

UNIVERSIDADE FEDERAL DE CAMPINA GRANDE

Relação de Fadiga de Misturas Asfálticas com o Dimensionamento e Pavimentos Flexíveis: “Perspectivas e Evolução dos Procedimentos de Determinação”

Prof. Titular John Kennedy Guedes Rodrigues

REVESTIMENTOS ASFÁLTICOS : DESEMPENHO MECÂNICO

MeDiNa 2.0
MÉTODO DE DIMENSIONAMENTO NACIONAL DE PAVIMENTOS

TRINCAMENTO POR FADIGA





Deformações permanentes



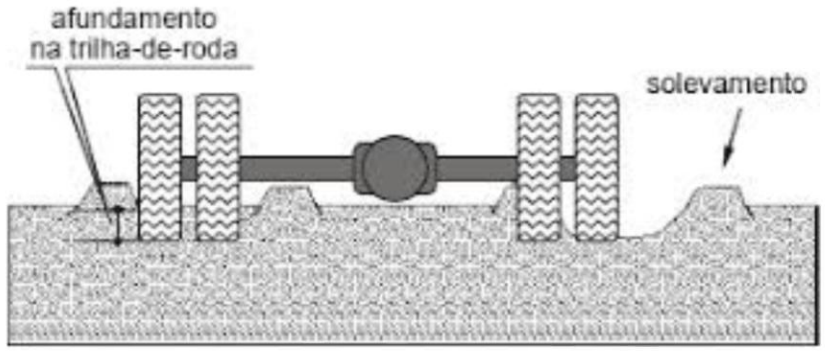
- Temperetura elevada;
- Tráfego e magnitude da carga;
- Tempo de carregamento.

Trincas por fadiga



- Variações bruscas de temperatura
- Tráfego e magnitude da carga;
- Envelhecimento oxidativo do ligante.

DEFORMAÇÃO PERMANENTE

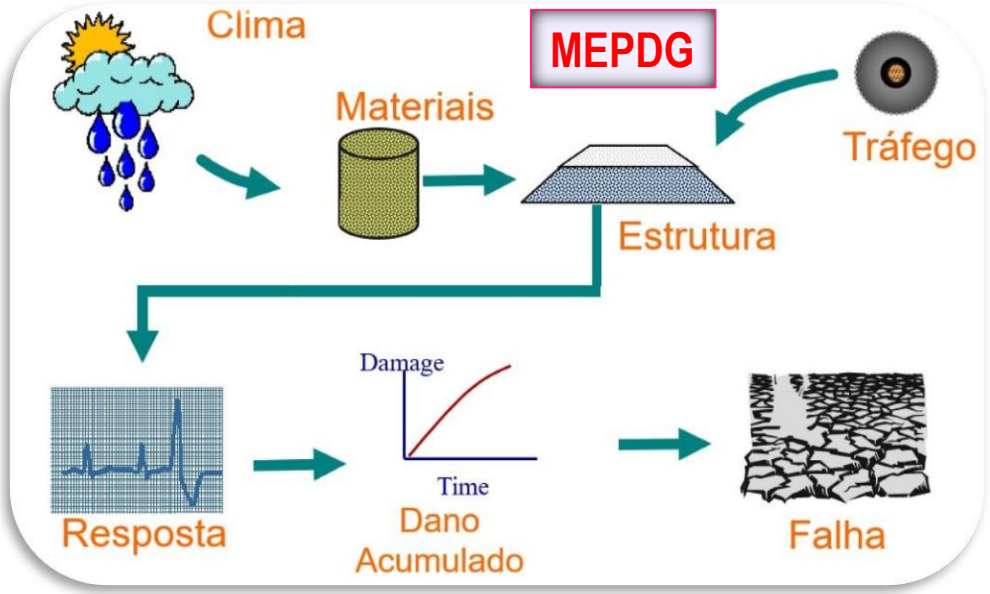




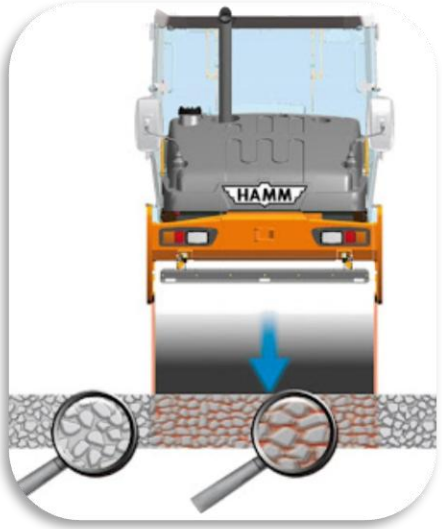


PAVIMENTOS FLEXÍVEIS: FADIGA & CONCEITOS E FILOSOFIA DE PROJETO
"O PAPEL DOS PROCESSOS PROJETO/EXECUÇÃO/CONTROLE"

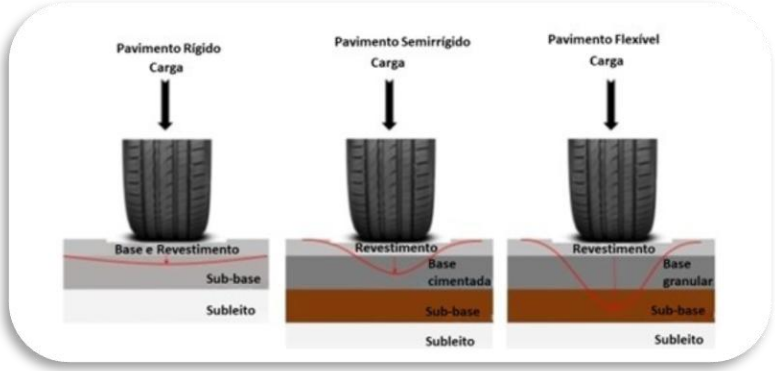
Componentes de Dimensionamento



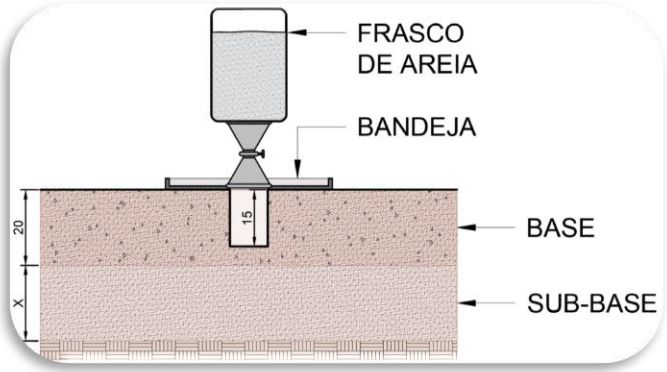
EXECUÇÃO



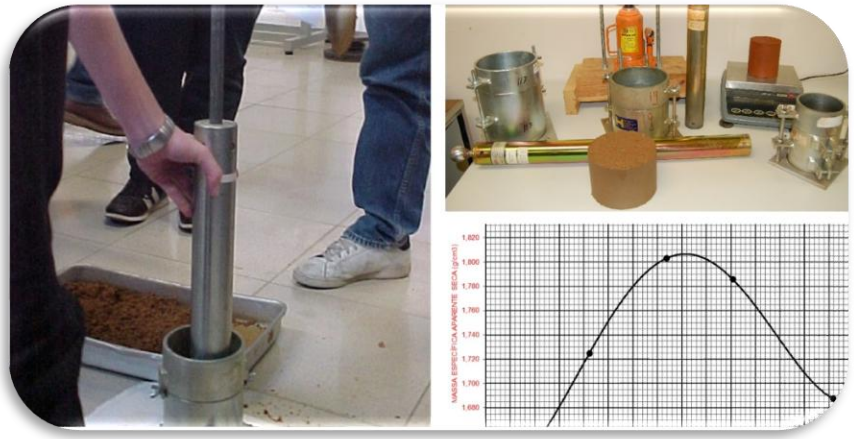
SOLICITAÇÕES



CONTROLE



EXPERIMENTOS (SOLOS)



PROPRIEDADES DOS MATERIAIS (SOLOS)

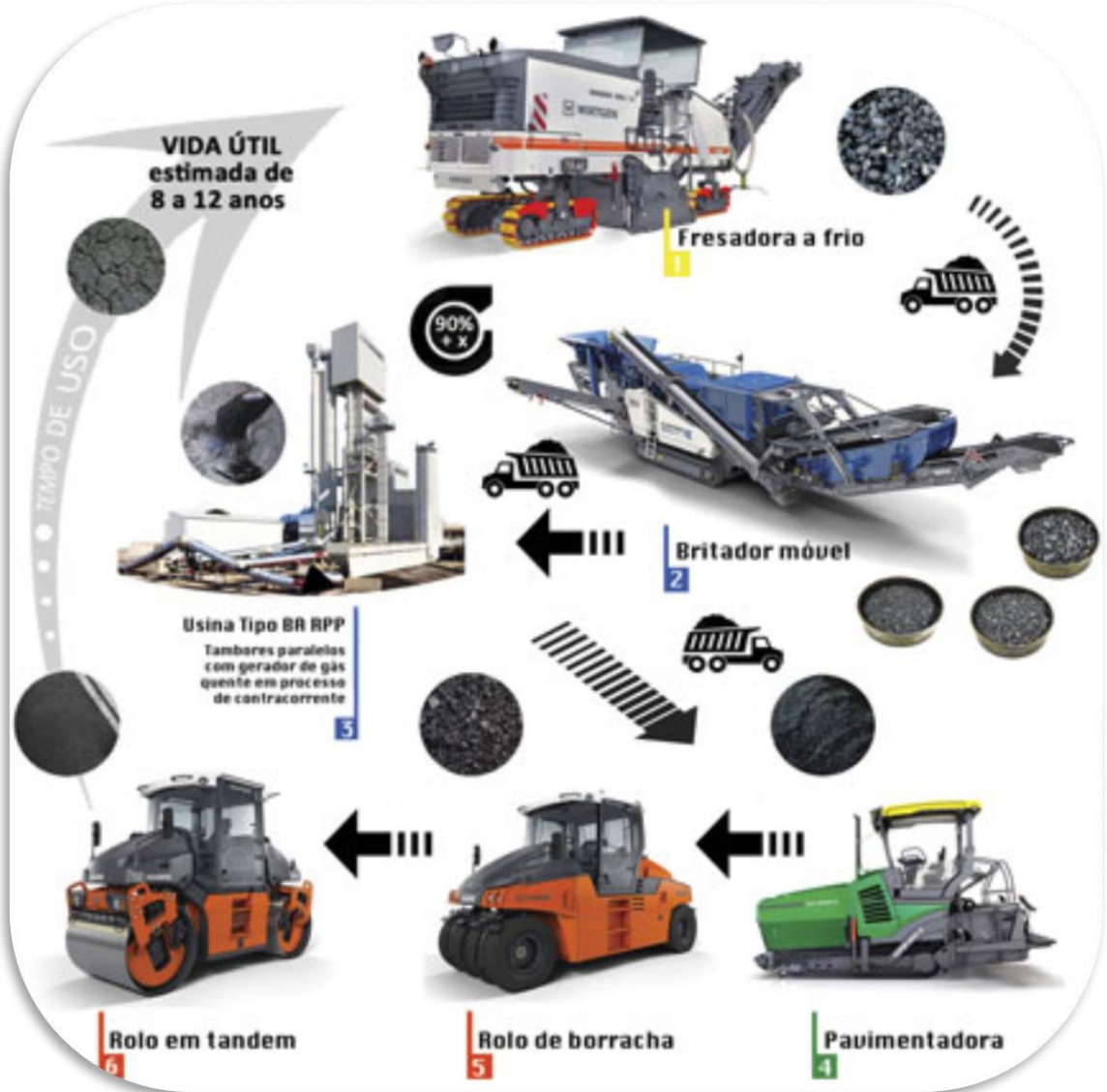


EXPERIMENTOS



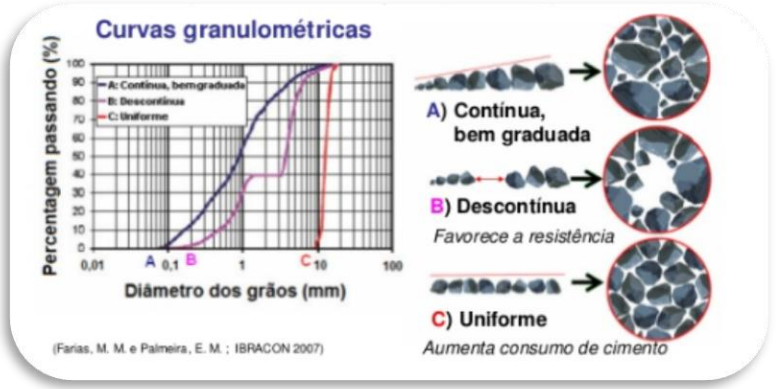
PAVIMENTOS FLEXÍVEIS: FADIGA & CONCEITOS E FILOSOFIA DE PROJETO

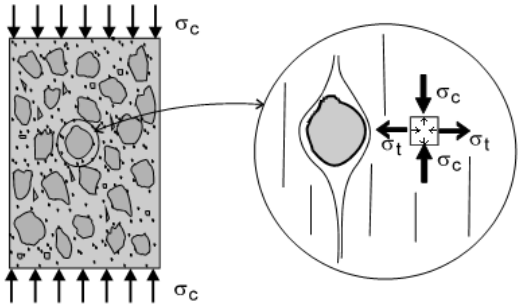
PROCESSOS CONSTRUTIVOS



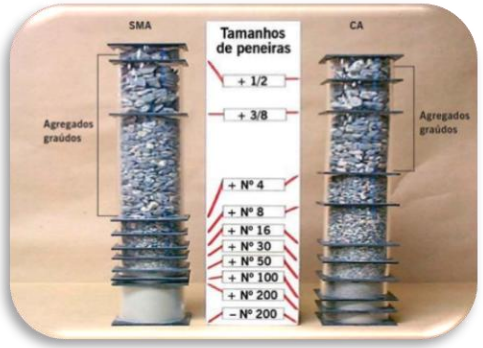


MÉTODOS DE ENSAIOS









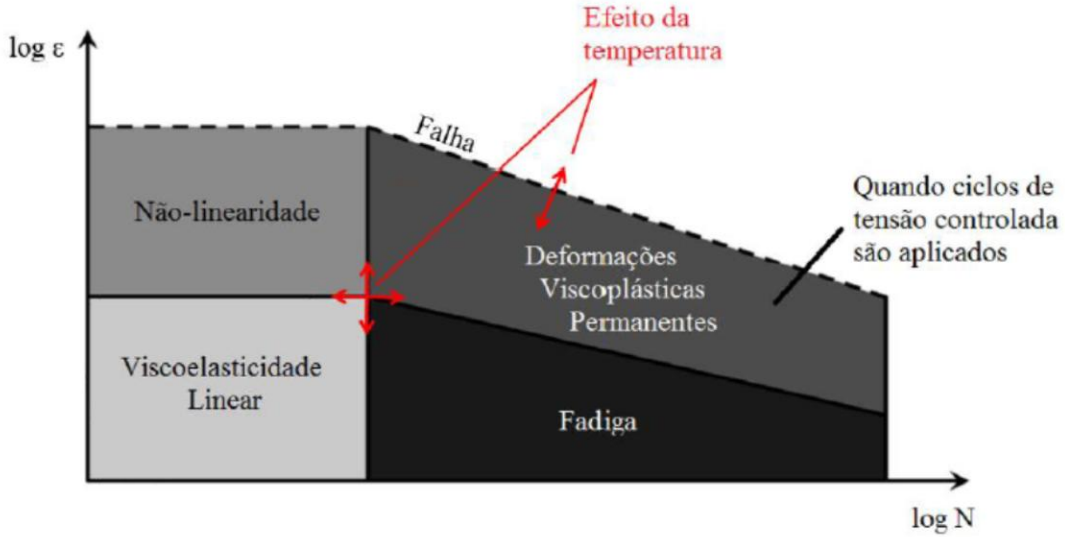
COMPORTAMENTO MECÂNICO DE MISTURAS ASFÁLTICAS





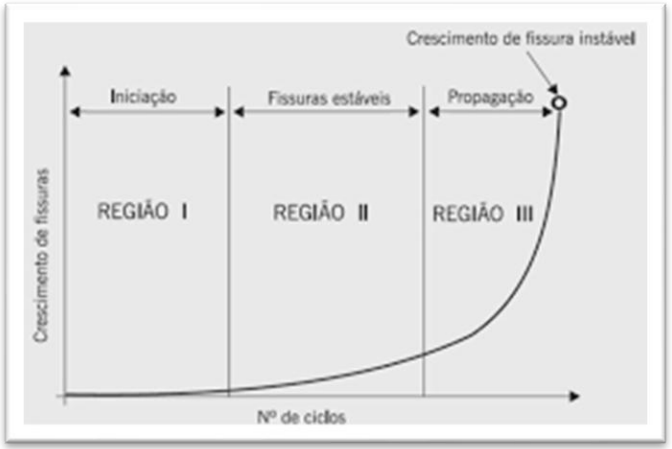


Figura 2 – Representação esquemática das regiões de comportamento mecânico conceitual em função do nível de deformação aplicado e do número de ciclos, para materiais viscoelásticos



Fonte: adaptado de Mangiafico (2014 p. 26)



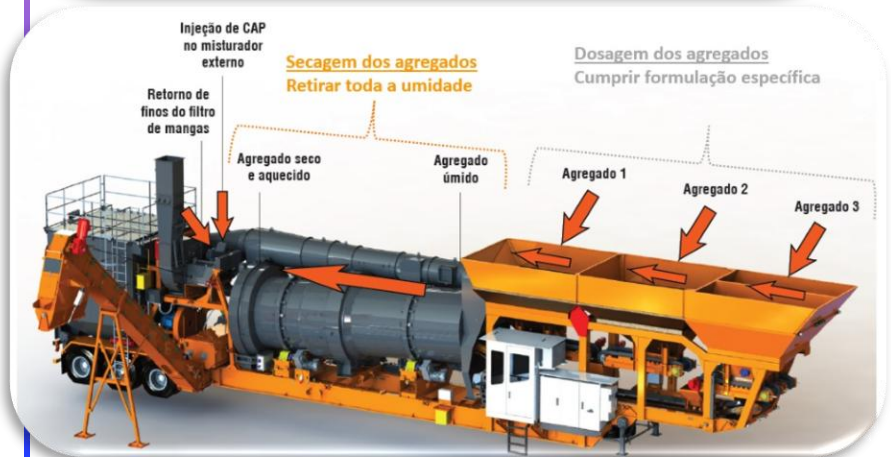


Fonte: Pivetta F. C. 2018

DOSAGEM MISTURAS ASFÁLTICAS: FADIGA & IMPORTÂNCIA DA VOLUMETRIA

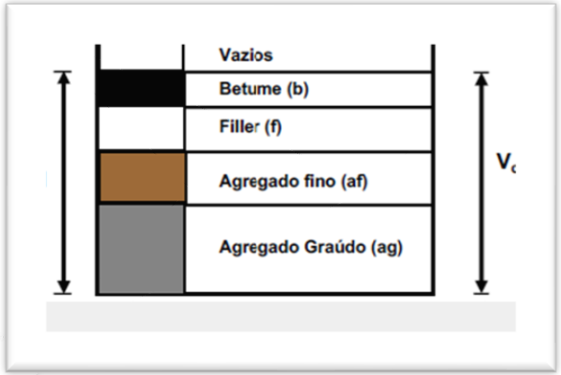
MISTURA SOLTA: USINAGEM





"DMT"

$$DMT = \frac{M}{V_c} = \frac{100}{\frac{\%CAP}{d_{CAP}} + \frac{\%f}{d_f} + \frac{\%am}{d_{am}} + \frac{\%ag}{d_{ag}}}$$



Massa Específica Máxima (Teórica) da Mistura - SOLTA

$$Gmm = \frac{P_{asf} + P_{ag}}{V_{asf} + V_{ag-ef}}$$

Mas não se determinam **Volumes** em laboratório, e sim **Pesos.**

"RICE TEST"

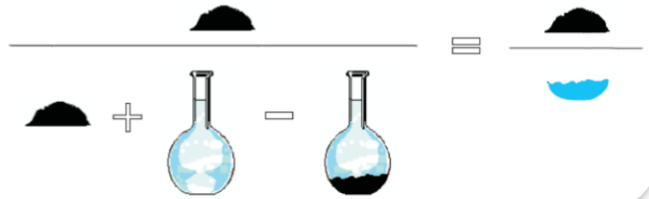
$$G_{mm} = \frac{A}{A+B-C} \times 0{,}9971$$

Onde:

A = massa da amostra seca em ar, g;

B = massa do recipiente com volume completo com água, g;

C = massa do recipiente + amostra submersa em água, g.





