimate the fatigue behavior of the asphalt concrete. This hypothesis is basis for the development of this study, where the effects of the asphalt type and aging level on the fatigue behavior of asphalt concrete mixtures is investigated by means of the study of FAMs.

Three modified asphalt binders were chosen to comprise this experimental plan, i. e., an asphalt modified with polyphosphoric acid, an asphalt modified with the SBS copolymer and an asphalt binder modified with crumb rubber. The SBS and crumb rubber modified asphalts were chosen because they are the two most used modified asphalt binders, and the asphalt modified with PPA was chosen because it represents an effective alternative for paving. The neat asphalt was used as the reference binder and corresponds to the base material used to produce the modified ones. Three aging levels were adopted, i. e., short-term, 30 days and 60 days, in order to check the effects of different aging levels on the fatigue behavior of the materials. As a complement for the experiment, asphalt mastics were compounded with the four asphalt binders and using three filler/asphalt ratios, i. e., 0.15, 0.30 and 0.45. Such mastics were submitted to short- and long-term aging as per the conventional procedures of the Superpave specification, i. e., short-term aging in the rolling thin film oven (RTFOT) and long-term aging in the pressure aging vessel (PAV). The four binders were also aged in short- and long-term. The objective was to compare the fatigue behavior of the materials in the three scales.

This chapter is divided in five sections. The first three are dedicated to the presentation of the main conclusions regarding the effects of the modified binders and the aging level on the fatigue life of the asphalt mastics, the asphalt binders, and the fine aggregate matrices respectively. The fourth section shows the rank order of the materials and the correlations

between the different scales. The fifth section is intended to present the final remarks on the subjects studied here.

8.1 FATIGUE BEHAVIOR OF THE ASPHALT MASTICS

The following conclusions deserve to be mentioned:

- the increase of the f/a ratio decreased the A values and affected the B values only slightly – this means that the increase of the amount of filler reduces the integrity of the materials with negative implications on the fatigue life of the materials, and similar B values for all filler/asphalt ratios imply that the materials will not change their rate of damage accumulation significantly because of the incorporation of higher amounts of mineral filler; such patterns showed to be independent of the aging level, what means that the increase in the level of severity of the aging did not affect the pattern of effect of the f/a ratio on A and B values;
- the increase of the f/a ratio increases the fatigue damage tolerance index (a_f), indicating that the mastics present a higher tolerance to fatigue damage in the extent that the f/a ratio increases; such increase was observed for both aging levels;
- the increase of aging from short-term to long-term is capable of increasing the A values proportionally – what means that the materials suffer an increase in their integrity due to aging – and such increase in integrity reduces when the f/a ratio increases;
- aging increases the B values, with implications on the damage accumulation ratio of the materials, and the increase in the f/a ratio increases such parameter only slightly – this is valid for the mastics prepared with the neat binder, the AC+PPA and the AC+SBS and only partially to the mastic prepared with the AC+rubber, once that the A values increases with the f/a instead of decreasing;
- the increase of the aging level do not affect the a_f values of the mastics prepared with the neat binder, the AC+PPA and the AC+SBS; a slight increase of the a_f values is observed for the mastics prepared with the AC+rubber, what implies that the mastics prepared with the AC+rubber have a higher tolerance to fatigue damage after long-term aging – such conclusion diverges from the results observed for the FAM produced with the AC+rubber at 60 days, where the fatigue lives are much lower than the ones observed at 30 days;

- the use of modified binder increases the A and B values of the mastics, regardless of the f/a ratio; the mastics prepared with the AC+rubber presented the highest increase of A values and the mastics prepared with the AC+PPA presented the highest increase of B values, as compared to the neat binder;
- the use of modified binders increased the a_f values, what means that they are able to increase the fatigue life of the materials; the highest increase was observed for the mastics produced with the AC+rubber;
- as mentioned before in relation to the rank order of the FAMs, the rank order of the mastics also showed to be strongly dependent on the strain level and because of that two strain levels were also adopted in this analysis (2 and 20 %) – under such conditions, the mastics prepared with the AC+PPA presented the highest fatigue life at short-term aging, and the mastics prepared with the AC+rubber presented the highest fatigue life at long-term aging; the final rank order indicated that the mastics produced with the AC+rubber presented the highest fatigue life.