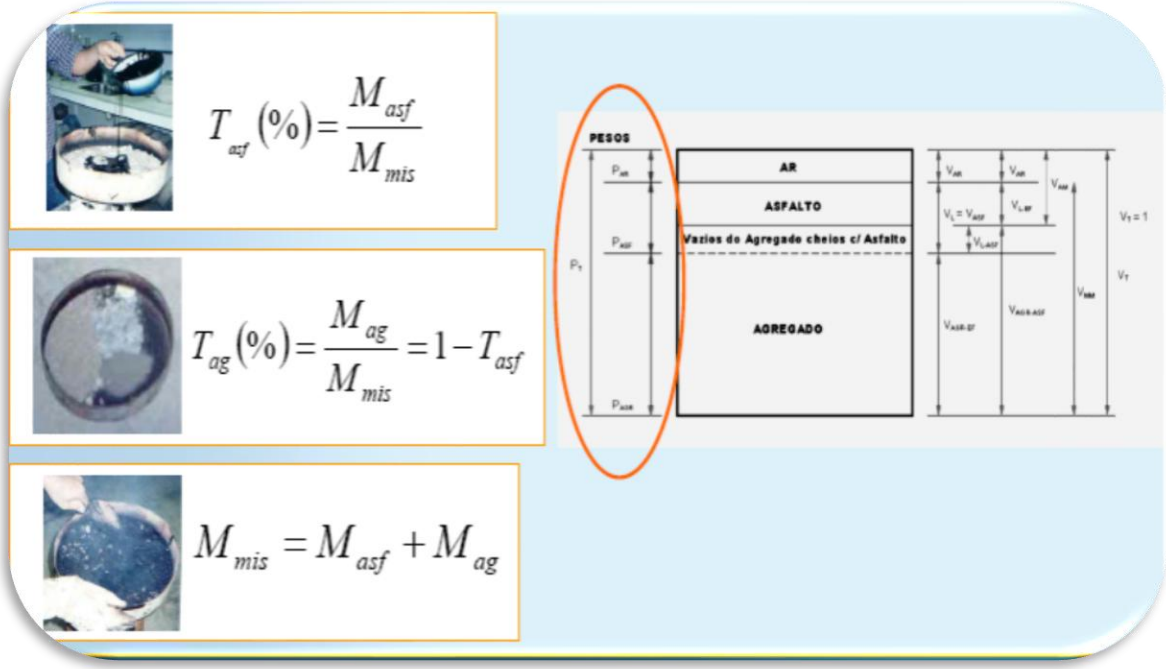
DOSAGEM MISTURAS ASFÁLTICAS: FADIGA & IMPORTÂNCIA DA VOLUMETRIA





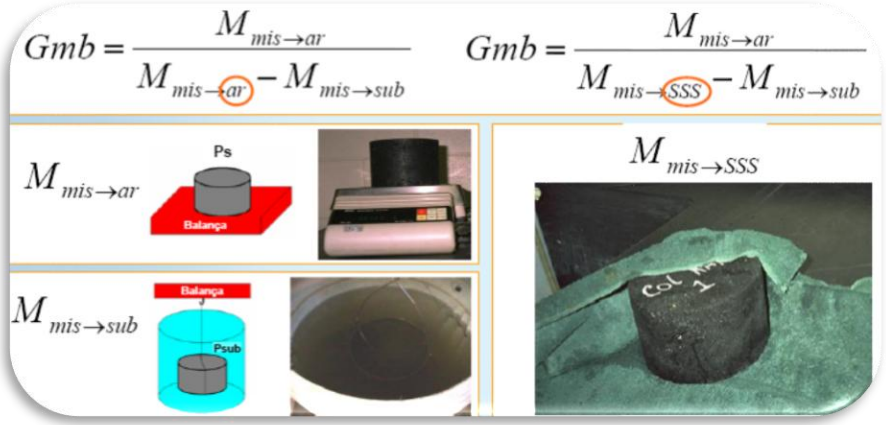


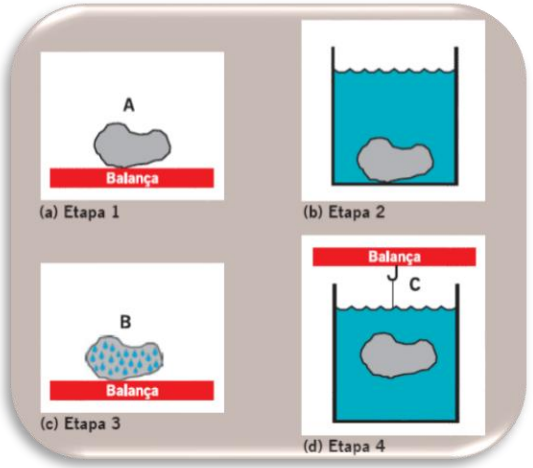
MISTURA COMPACTADA/Massa Especifica Aparente





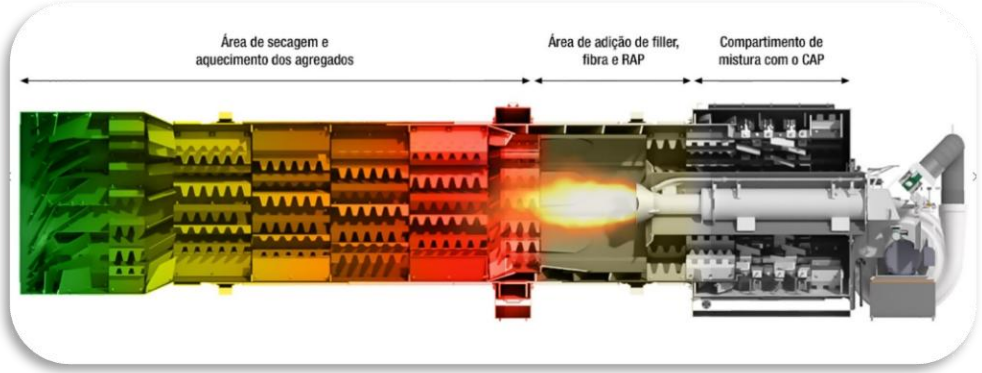
Garantia de um grau de compactação compativel !!!!



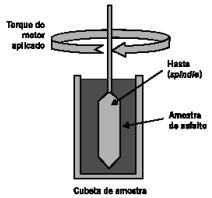


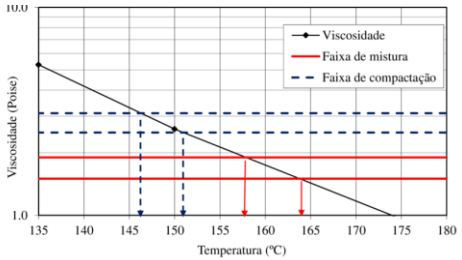
DOSAGEM MISTURAS ASFÁLTICAS: FADIGA & IMPORTÂNCIA DA VOLUMETRIA

"MISTURA ASFÁLTICA"
FADIGA & USINAGEM/LABORATÓRIO











TIPO DE MISTURADOR - HOMOGENEIZAÇÃO











DOSAGEM MISTURAS ASFÁLTICAS: FADIGA & IMPORTÂNCIA DA VOLUMETRIA

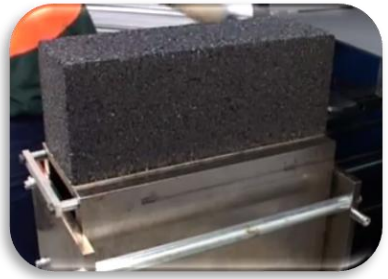
FADIGA & COMPACTAÇÃO : CAMPO / LABORATÓRIO

COMPACTAÇÃO POR AMASSAMENTO













COMPACTAÇÃO EM CAMPO



COMPACTAÇÃO POR IMPACTO ??

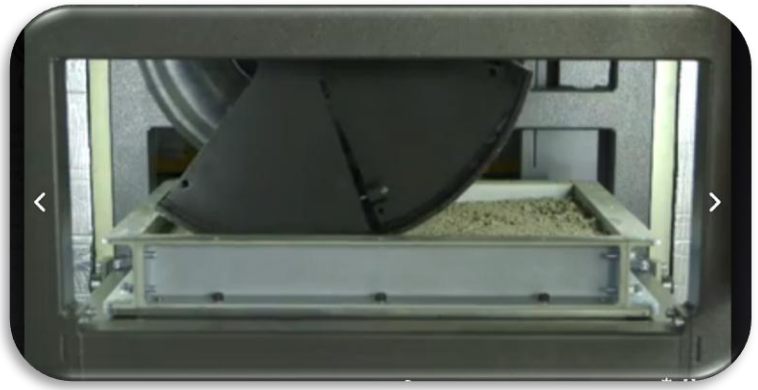


DOSAGEM MISTURAS ASFÁLTICAS: FADIGA & IMPORTÂNCIA DA VOLUMETRIA

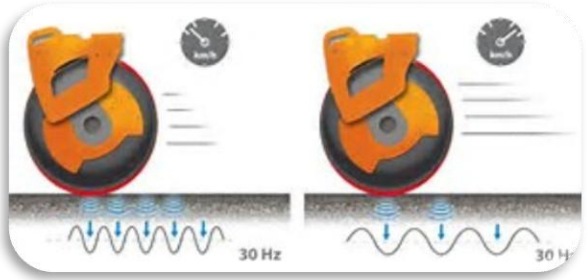
COMPACTAÇÃO POR AMASSAMENTO







IDEAL !!!!







USP/POLI



FADIGA & COMPACTAÇÃO : CAMPO / LABORATÓRIO

DOSAGEM MISTURAS ASFÁLTICAS: FADIGA & IMPORTÂNCIA DA VOLUMETRIA: DOSAGEM

COMPACTAÇÃO POR AMASSAMENTO: PLACAS





IDEAL !!!!





FADIGA & COMPACTAÇÃO : CAMPO / LABORATÓRIO

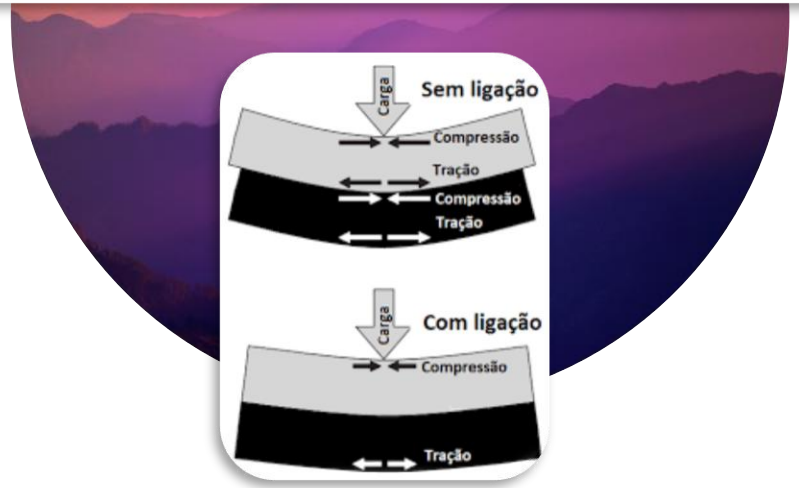
PAVIMENTOS FLEXÍVEIS: FADIGA & REPRODUÇÃO NO ESTADO CRÍTICO
SOLICITAÇÕES : FLEXÃO > ESFORÇOS: COMPRESSÃO/TRAÇÃO/CISALHAMENTO

"Layout de Níveis de Tensões : Compressão/Tração

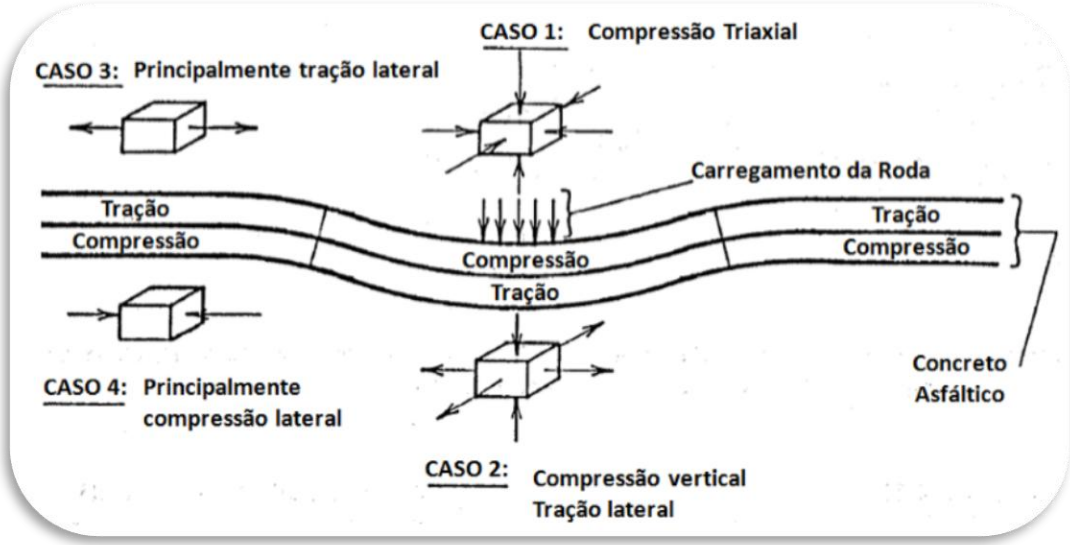


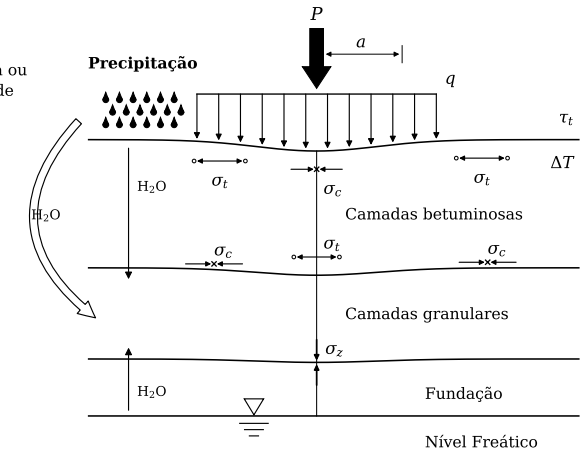
Sem aderência

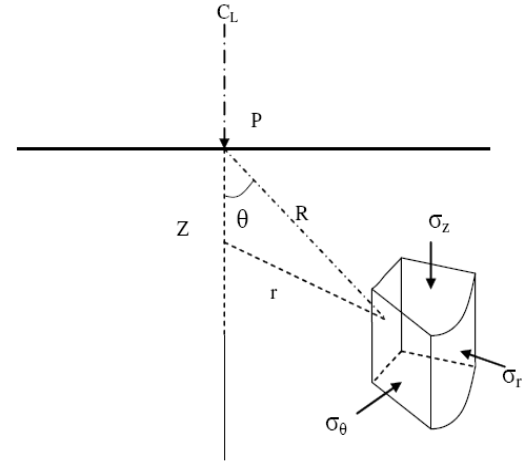
Com aderência



"Hipóteses de trabalho: Considerando o Regime Elástico Linear"



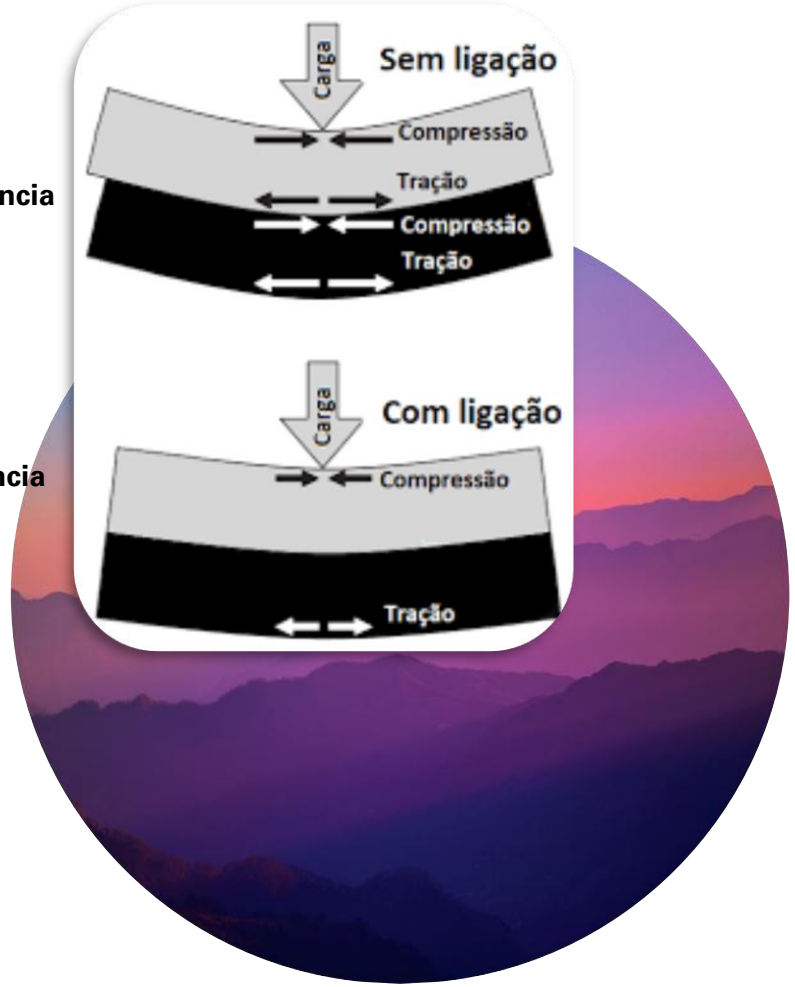




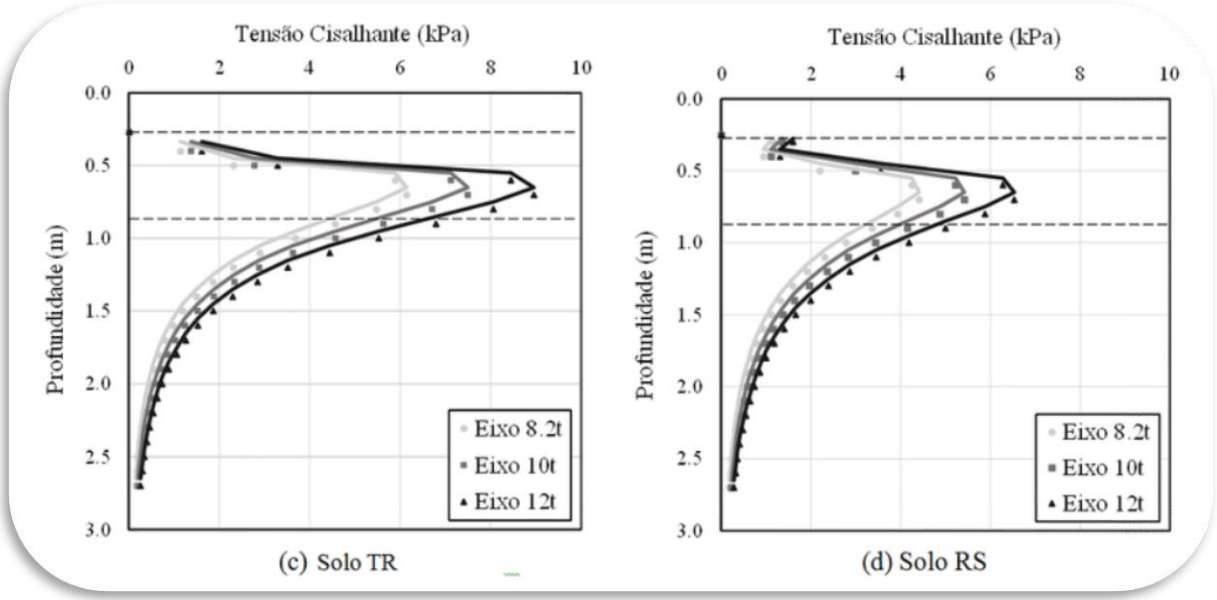
Fonte: (HUANG, 1993 ; Minhoto, 2005).