8.2 FATIGUE BEHAVIOR OF THE ASPHALT BINDERS

The following conclusion was drawn:

- as mentioned before in relation to the rank order of the FAMs and the asphalt mastics, the rank order of the asphalt binders also showed to be strongly dependent on the strain level and because of that two strain levels were also adopted in this analysis (2 and 20 %) – under such conditions, the neat binder presented the highest fatigue life at both short- and long-term aging, and for the final rank the AC+rubber presented the highest fatigue life.

8.3 FATIGUE BEHAVIOR OF THE FINE AGGREGATE MATRICES

The main conclusions are the following:

- similar $|G^*|$ values were obtained for the majority of the materials, as in the case of the FAMs prepared with the neat binder, the AC+PPA and the AC+SBS – this indicates that there is no clear effect of the stiffness of the asphalt binder on the stiffness of the FAMs;

- aging increased the stiffness of the FAMs prepared with the neat binder – with a slight effect – and the stiffness of the FAMs prepared with the AC+rubber – with a significant effect;
- the FAMs prepared with the AC+PPA presented an unexpected variation of stiffness, once that the $|G^*|$ values for 30 days are higher than those obtained for the FAMs aged in 60 days; no variation of stiffness was observed for the FAMs prepared with the AC+SBS after the application of the three aging levels, what represents a very unusual result;
- the FAMs prepared with the modified binders presented lower values for the phase angle (δ) compared to the FAM prepared with the neat binder – this reduction is expected, once that the modifiers increase the elastic response of the asphalt binders;
- for most of the materials, the relaxation rate (m) reduces with the aging level, but such trend is not applicable to all the materials, once that for the FAM prepared with the AC+rubber the m values increase with the extended aging, and for the FAMs produced with neat binder the aging did not affect the relaxation property of the material;
- the m values for the FAMs prepared with the modified binders are lower than those obtained for the FAMs prepared with the neat binder, what means that FAMs prepared with modified binders present a lower relaxation rate and, as consequence, these materials will present higher rates of damage accumulation;
- characteristic curves (C vs. S) were obtained for all the materials and used to estimate the coefficients of the fatigue models – such models were used to predict the fatigue life of the materials, assuming a pseudo stiffness reduction of 50 %, and the predicted number of axle load repetitions (N_f) were used to rank the materials;
- for most of the cases, it was possible to observe the superposition of the C vs. S curves with the average of the linear viscoelastic properties of the material ($|G^*|_{lve}$ and α) – the average fatigue curves of the materials with similar C vs. S curves overlapped, what means that to compare the damage behavior of the FAMs with basis on the C vs. S curves using the average linear viscoelastic properties is a good solution;
- the parameters A and B of the fatigue model ($N_f = A \cdot \gamma^{-B}$) are affected by the type of asphalt binder and the aging level in different ways: the A values increase when modified binder are used but the effect of longer aging is not clear, and in relation to

the B values, the use of modified binder yields FAM with slightly higher rates of damage accumulation;

- the fatigue curves showed how the aging levels affected the performance of the four asphalt binders: (i) for the short- and long-term aging (30 days), all the FAMs produced with the modified binders presented fatigue lives greater than the FAM produced with the neat binder – out of the FAMs produced with modified binders, the FAM produced with the AC+rubber resulted in higher fatigue life for both aging conditions, followed by the FAM produced with the AC+PPA and the FAM produced with the AC+SBS, (ii) for the 60 days aging, the FAMs produced with the AC+SBS and the AC+PPA presented similar fatigue lives – their fatigue lives are greater than the ones obtained for the FAM produced with the neat binder – and the FAM produced with the AC+rubber presented fatigue lives lower than the other materials, what is a reversed performance as compared to the performance of this material at less severe aging conditions; it was also observed that the use of modifiers, such as PPA and SBS resulted in similar fatigue lives for all aging conditions;
- the fatigue life of the materials diminish for increasing aging levels, except for the FAM produced with the neat binder and with the AC+PPA, once that the fatigue lives resulted similar; the FAM produced with the AC+rubber has a great sensitivity to aging at 60 days, presenting fatigue lives that are much lower than the ones obtained for the other materials – this is related to the high sensitivity of this material to long-term aging, what is expressed in terms of a high initial stiffness and a correspondent low integrity (low A value), as compared to the other materials;
- the rank order of the FAMs are strongly dependent on the strain level and because of that two strain levels were adopted in this analysis (1 and 10 %) – under such conditions, the rank order showed that the FAM produced with the AC+rubber presented a good fatigue behavior when aged in short-term and 30 days and the worst performance when subjected to long-term aging (60 days); the fatigue behavior of the FAM produced with neat binder drew attention because its fatigue lives for high strains are higher than the ones obtained for the FAMs produced with the modified binders in most of the aging conditions, due to the increase of the damage evolution rate with the use of modified binders;
- the FAM produced with the AC+SBS presented the best position in the final rank order, and the FAM produced with the neat binder occupied the last position – such

results are consistent, once that it is expected that modified binders are able to improve the fatigue behavior, as compared to neat binders.