PAVIMENTOS FLEXÍVEIS: FADIGA & CONCEITOS E FILOSOFIA DE PROJETO
TENSÕES E NÍVEIS DE DESLOCAMENTOS VERTICAIS

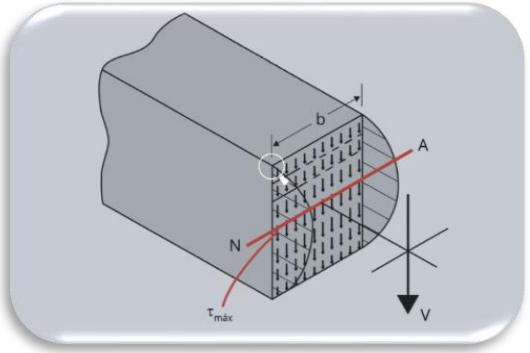
“Layout de Níveis de Tensões de Cisalhamento: aderência das camadas

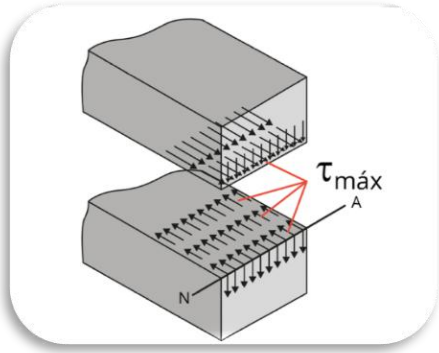


“Cisalhamento em função do Eixo”



SEÇÃO TRANSVERSAL



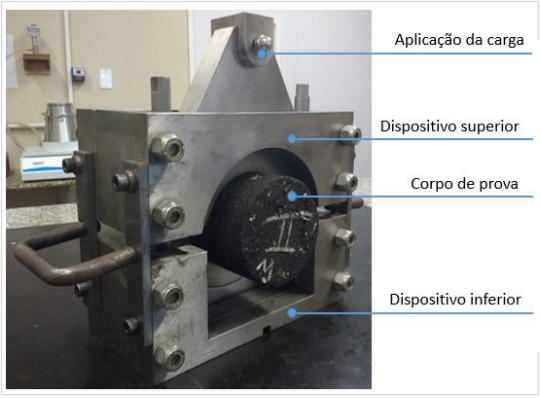


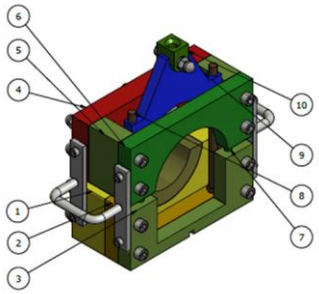
FALHA NA LIGAÇÃO ENTRE AS CAMADAS:APA/BINDER

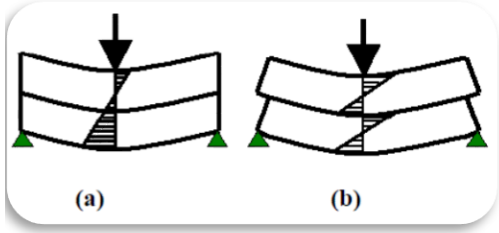
AEROPORTUÁRIO GOVERNADOR ALUÍZIO ALVES - RN

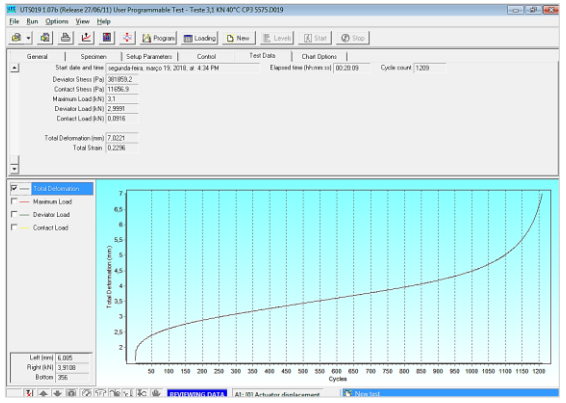
Tensões de Cisalhamento Máximas - Pista de Pouso e Decolagem

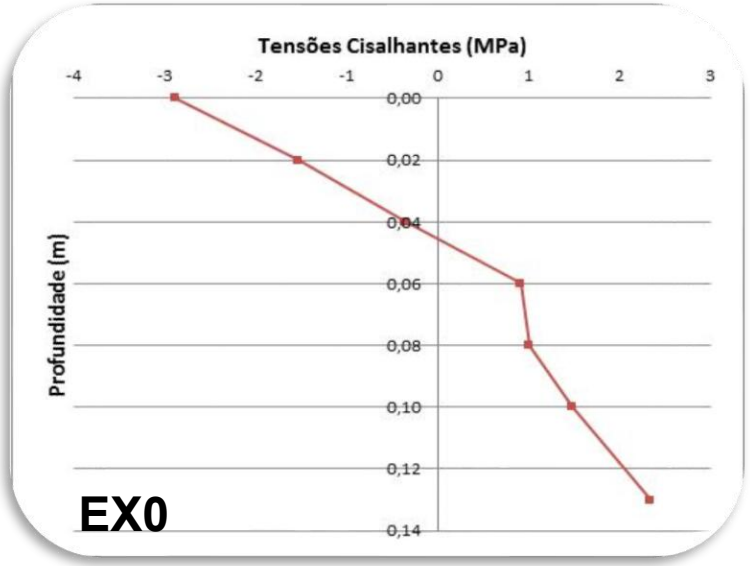
ENSAIO LEUTNER











ESTÁTICO - DINAMICO

✓ SLEEP PAGE!!!



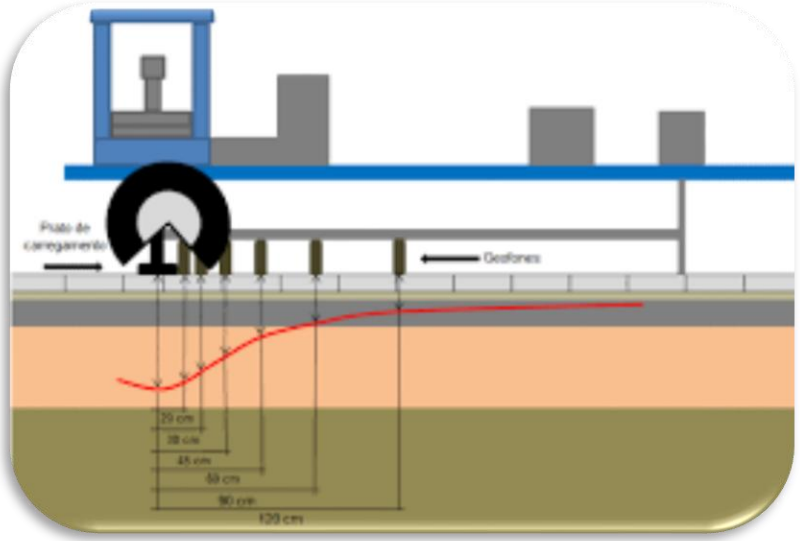


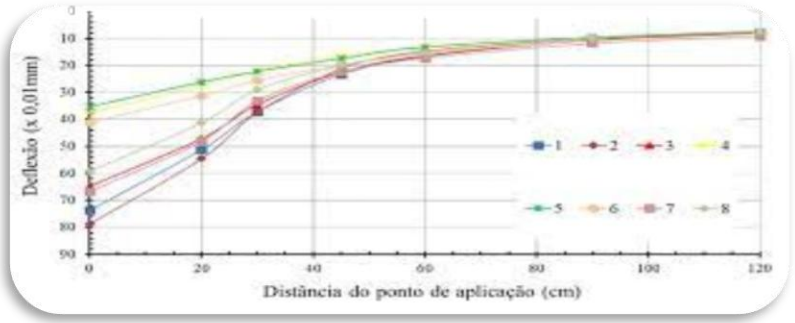
Principal causa: Ausência de controle na execução!

COMPATIBILIDADE DE RIGIDEZ ENTRE CAMADAS !

Níveis de Deflexão & Fases de Vida de Fadiga

“Bacia de deslocamento & vida útil”

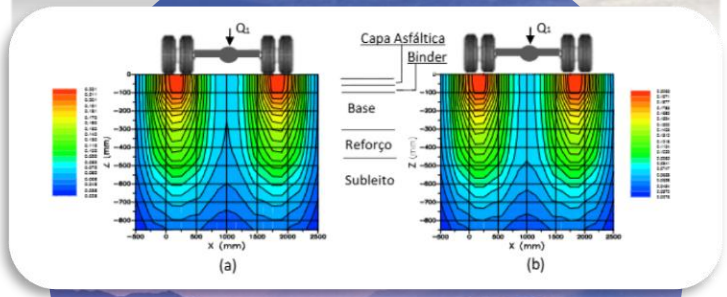


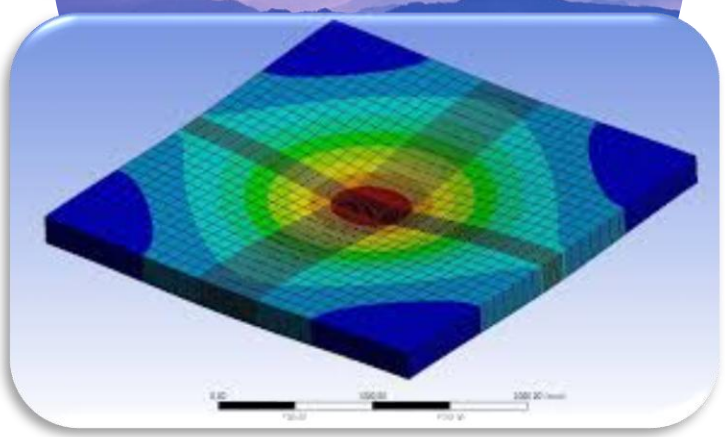


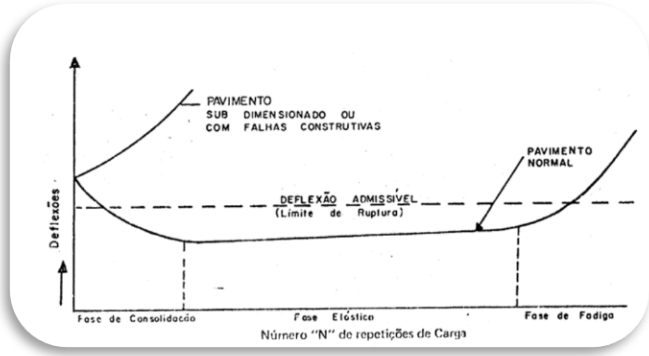




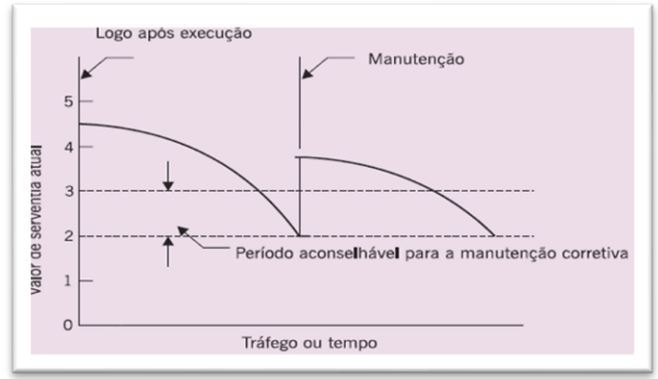












Índice de Serventia

FADIGA EM MISTURAS ASFÁLTICAS

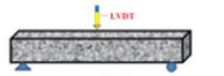
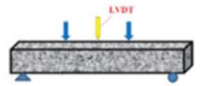
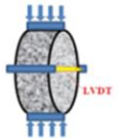
PROCEDIMENTOS / ENSAIOS UTILIZADOS EM LABORATÓRIO!!!



EQUIPAMENTO : UTM



ENSAIOS DE FADIGA

Modo de Carregamento	Diagrama esquemático	Especificação/referência
Uniaxial Compressão/Tração		AASHTO (2018), Di Benedetto *et al.* (2011), Witczak *et al.* (2013), Zeiada *et al.* (2014)
Flexão de vigas		CEN (2018a), Ren *et al.* (2021), Sun *et al.* (2018)
		AASHTO (2014a), ASTM (2010), CEN (2018a), Research Institute of Highway of Minitry od Transport (2011)
Tração indireta	 	CEN (2018a), Li *et al.* (2019), Maggiore *et al.* (2012)
	 	CEN (2018a), Cheng *et al.* (2021a), Nguyen *et al.* (2013)
Flexão semicircular		AASHTO (2016), CEN (2018b)
Cisalhamento dinâmico		AASHTO (2014), Ahmed e Khalid (2015), Apostolidis *et al.* (2018)

ACESSÓRIOS

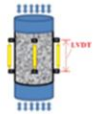
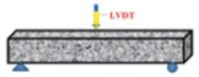
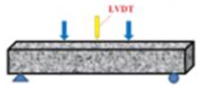
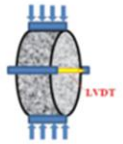


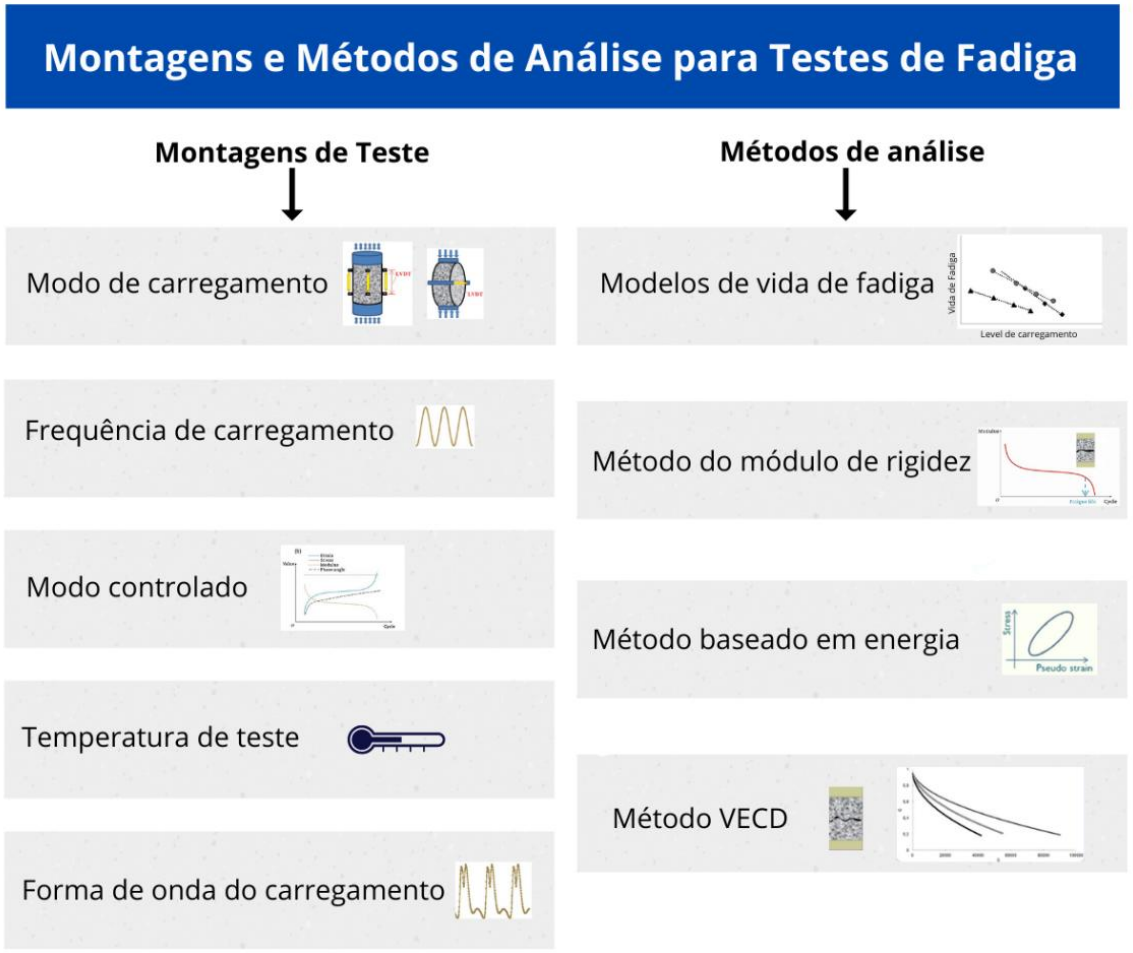
FADIGA EM MISTURAS ASFÁLTICAS



PROCEDIMENTOS / ENSAIOS UTILIZADOS EM LABORATÓRIO!!!



Modo de Carregamento	Diagrama esquemático	Especificação/referência
Uniaxial Compressão/Tração	 	AASHTO (2018), Di Benedetto *et al.* (2011), Witczak *et al.* (2013), Zeiada *et al.* (2014)
Flexão de vigas		CEN (2018a), Ren *et al.* (2021), Sun *et al.* (2018)
		AASHTO (2014a), ASTM (2010), CEN (2018a), Research Institute of Highway of Minitry od Transport (2011)
Tração indireta	 	CEN (2018a), Li *et al.* (2019), Maggiore *et al.* (2012)
	 	CEN (2018a), Cheng *et al.* (2021a), Nguyen *et al.* (2013)
Flexão semicircular		AASHTO (2016), CEN (2018b)
Cisalhamento dinâmico		AASHTO (2014), Ahmed e Khalid (2015), Apostolidis *et al.* (2018)

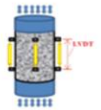
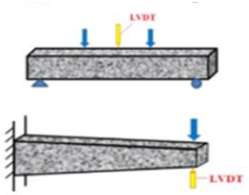
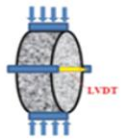


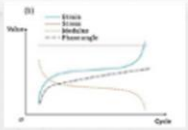
Fonte: adaptado de Huailei Cheng *et al.* (2022).

FADIGA EM MISTURAS ASFÁLTICAS

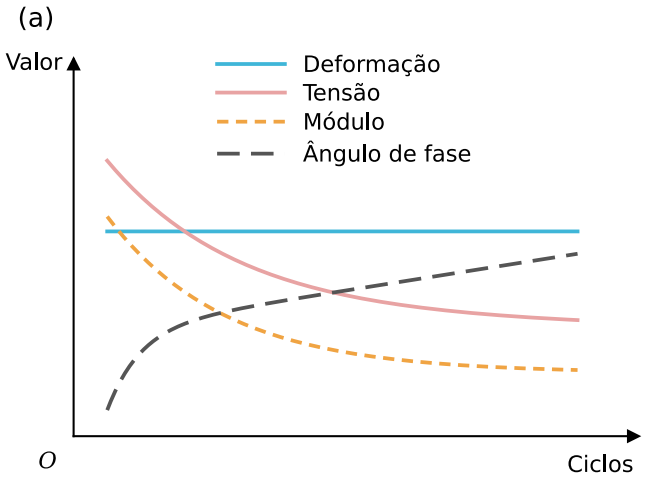


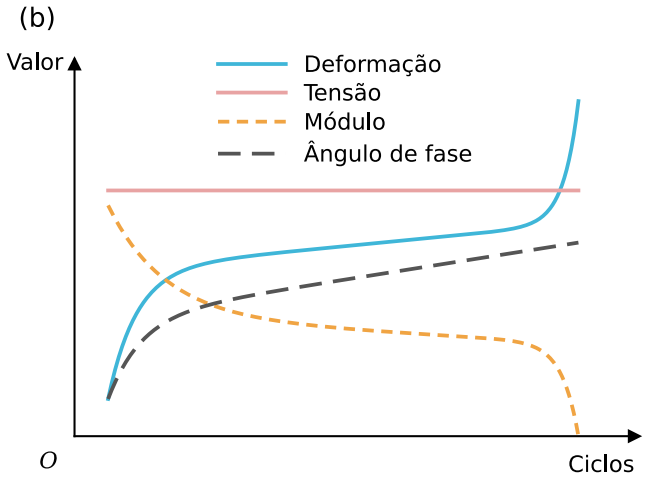


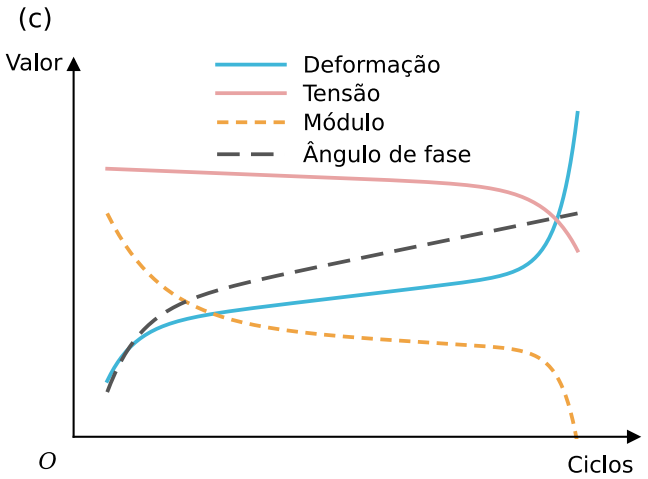
Modo de Carregamento	Diagrama esquemático
Uniaxial Compressão/Tração	
 Flexão de vigas	
 Tração indireta	
	

Modo controlado 

(a) Deformação controlada, (b) Tensão controlada e (c) Deslocamentos controlados.