8.4 RANK ORDER AND CORRELATIONS

The following conclusion were drawn:

- regarding the FAMs properties, good correlations were obtained for the the $|G^*|_{lve}$ and N_f at 10 % and between the α values and the N_f at 10 % - correlation of -0.65 was obtained between $|G^*|_{lve}$ and N_f at 10 %, what means that higher fatigue lives are associated to lower stiffness – but this is valid only for high strains – and a correlation of +0.85 was obtained between the α values and the N_f at 10 %, which means that higher fatigue lives are associated to higher damage evolution rates – but this is valid only for low strains;
- good correlations were observed between the fatigue characteristics of the FAMs and the fatigue characteristics of the asphalt mastics and the asphalt binders;
- the A and B values obtained for the asphalt binders and the asphalt mastics aged in short-term in the RTFO correlated well with the A and B values obtained for the FAMs aged in short-term (r values ranged from 0.52 to 0.87, except for one correlation equal to 0.07) and the A and B values obtained for the asphalt binders and asphalt mastics aged in long-term in the PAV correlated better with the A and B values obtained for the FAMs aged in 30 days (r values ranged from 0.44 to 0.95) than with the A and B values for the FAMs aged in 60 days (r values ranged from 0.34 to 0.71), except for one correlation equal to 0.06);
- the a_f values obtained for the asphalt binders and the asphalt mastics aged in short-term in the RTFO correlated well with the N_f values at 0.1 and 10 % strain obtained for the FAMs aged in short-term (r values ranged from 0.55 to 0.70, except for correlations equal to 0.01 and 0.09 for the asphalt mastic $f/a=0.45$) and the a_f values obtained for the asphalt binders and asphalt mastics aged in long-term in the PAV correlated better with the N_f values at 0.1 and 10 % strain obtained for the FAMs aged in 30 days (r values ranged from 0.70 to 0.98) than with the N_f values at 0.1 and 10 % strain for the FAMs aged in 60 days (r values ranged from 0.27 to 0.81), except for one correlation equal to 1.00 and another one equal to 0.98;

- no coincidence was observed among the three scales, except for between the binder and the mastic for the binders modified with crumb-rubber and SBS, which occupied the first and the last position in the final rank order, respectively; the AC+PPA presented an intermediate position, and the neat binder loses position when the scale approaches the full mixture scale.

8.5 FINAL REMARKS

The most expressive improvement of the fatigue behavior of the FAMs due to the use of modified binders was observed for the materials aged in short-term and in long-term at 30 days, once that all of the FAMs prepared with the modified binders presented higher fatigue life compared to the FAM prepared with the neat binder. The FAM produced with the AC+rubber stood out among the other FAMs, with the highest fatigue life for the materials aged in short-term and in long-term at 30 days, and the lowest fatigue life for the long-term at 60 days. The FAM prepared with the AC+rubber presented the highest sensitivity to the aging level, with a significant increase in the initial stiffness as a function of the extended aging, resulting in a lower integrity compared to the other materials.

The fatigue behavior of the FAMs prepared with the neat binder draws one's attention because it occupies the first position in the rank order for the highest strain level (10 %), when the materials are aged in long-term at 30 and 60 days. This behavior can be explained by the similarity of the initial stiffness for the FAMs prepared with the neat binder and the AC+PPA and the AC+SBS, and by the high values of the damage accumulation rate of the FAMs prepared with the AC+PPA and the AC+SBS.

In the scale of the asphalt binder and asphalt mastic, the use of modified binders increases the a_f values regardless of the aging level, showing that the mastics produced with the modified binders have a higher tolerance to fatigue damage compared to the mastics produced with the neat binder. The increase of the a_f values with the use of modified binders showed to be more significant for the mastics produced with the AC+rubber, resulting in the first positions in the final rank order for the asphalt mastics.