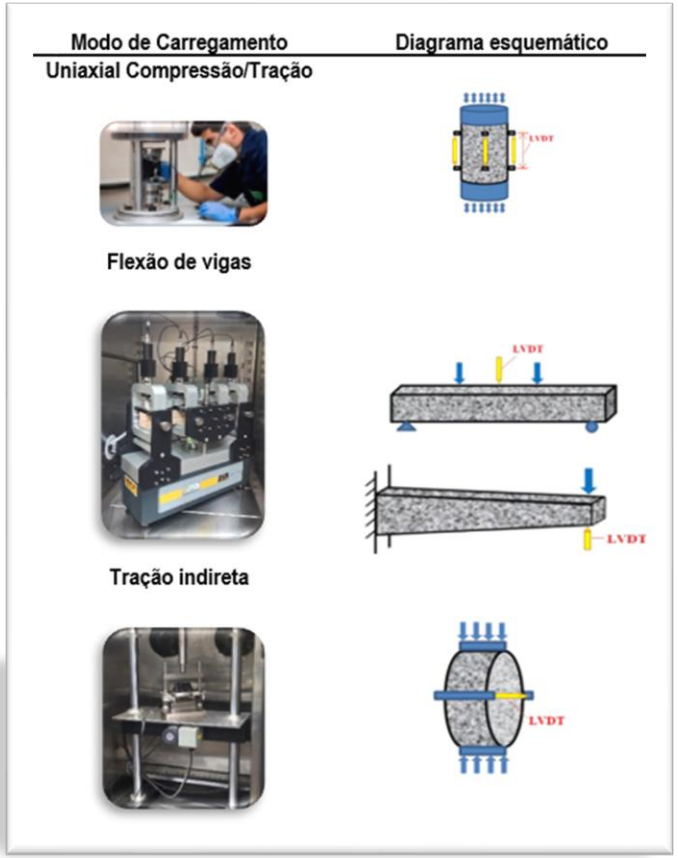
INFERENCIAS: ÂNGULO DE FASE !!

Fonte: adaptado de Huailei Cheng *et al.* (2022).

FADIGA EM MISTURAS ASFÁLTICAS

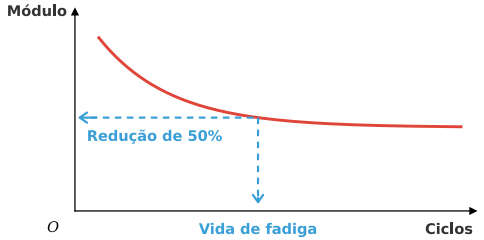
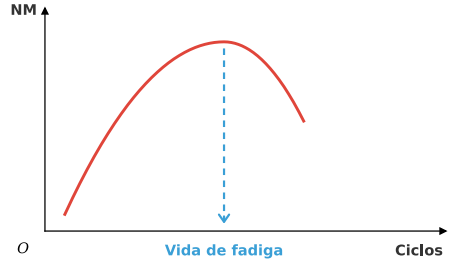
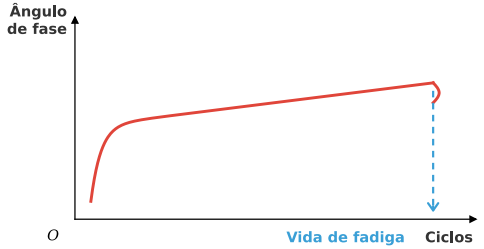






Fonte: adaptado de Huailei Cheng *et al.* (2022).

CRITÉRIOS DE RUPTURA !!

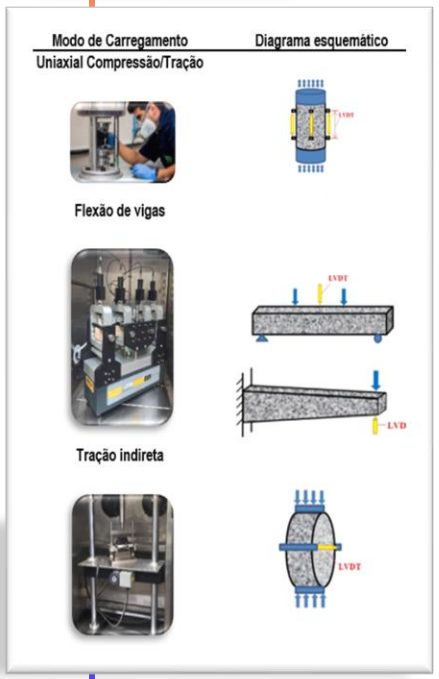
Critério	Indicador	Diagrama esquemático
Critério de trincamento	Surgimento de macrotrinca / curva do módulo de rigidez	
Critério de redução de 50% da rigidez	Curva do módulo de rigidez	
Critério do módulo de rigidez normalizado × repetições (NM)	Produto do módulo de rigidez normalizado pelo número de repetições, calculado por: $NM = \frac{S_i N_i}{S_0 N_0}$ onde S_i é a rigidez da mistura na repetição i, N_i é o número de repetições, S_0 é o módulo inicial (MPa) e N_0 é o número de repetições em que o módulo inicial é estimado.	
Critério do ângulo de fase	Ângulo de fase	
		

CRITÉRIOS DE RUPTURA !!

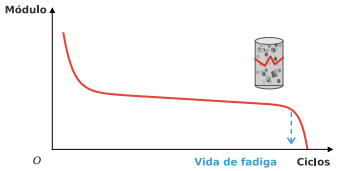
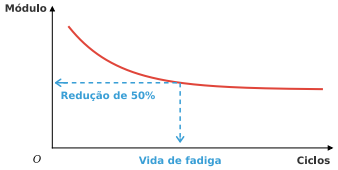
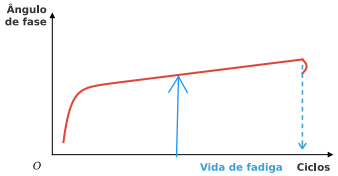
FADIGA EM MISTURAS ASFÁLTICAS

Fase de Micro trincamento & Propagação de trincas associada a deterioração acelerada !







Critério	Indicador	Diagrama esquemático
Critério de trincamento	Surgimento de macrotrinca / curva do módulo de rigidez	
Critério de redução de 50% da rigidez	Curva do módulo de rigidez	
Critério do módulo de rigidez normalizado × repetições (NM)	Produto do módulo de rigidez normalizado pelo número de repetições, calculado por: $NM = \frac{S_i N_i}{S_0 N_0}$ onde S_i é a rigidez da mistura na repetição i, N_i é o número de repetições, S_0 é o módulo inicial (MPa) e N_0 é o número de repetições em que o módulo inicial é estimado.	
Critério do ângulo de fase	Ângulo de fase	

Fonte: A. Cocurullo, G. D. Airey , A. C. Collop and C. Sangiorgi (2008).

1 - Temperatura diferentes!

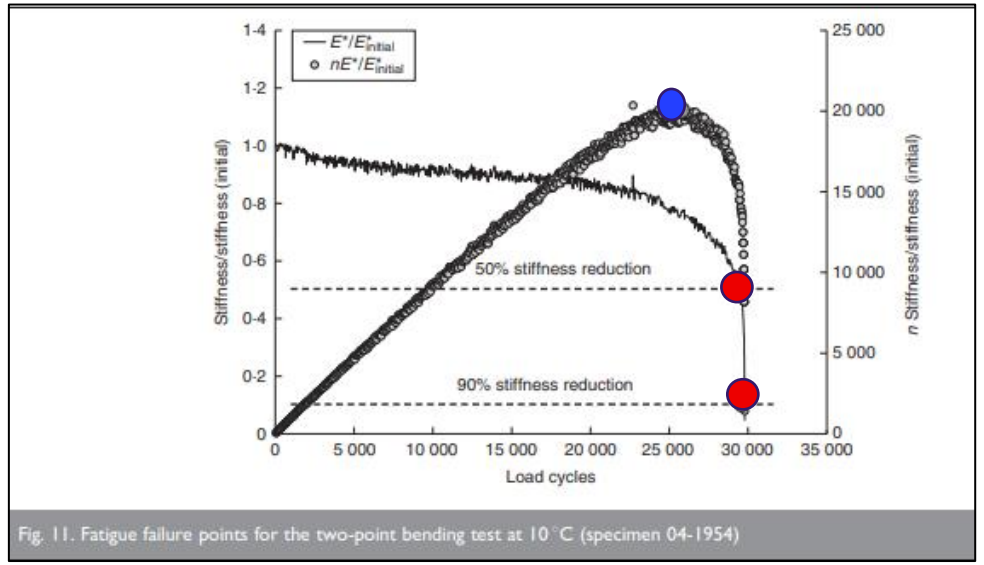


Fig. 11. Fatigue failure points for the two-point bending test at 10 °C (specimen 04-1954)

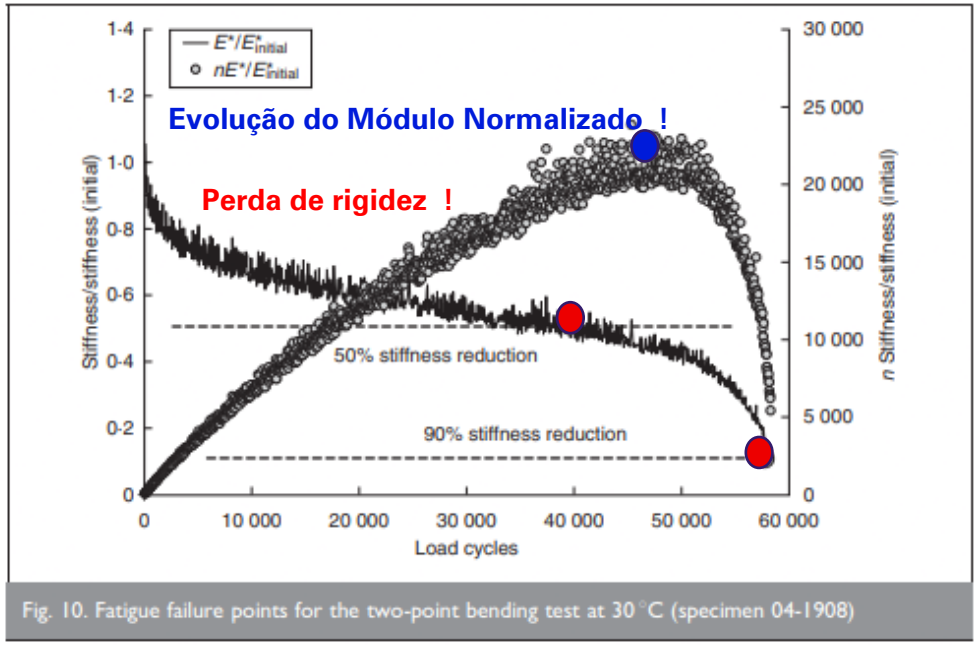
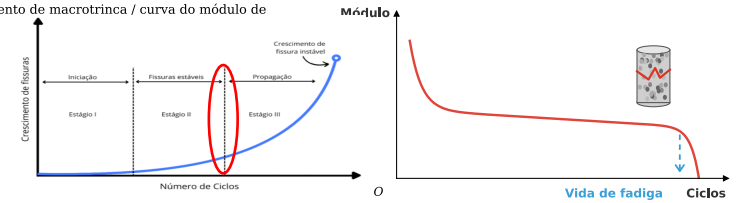
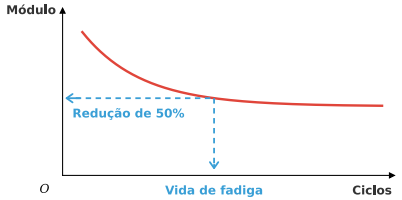
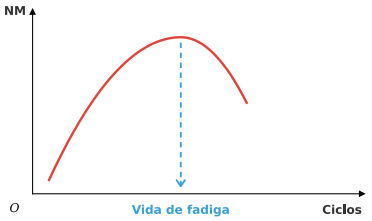
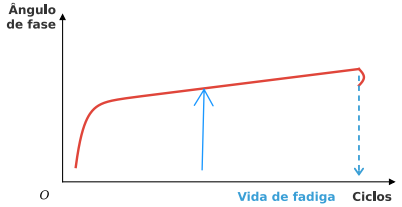


Fig. 10. Fatigue failure points for the two-point bending test at 30 °C (specimen 04-1908)



FADIGA EM MISTURAS ASFÁLTICAS

CRITÉRIOS DE RUPTURA !!

Critério	Indicador	Diagrama esquemático
Critério de trincamento	Surgimento de macrotrinca / curva do módulo de rigidez	
Critério de redução de 50% da rigidez	Curva do módulo de rigidez	
Critério do módulo de rigidez normalizado × repetições (NM)	Produto do módulo de rigidez normalizado pelo número de repetições, calculado por: $NM = \frac{S_i N_i}{S_0 N_0}$ onde S_i é a rigidez da mistura na repetição i, N_i é o número de repetições, S_0 é o módulo inicial (MPa) e N_0 é o número de repetições em que o módulo inicial é estimado.	
Critério do ângulo de fase	Ângulo de fase	

Fonte: A. Cocurullo, G. D. Airey , A. C. Collop and C. Sangiorgi (2008).

1 - Temperatura diferentes!

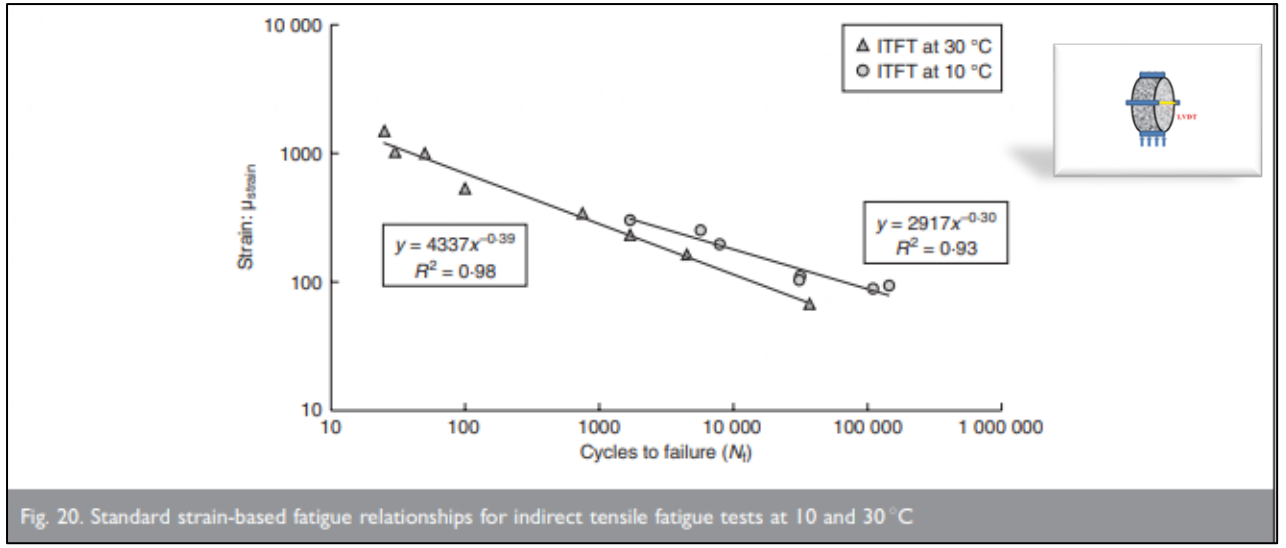


Fig. 20. Standard strain-based fatigue relationships for indirect tensile fatigue tests at 10 and 30 °C

2 - Ensaios diferentes !

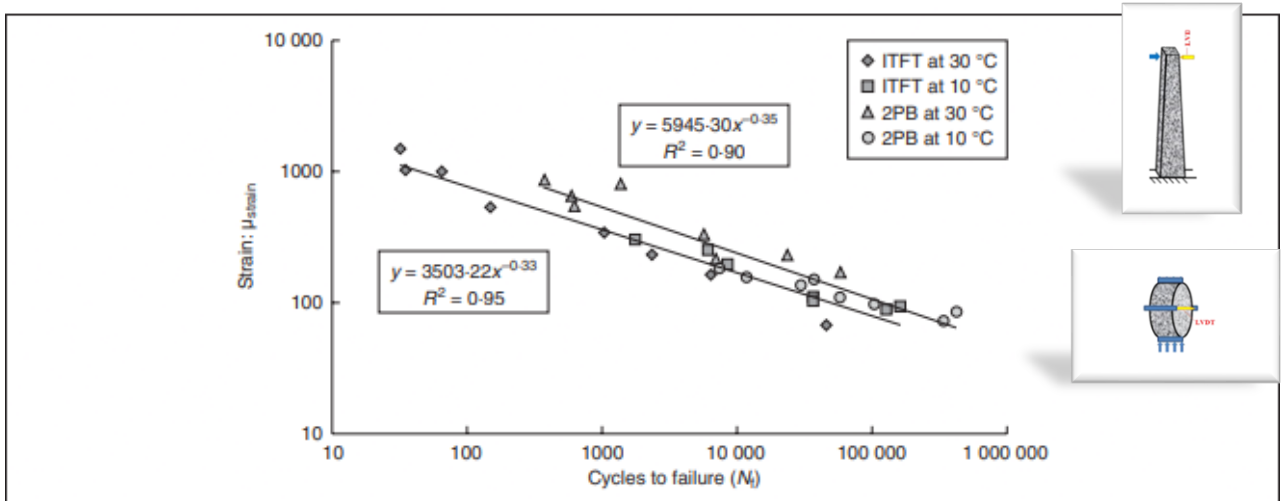


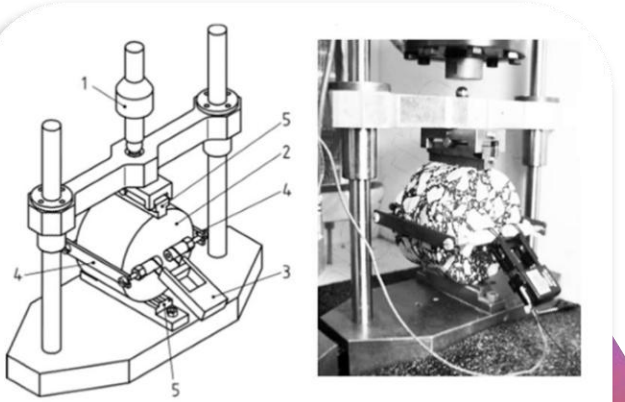
Fig. 21. Standard strain-based fatigue relationships for indirect tensile and two-point bending fatigue tests at 10 and 30 °C based on a 90% decrease in initial stiffness failure point

“TRAÇÃO INDIRETA POR COMPRESSÃO DIAMETRAL”

“Layout de Níveis de Tensões de Cisalhamento: Método de Ensaio em Laboratório



IDÉAL !!!





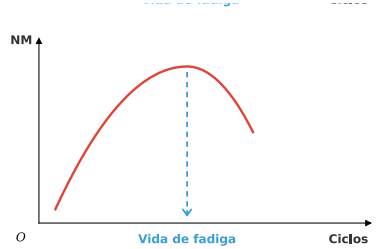
“Tensões T/C em função do Eixo”

Critério do módulo de rigidez normalizado × repetições (NM)

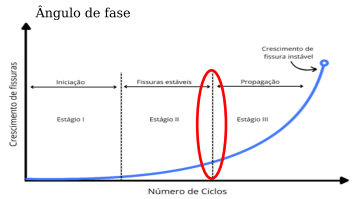
Produto do módulo de rigidez normalizado pelo número de repetições, calculado por:

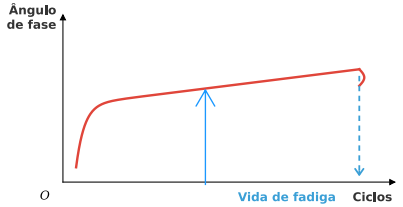
$$NM = \frac{S_i N_i}{S_0 N_0}$$

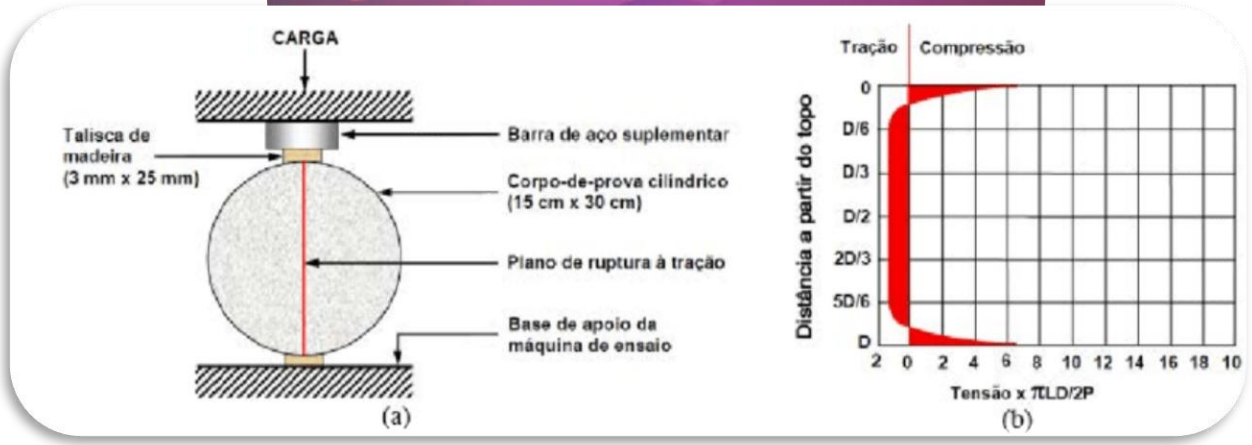
onde S_i é a rigidez da mistura na repetição i, N_i é o número de repetições, S_0 é o módulo inicial (MPa) e N_0 é o número de repetições em que o módulo inicial é estimado.

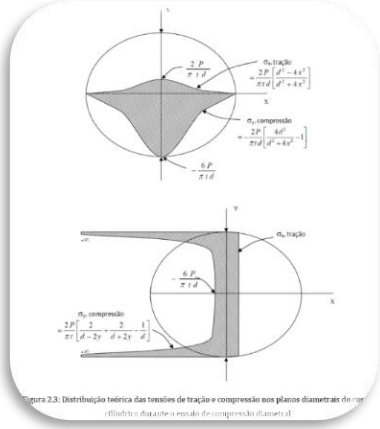


Critério do ângulo de fase









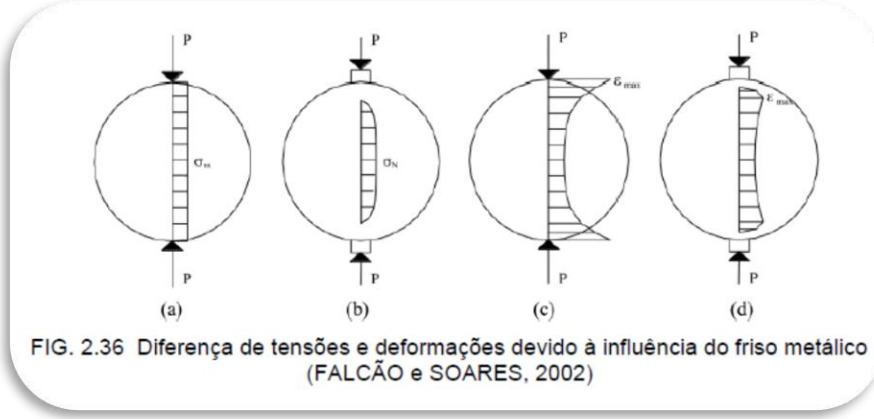
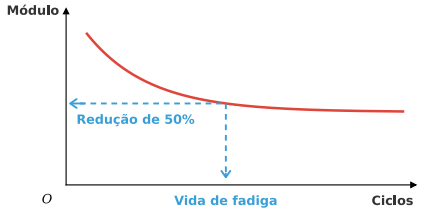


FIG. 2.36 Diferença de tensões e deformações devido à influência do friso metálico (FALCÃO e SOARES, 2002)

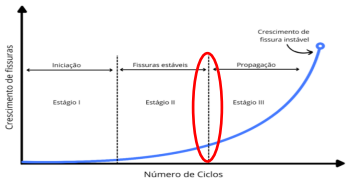


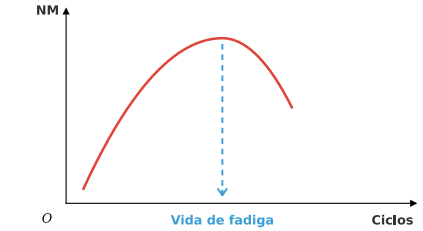
TRAÇÃO POR FLEXÃO 4 PONTOS

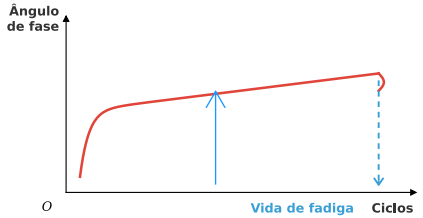


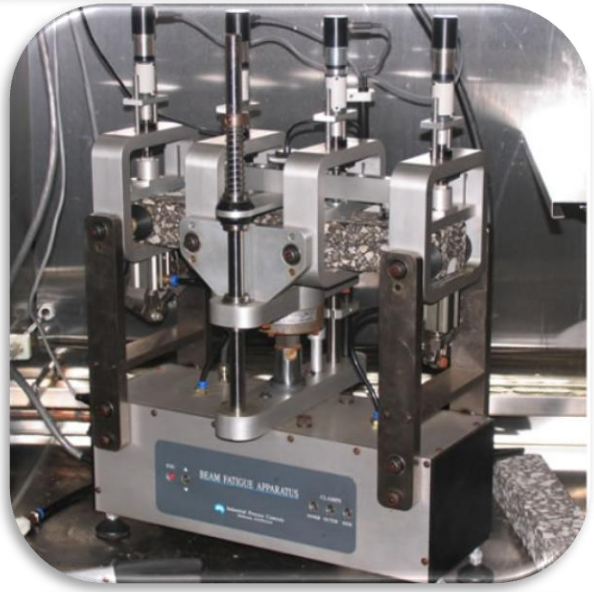


“Layout de tipos de Tensões : Método de Ensaio em Laboratório

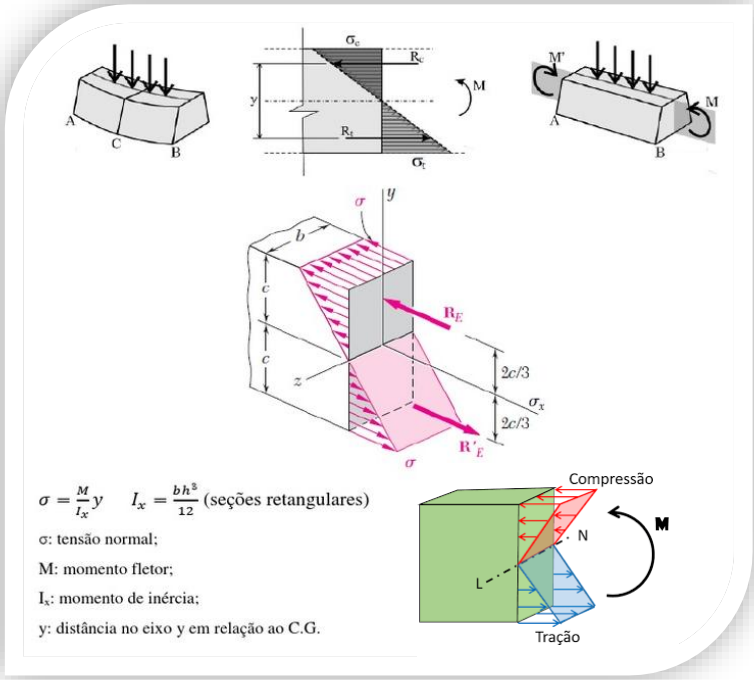


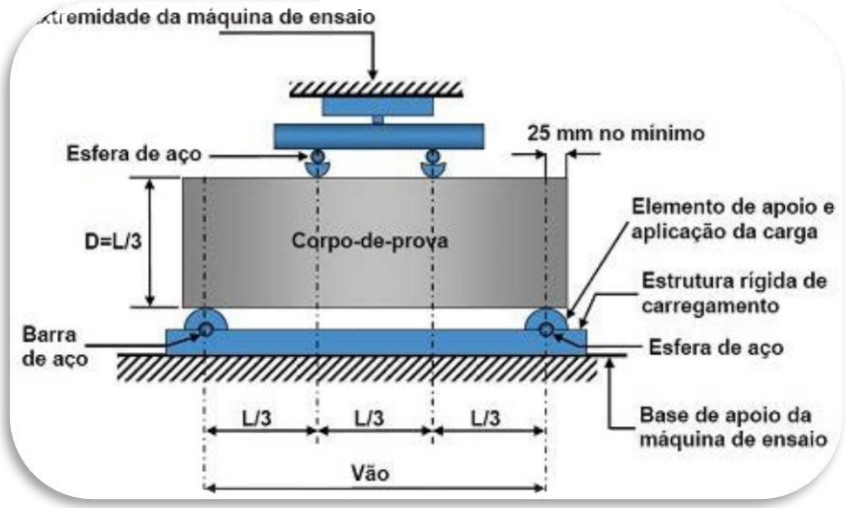




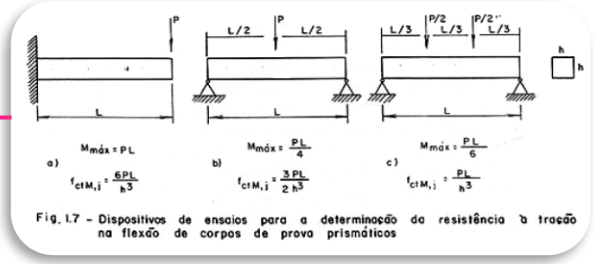


“Tensões T/C em função do Eixo”





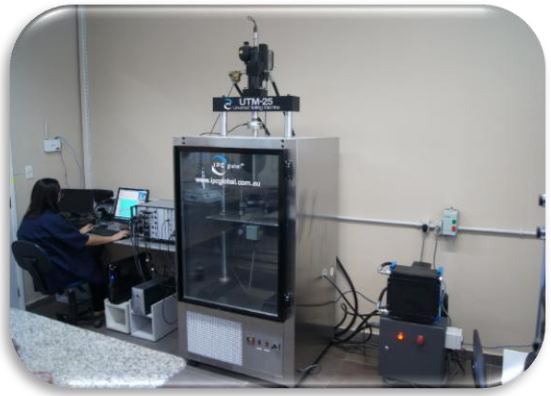






TRAÇÃO/COMPRESSÃO AXIAL

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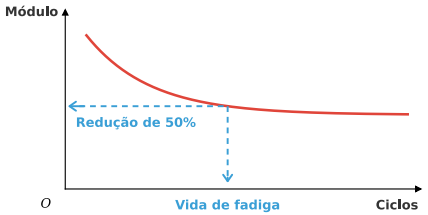


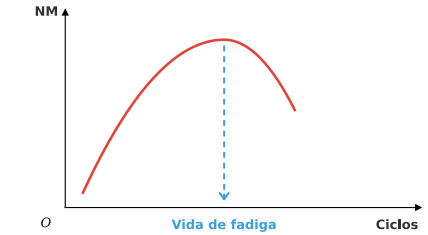
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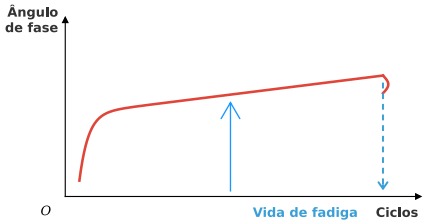


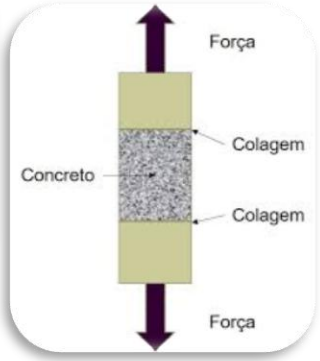


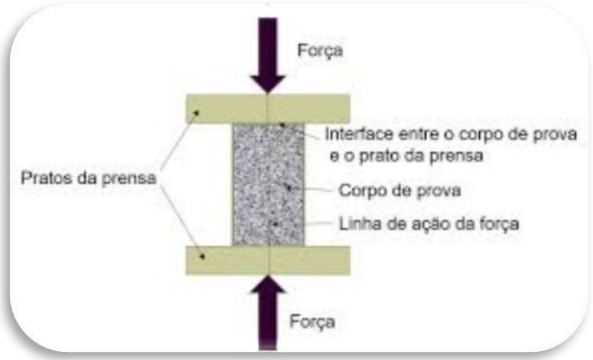




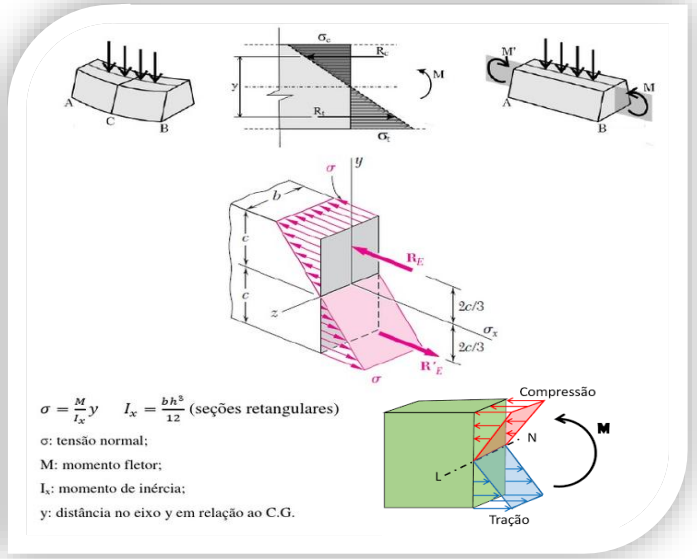


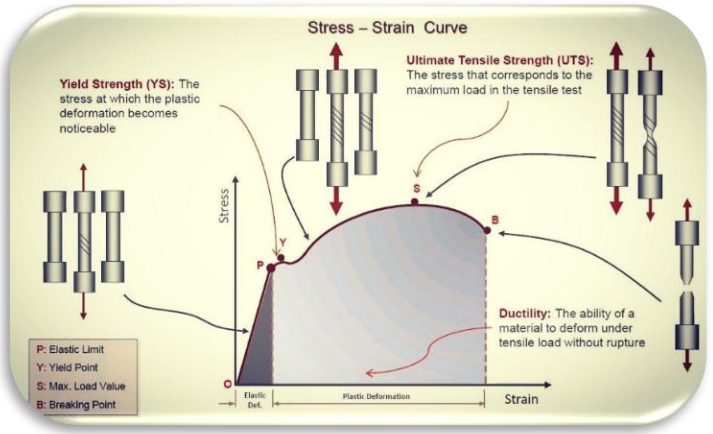






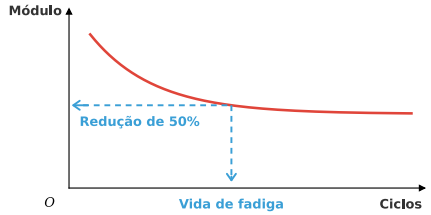
“Tensões T/C em função do Eixo”



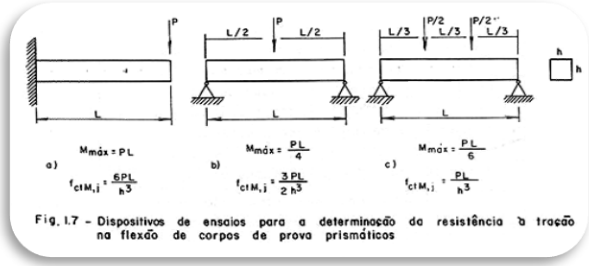


TRAÇÃO POR FLEXÃO 2 PONTOS

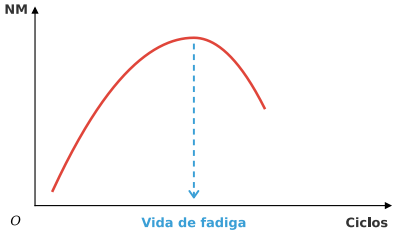


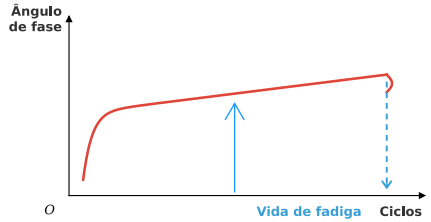


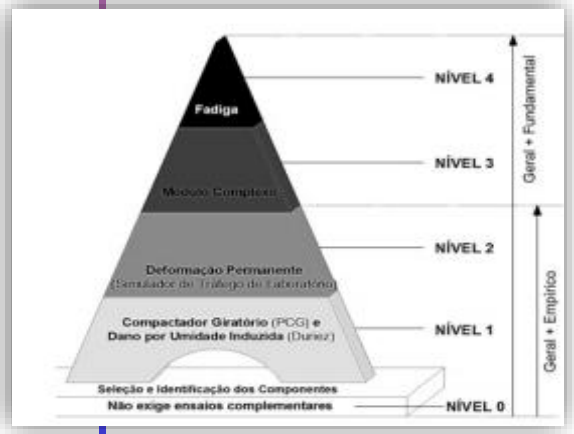




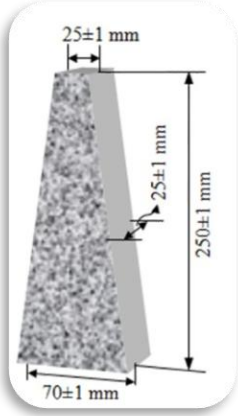












Característica do corpo de prova trapezoidal para o ensaio de módulo complexo e fadiga comportamento tensão x deformação da flexão senoidal.

Fonte: Review and prospect of four-point bending fatigue test of asphalt mixture

Yongjun Meng [a,b,c,d,*], Dichao Liu [a], Hongliu Rong [a], Xiaolong Yang [a]

VIGA DE 4 PONTOS





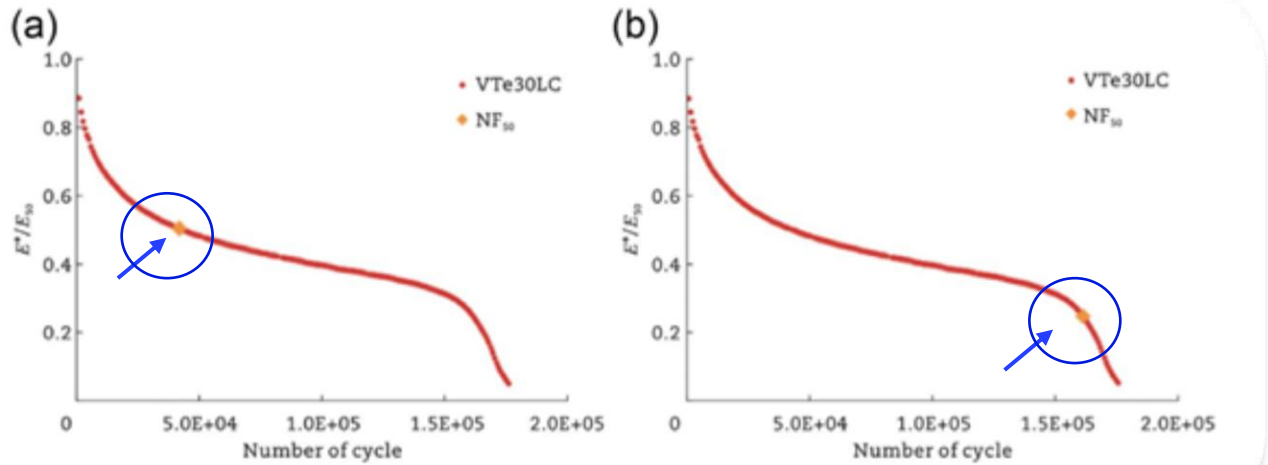


Fig. 19. Determined failure point by different approaches. (a) Traditional fatigue analysis. (b) Phase angle approach.