Regarding the type of asphalt binder, the modified binders and the mastics produced with the modified binders presented the highest tolerance to fatigue damage (a_f) compared to the neat binder and the mastic prepared with the neat binder. In the FAM scale, the improvement of the fatigue behavior, i.e., the increase of the number of axle loads, with the use of modified binders is noticeable only for the long-term aging at 30 days. For the three scales, the asphalt

binder modified with crumb-rubber presented the best position in the final rank, showing the best performance in terms of fatigue damage.

As far as the aging level is concerned, the a_f values for the mastics prepared with the neat binder, the AC+PPA, and the AC+SBS were not affected by the extended aging. A slight increase in the a_f values was observed for the mastics prepared with the AC+rubber, showing that such mastics have a higher tolerance to fatigue damage. In the FAM scale, the aging level decreased the number of axle loads to a specific strain level that takes the material to failure, i.e., the fatigue life of the FAMs decrease, except for the FAM produced with the neat binder and with the AC+PPA, which presented similar fatigue life regardless of the aging level

The best correlation between the three scales regarding the short- and long-term aging is the one obtained between the asphalt binder and the mastics aged in the PAV with the FAMs aged in long-term at 30 days. The correlation between the A and B values for the asphalt binder and the mastics aged in the PAV and the A and B values for FAMs aged in long-term at 30 days presented r values ranging from 0.44 to 0.95. The correlation between the a_f values for the asphalt binders and mastics aged in the PAV with the N_f values at 0.1 and 10 % for the FAMs aged in long-term at 30 days presented r values ranging from 0.70 to 0.98. Based on these comparisons of the fatigue characteristics of the three scales, it can be suggested that the long-term aging of the FAMs at 30 days is adequate to simulate effects similar to those observed for the materials aged in the PAV.

Concerning the procedure used to characterize the fatigue properties of the FAMs, the initial plan was to analyze the effect of healing on the fatigue behavior of the FAMs. However, this initial plan became impracticable because of the long time required to achieve a specific level of stiffness after the material recovers part of its stiffness with the introduction of rest periods. The next bet was to run the time sweep in controlled strain mode at 10 Hz. But due to some limitations of the DSR, it was impracticable to run the test in controlled strain mode, once that the equipment showed to be incapable of applying a specific strain level for the frequency of 10 Hz. Because of that, the test started to be carried out in stress control. Nevertheless, it was not possible to run the test at 10 Hz due to the torque limitations of the DSR. At 10 Hz, FAMs are stiffer than at lower frequencies, and the equipment was incapable of applying the required stress level. In order to overcome the problems with the FAM stiffness at 10 Hz, the tests with the FAMs were carried out in controlled stress mode at 1 Hz and 25 °C. Because of such limitations of the DSR, it was not possible to evaluate the effect of lower temperatures on the fatigue properties of the FAMs.

Plenty of time was spent to define the adequate design method for the FAMs prepared with the modified binder, with the procedures for the production and compaction of the FAM samples, with the implementation of an adequate procedure in the DSR, and with the tests carried out at lower stress level. The initial idea of evaluating other variables, such as type of mineral aggregate and gradation on the fatigue behavior of the FAMs became unpractical. The author suggests that the test with FAMs in the DSR should be carried out at higher strain levels, i.e., 300 to 400 kPa, at 1 Hz and 25 °C in order to accelerate the damage in the sample and reduce the duration of the tests.

8.6 SUGGESTIONS FOR FUTURE WORKS

The following suggestions for future works are presented:

- to evaluate the effect of different types of aggregates on the fatigue behavior of FAMs produced with modified asphalt binders;
- to evaluate the effect of different air voids and binder contents on the fatigue behavior of FAMs produced with modified asphalt binders;
- to evaluate the effects of other modified binders on the fatigue behavior of FAMs;
- to carry out tests with FAMs at lower temperatures, once that the temperature of 25 °C can be considered high to investigate the damage process caused only by fatigue;
- to run tests with the FAMs in an equipment with a higher torque capability in order to accelerate the test duration, and one that applies both modes of loading (uniaxial and shear), in order to verify if the loading mode can affect the damage characteristics and the fatigue life of the FAMs;
- to use another failure criterion to evaluate the fatigue behavior of the FAMs, as the G^R (rate of change of the average released pseudostrain energy);
- to evaluate the asphalt concrete properties in order to verify which of the three scales best correlates with the asphalt concrete properties.

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