CURVA DE FADIGA

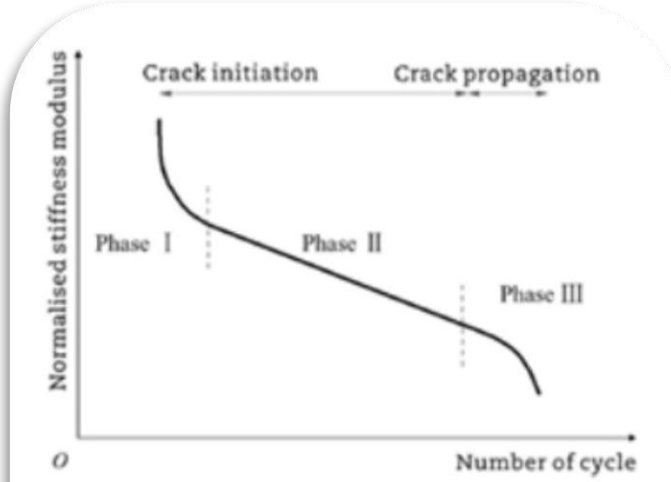


Fig. 14. Typical fatigue curve response.

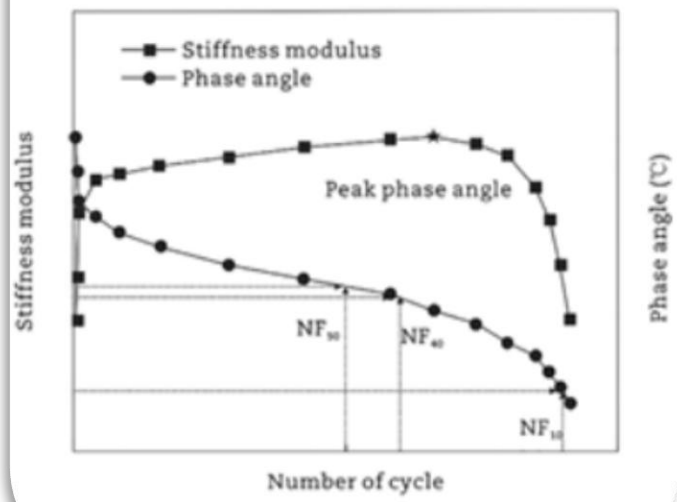


Fig. 15. Traditional approach in fatigue analysis.

CURVA DE FADIGA: PERDA DE RIGIDEZ



4 PONTOS



IDT



TIPOS DE ENSAIOS

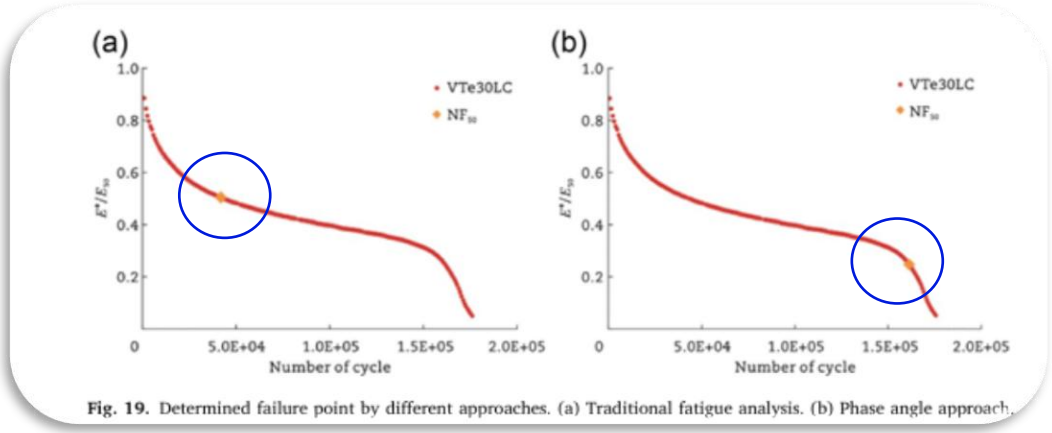


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Normas:AASHTO-T321 e a EN 12697-24

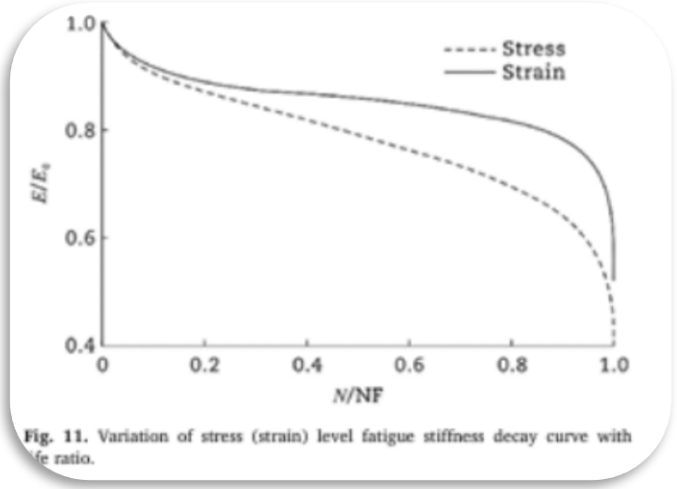


Fig. 11. Variation of stress (strain) level fatigue stiffness decay curve with ...fe ratio.

"CRITÉRIO DE PARADA DO ENSAIO DE FADIGA" !

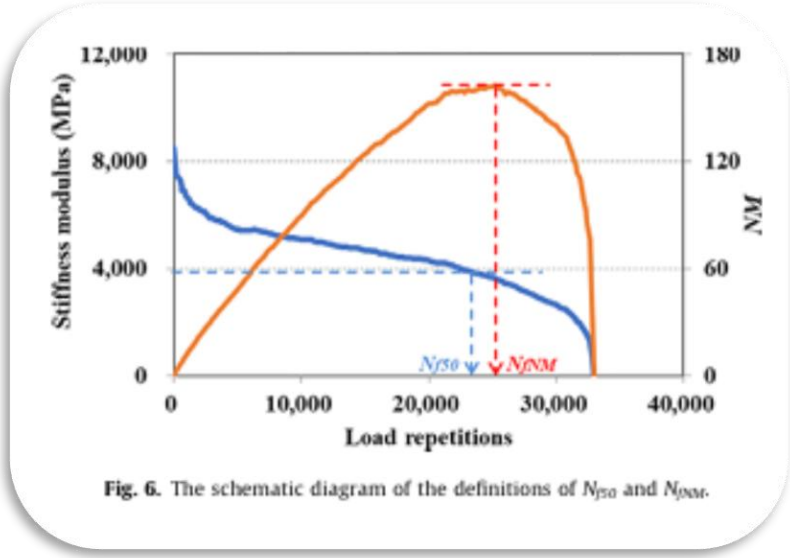


Fig. 6. The schematic diagram of the definitions of N_{f50} and N_{fNM}.

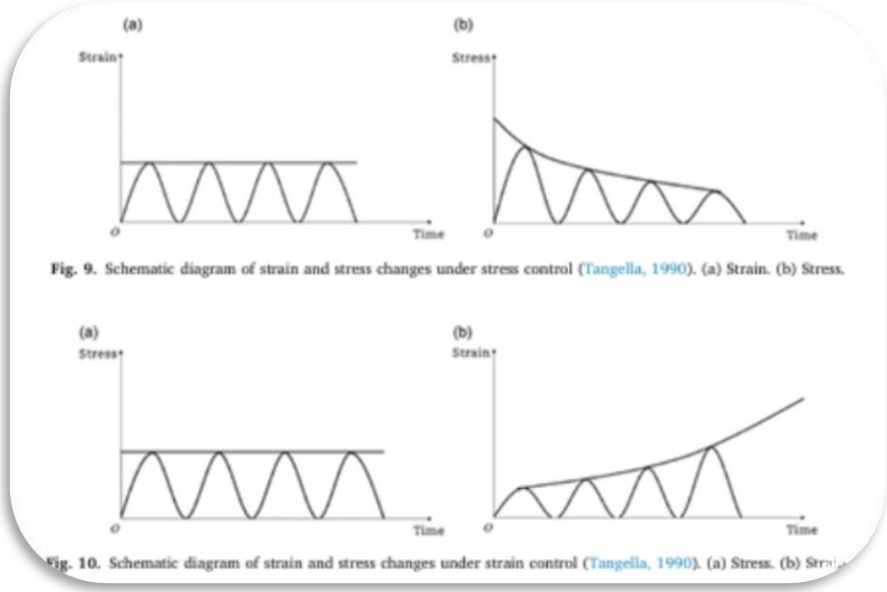


Fig. 9. Schematic diagram of strain and stress changes under stress control (Tangella, 1990). (a) Strain. (b) Stress.

Fig. 10. Schematic diagram of strain and stress changes under strain control (Tangella, 1990). (a) Stress. (b) Strain.

CURVA DE FADIGA: PERDA DE RIGIDEZ

Fonte:



Review and prospect of four-point bending fatigue test of asphalt mixture

Yongjun Meng [a,b,c,d,*], Dichao Liu [a], Hongliu Rong [a], Xiaolong Yang [a]



DISPERSÃO DE DADOS

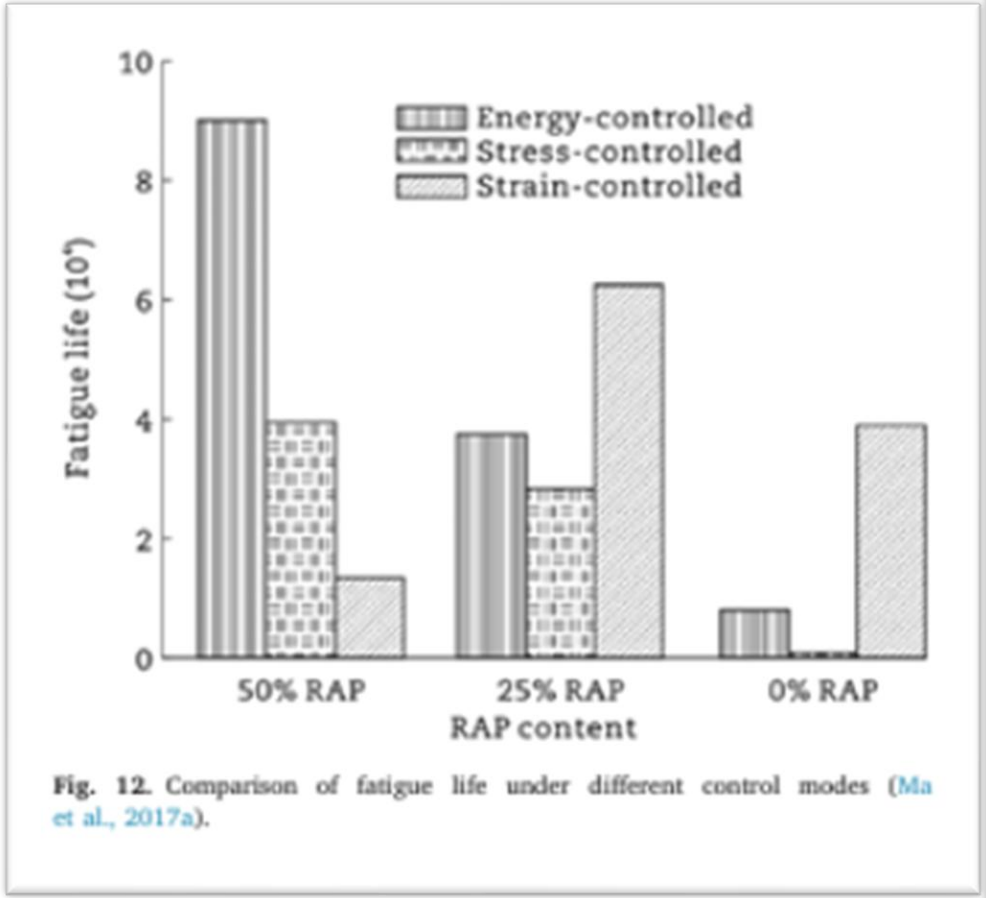


Fig. 12. Comparison of fatigue life under different control modes (Ma et al., 2017a).

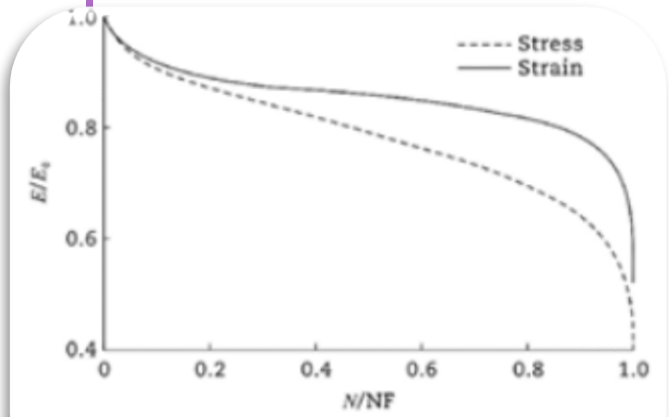


Fig. 11. Variation of stress (strain) level fatigue stiffness decay curve with life ratio.

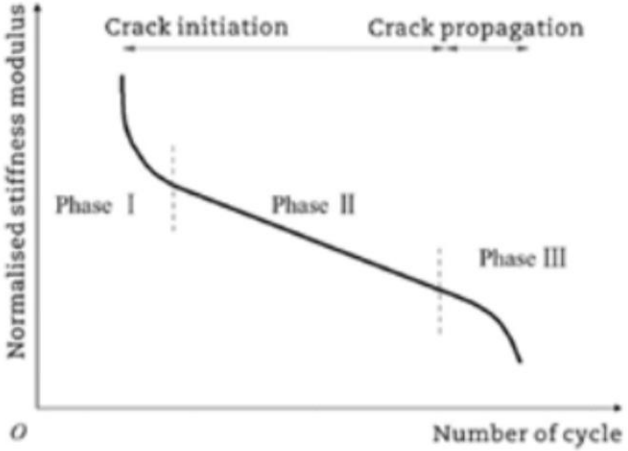


Fig. 14. Typical fatigue curve response.

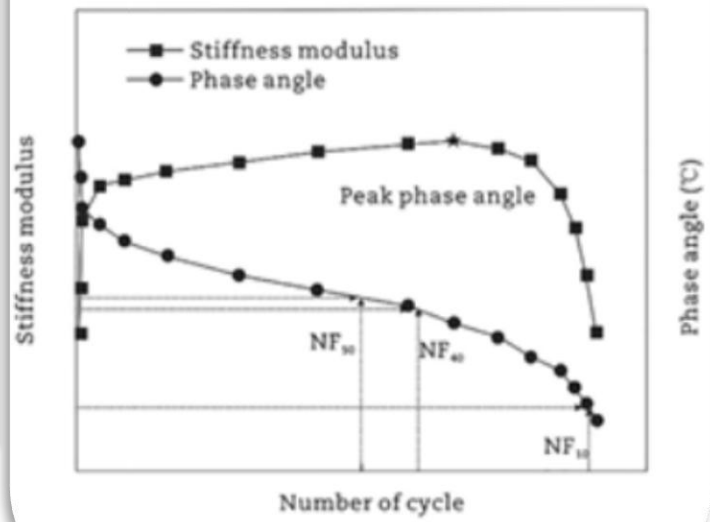


Fig. 15. Traditional approach in fatigue analysis.



Fonte:

Fatigue behaviours of asphalt mixture at different temperatures in four-point bending and indirect tensile fatigue tests

Huailei Cheng [a,b], Jianing Liu [c], Lijun Sun [a,*], Liping Liu [a], Yining Zhang [a]

CURVA DE FADIGA: PERDA DE RIGIDEZ MODELAGEM

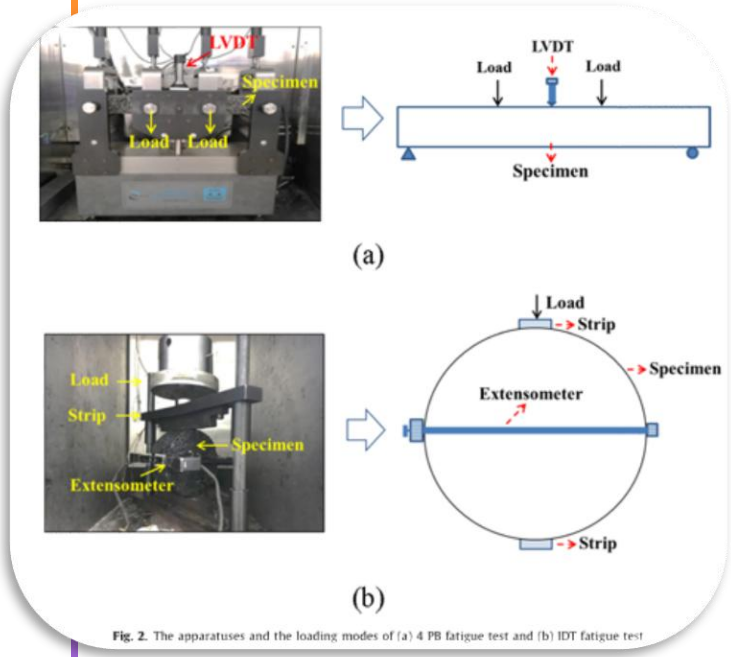


Fig. 2. The apparatuses and the loading modes of (a) 4 PB fatigue test and (b) IDT fatigue test

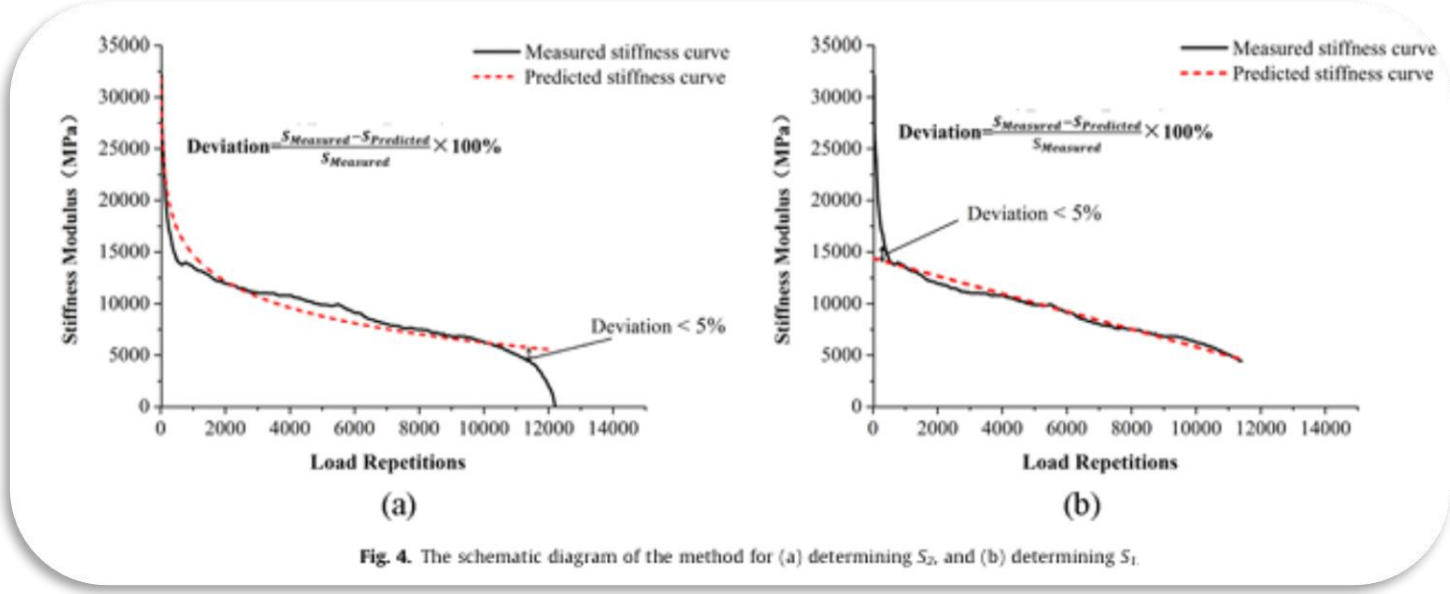


Fig. 4. The schematic diagram of the method for (a) determining S_2, and (b) determining S_1

$$S = a^{*}\ln(N) + b$$

$$S = S_0\left\{1 - e^{-\left(\frac{n}{\alpha}\right)^{\beta}}\right\}$$

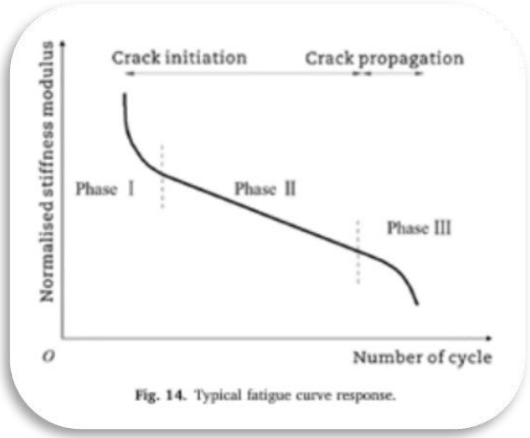


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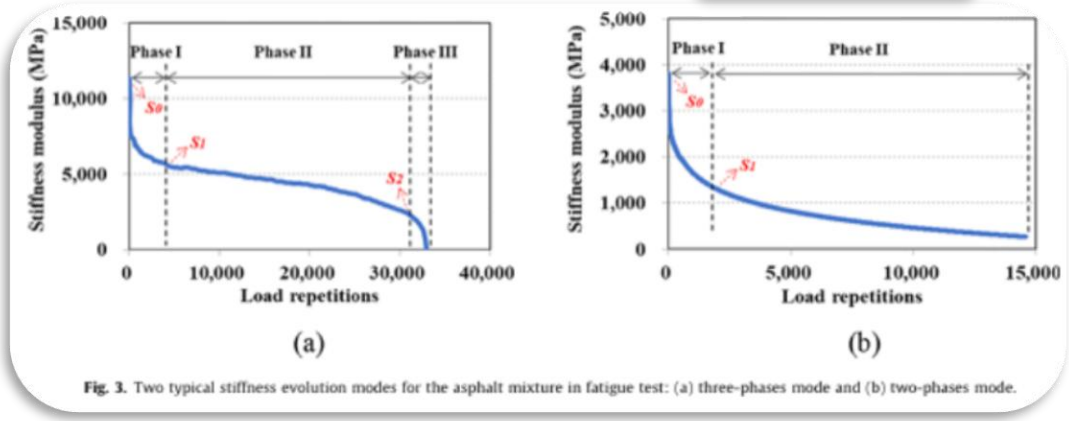


Fig. 3. Two typical stiffness evolution modes for the asphalt mixture in fatigue test: (a) three-phases mode and (b) two-phases mode.

Fonte:



Fatigue behaviours of asphalt mixture at different temperatures in four-point bending and indirect tensile fatigue tests

Huailei Cheng [a,b], Jianing Liu [c], Lijun Sun [a,*], Liping Liu [a], Yining Zhang [a]

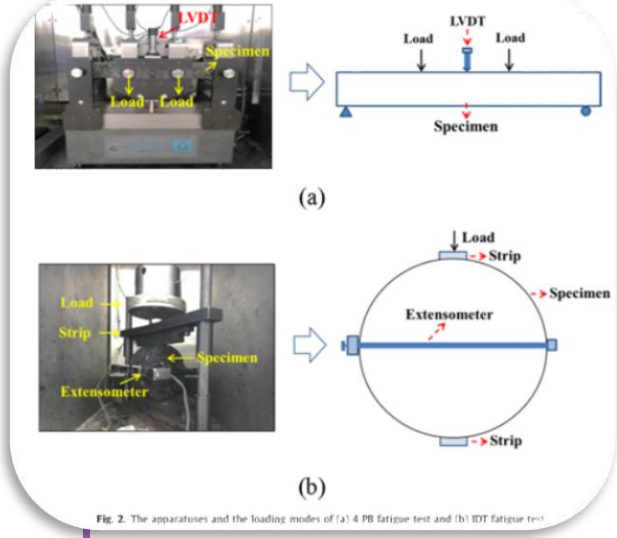


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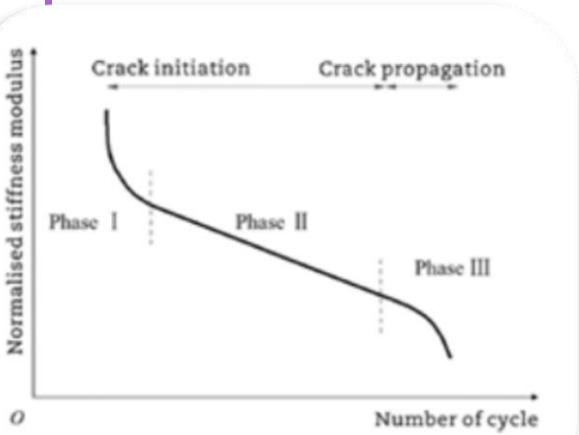


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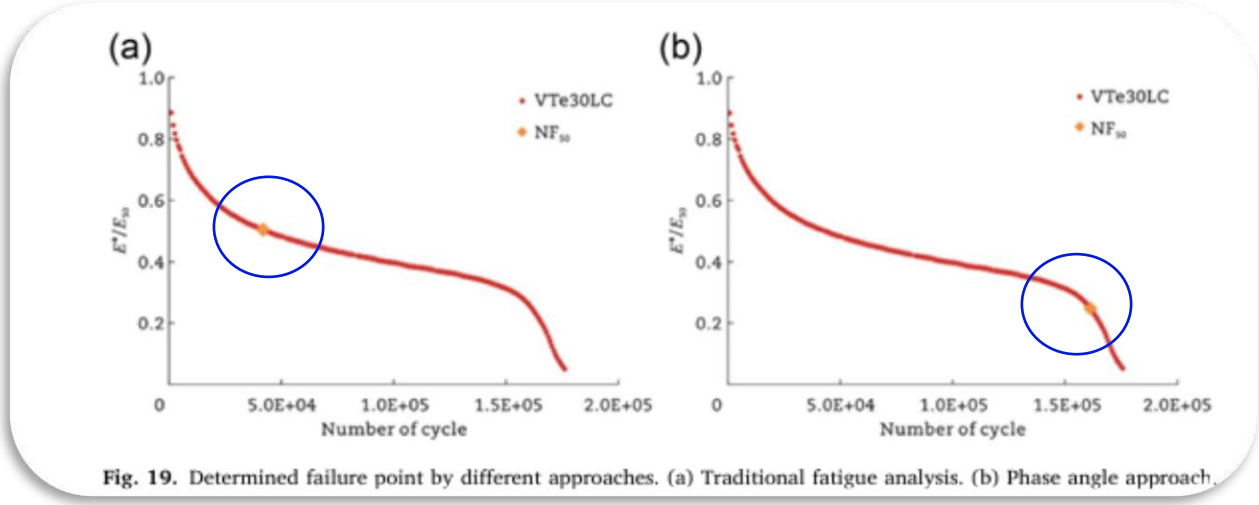


Fig. 19. Determined failure point by different approaches. (a) Traditional fatigue analysis. (b) Phase angle approach.

TEMP & FREQUÊNCIA CONSTANTE

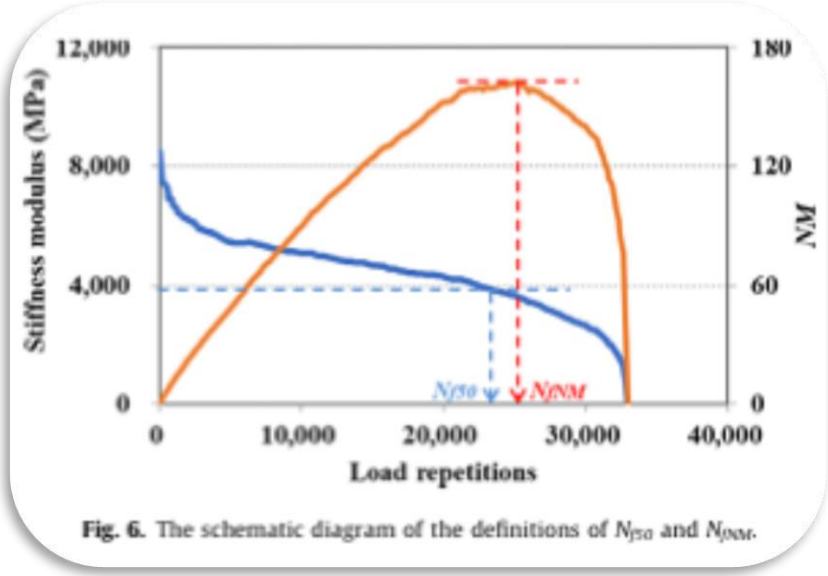


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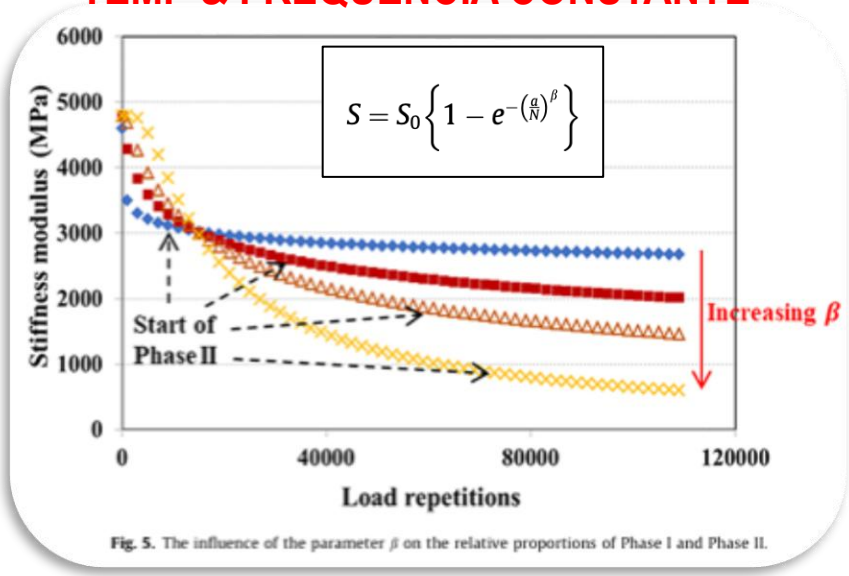


Fig. 5. The influence of the parameter β on the relative proportions of Phase I and Phase II.

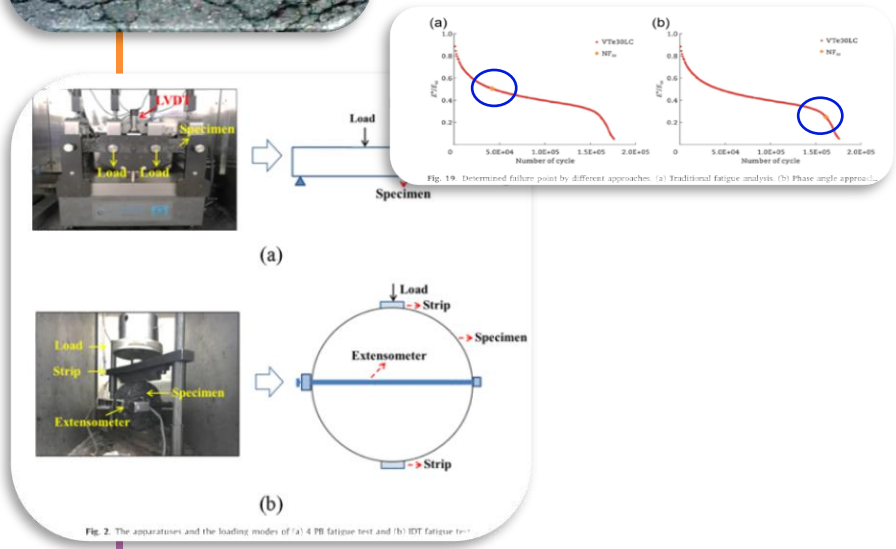


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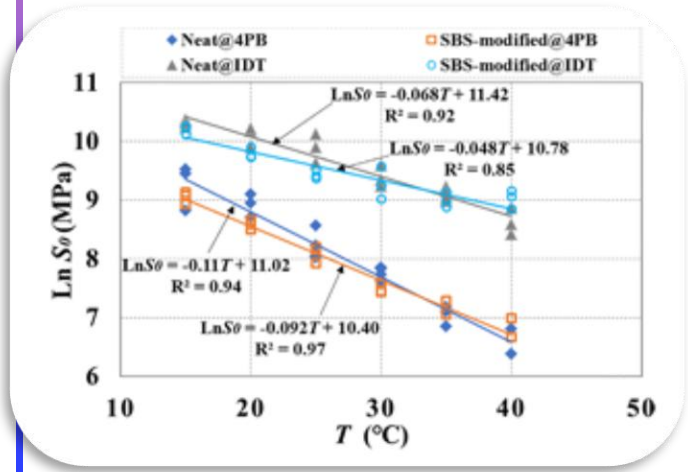
INFLUÊNCIA DA TEMPERATURA ??

Fatigue behaviours of asphalt mixture at different temperatures in four-point bending and indirect tensile fatigue tests

Huailei Cheng [a,b], Jianing Liu [c], Lijun Sun [a,*], Liping Liu [a], Yining Zhang [a]



DIFERENÇAS DE Mr 4P & IDT ?



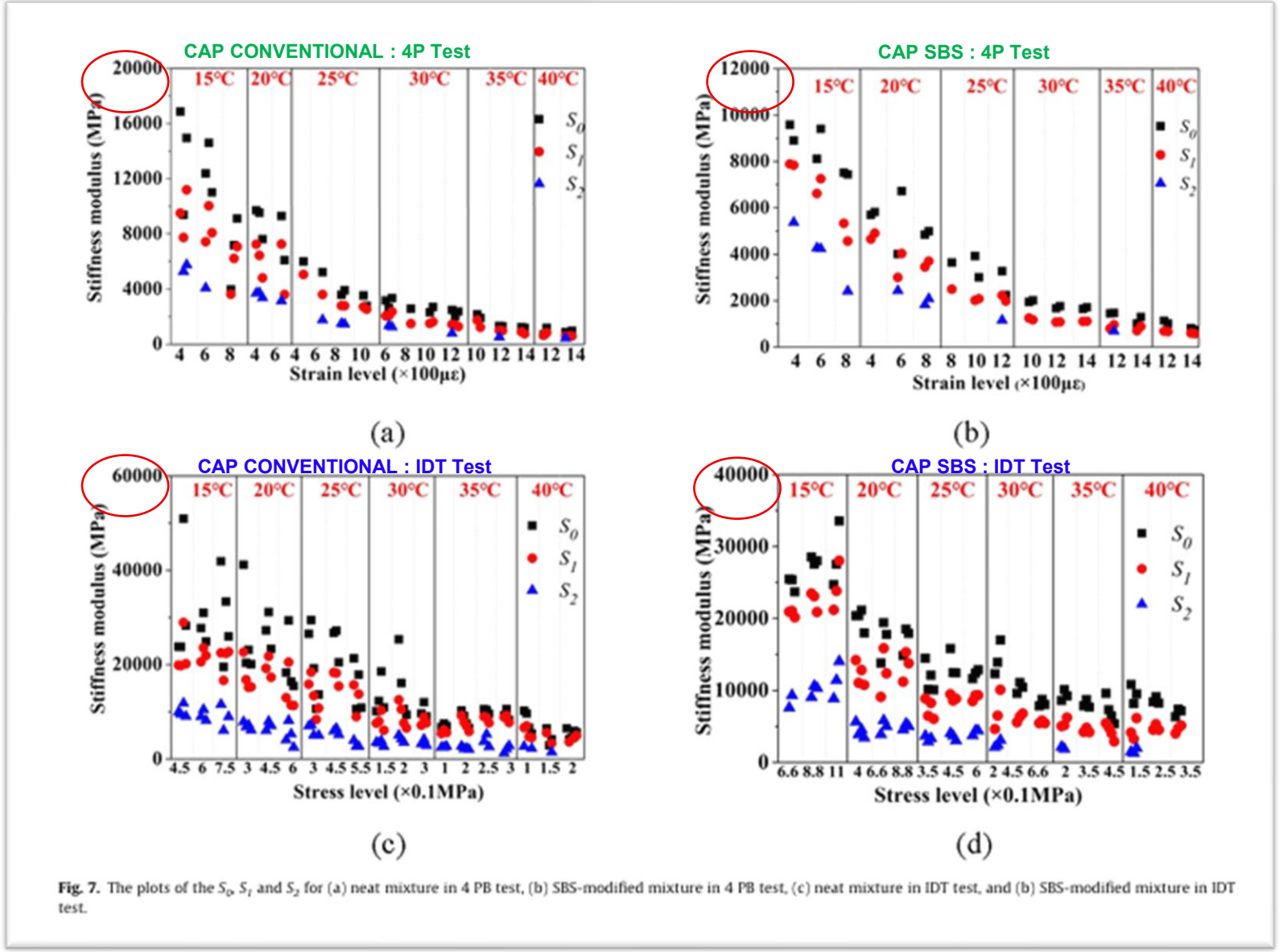


Fig. 7. The plots of the S_0, S_1 and S_2 for (a) neat mixture in 4 PB test, (b) SBS-modified mixture in 4 PB test, (c) neat mixture in IDT test, and (b) SBS-modified mixture in IDT test.

USO DA VIGA DE 4 PONTOS NOS ULTIMOS ANOS !

Fonte:

Review and prospect of four-point bending fatigue test of asphalt mixture

Yongjun Meng [a,b,c,d,*], Dichao Liu [a], Hongliu Rong [a], Xiaolong Yang [a]





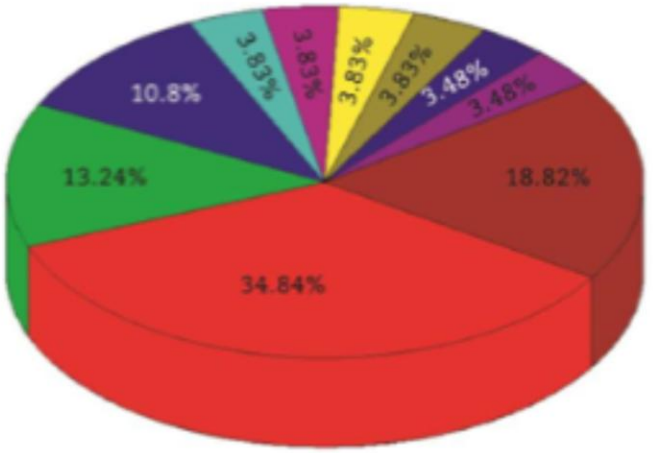


Fig. 26. Country distribution.

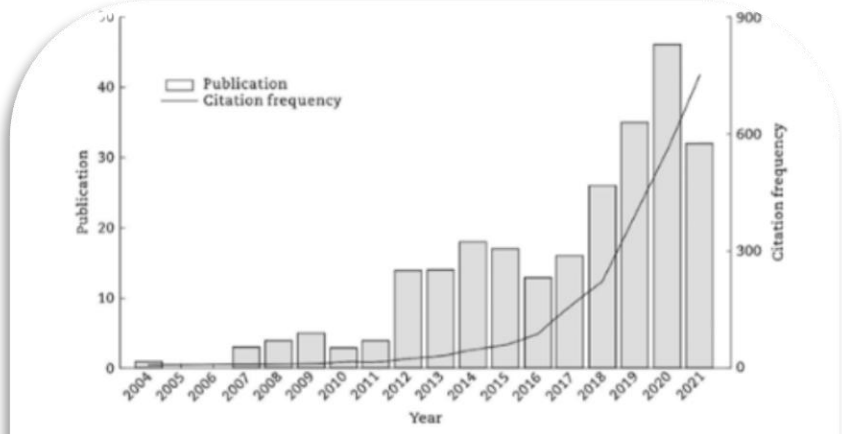


Fig. 22. Relevant publications and cited frequency of four-point bending test of asphalt mixture from 2004 to 2021.

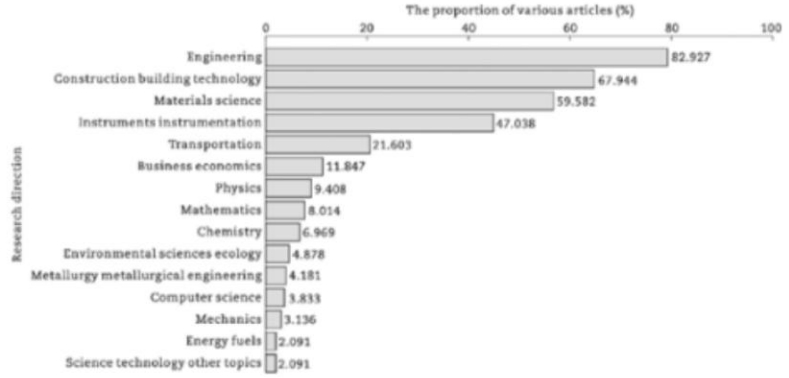
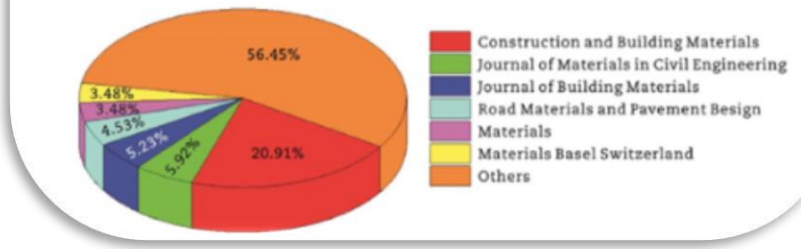


Fig. 23. Analysis of relevant research directions of asphalt mixture four-point bending test.



S-VECD - Simplified Viscoelastic Continuum Damage
Dano Contínuo Viscoelástico Simplificado







RIGIDEZ & CICLOS DE CARGA

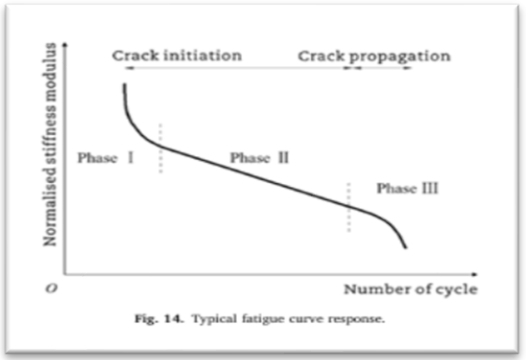
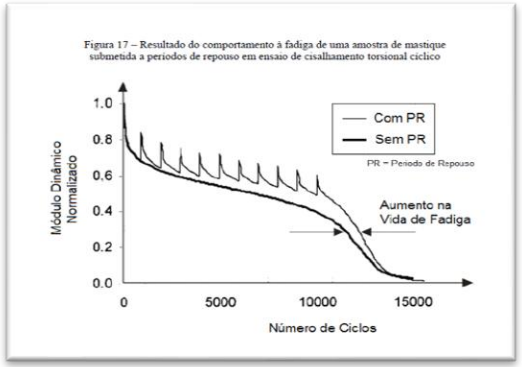


Fig. 14. Typical fatigue curve response.

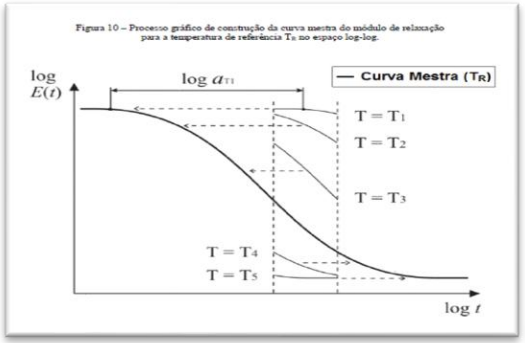
RIGIDEZ & CICLOS DE CARGA/DESCANSO

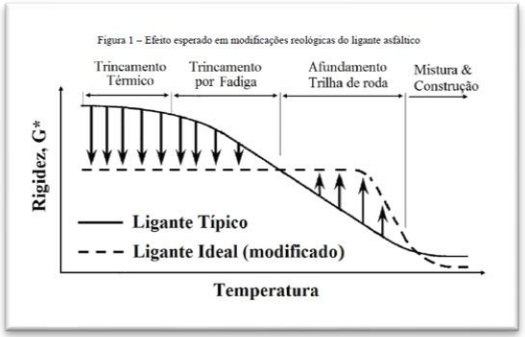
Self Healing !



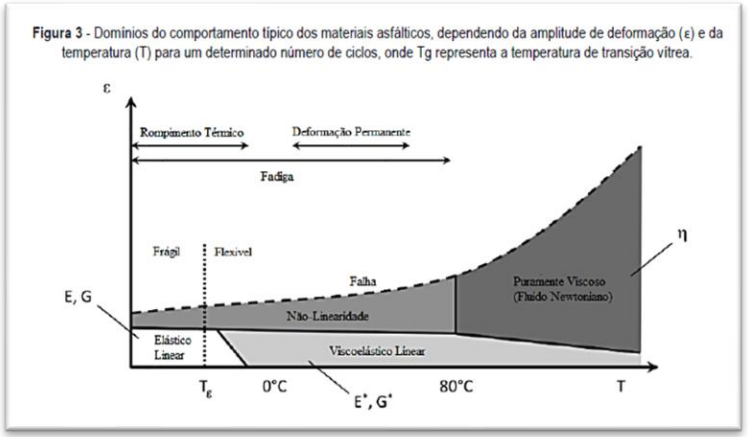


RIGIDEZ & TEMPERATURA





Fonte: Pivetta F. C. 2018



TEMPERATURA CONSTANTE: MESMA FREQUENCIA???

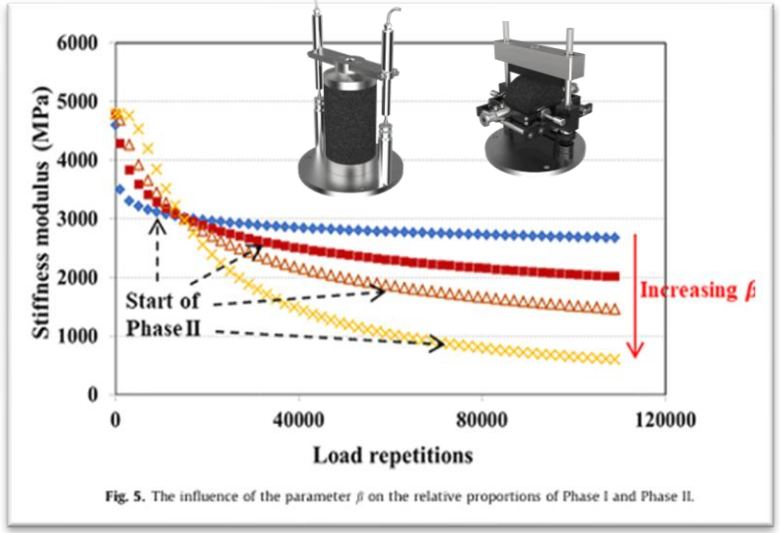


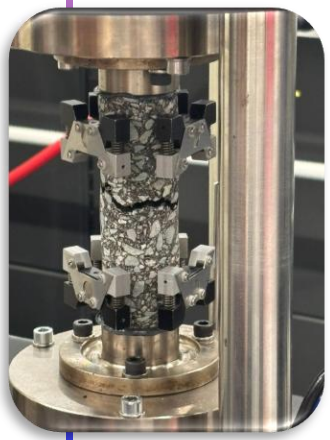
Fig. 5. The influence of the parameter β on the relative proportions of Phase I and Phase II.

COMPORTAMENTO MECÂNICO DE MISTURAS ASFÁLTICAS

S-VECD Simplified Viscoelastic Continuum Damage
Dano Contínuo Viscoelástico Simplificado







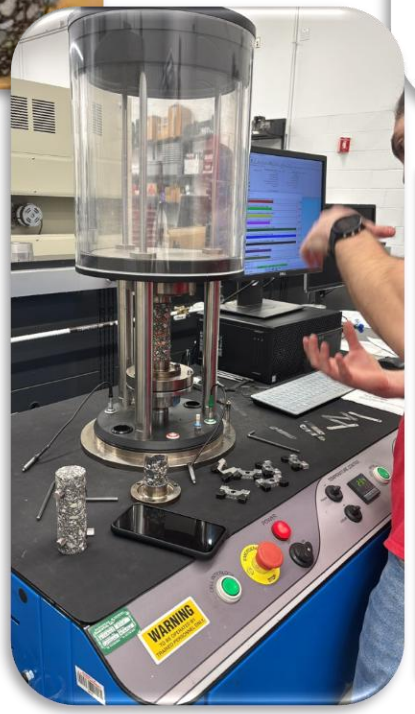
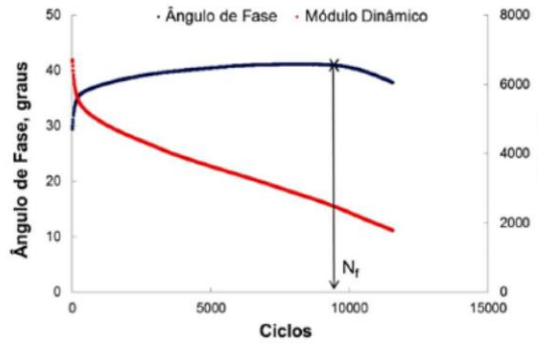
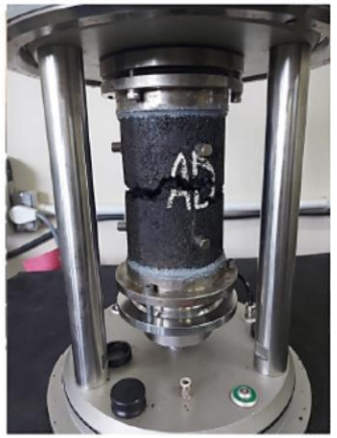


Figura 41 - Queda do ângulo de fase durante o ensaio de fadiga à tração direta (a) (NASCIMENTO *et al.*, 2014) e verificação da localização da macrotrinca (b)



S-VECD

(a)



(b)



Fonte:
RITA FLÁVIA RÉGIS QUEIROZ, 2022

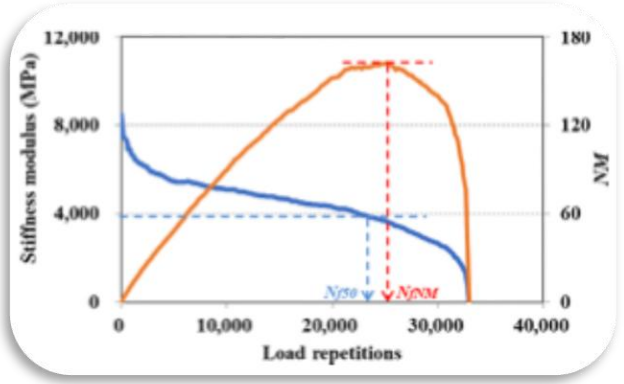


Figura 53 - Curvas mestras das misturas asfálticas estudadas na temperatura de referência de 20ºC, em escala semi-log

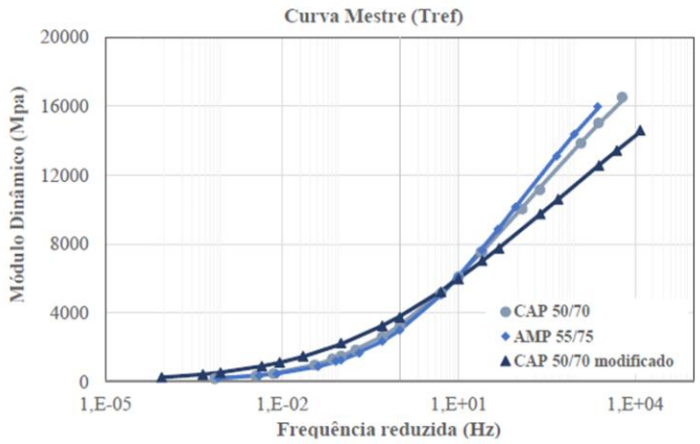
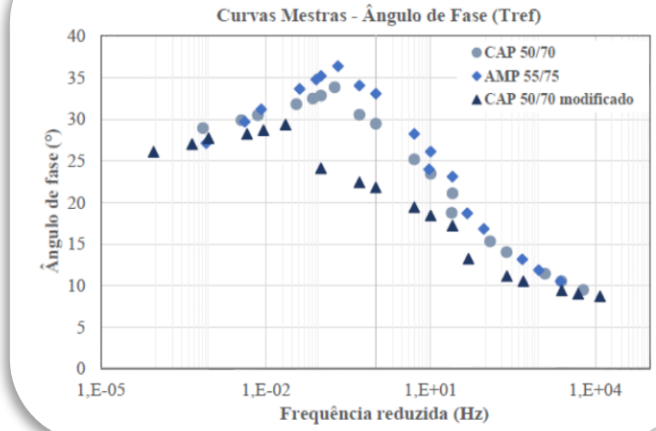


Figura 54 - Curvas mestras dos ângulos de fase para as misturas estudadas



COMPORTAMENTO MECÂNICO DE MISTURAS ASFÁLTICAS

S-VECD (Simplified Viscoelastic Continuum Damage - Dano Contínuo Viscoelástico Simplificado)

Fonte: Fatigue test setups and analysis methods for asphalt mixture: A state-of-the-art review

Huailei Cheng [a,b], Lijun Sun [a,*], Yuhong Wang [b], Liping Liu [a,**], Xingyu Chen [b]

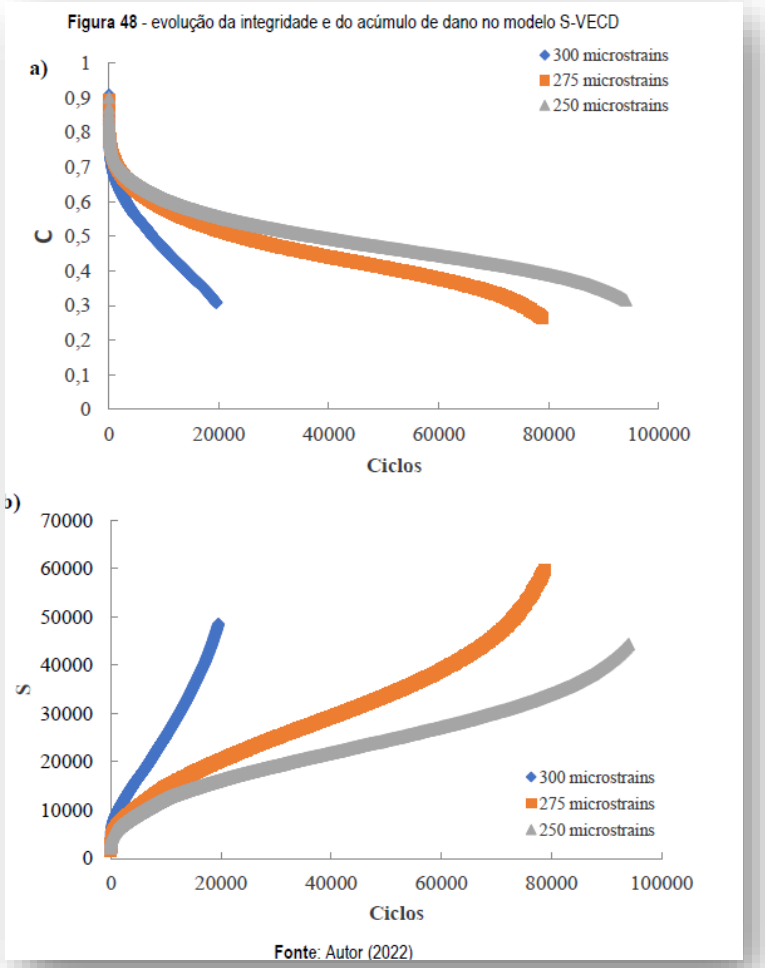




Quadro 2 – Resumo das implicações do princípio da correspondência elástico-viscoelástico e da teoria do trabalho potencial no equacionamento de materiais viscoelásticos com e sem dano

	Material Elástico	Material Viscoelástico
Sem Dano	$\sigma = E\varepsilon$	$\sigma = E_R\varepsilon^R$
Com Dano	$\sigma = C(S)\varepsilon$	$\sigma = C(S)\varepsilon^R$

Figura 48 - evolução da integridade e do acúmulo de dano no modelo S-VECD



Fonte: Autor (2022)

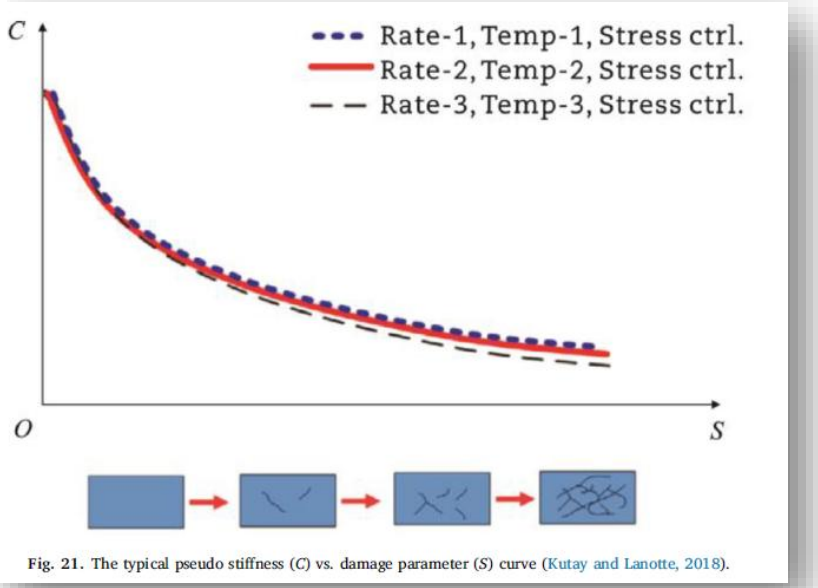
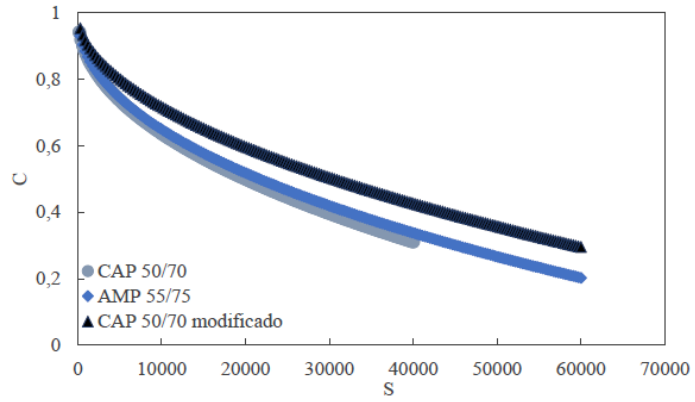


Fig. 21. The typical pseudo stiffness (*C*) vs. damage parameter (*S*) curve (Kutay and Lanotte, 2018).

Figura 60 - Curvas características de dano ajustadas de todas as misturas estudadas para a temperatura de 25ºC



Onde:
Pseudostiffness ou integridade = Pseudo rigidez = C
Acúmulo do dano = S

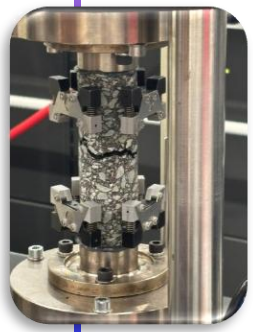
Fonte:
RITA FLÁVIA RÉGIS QUEIROZ, 2022

COMPORTAMENTO MECÂNICO DE MISTURAS ASFÁLTICAS

S-VECD (Simplified Viscoelastic Continuum Damage - Dano Contínuo Viscoelástico Simplificado





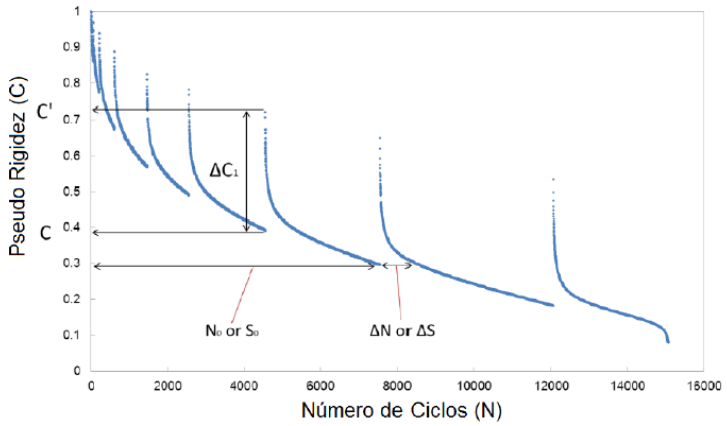




Considerando Self Healing

56

Figura 21 – Resultado da aplicação de períodos de repouso em mistura asfáltica representados no espaço C *vs* N para fins de avaliação de *healing*



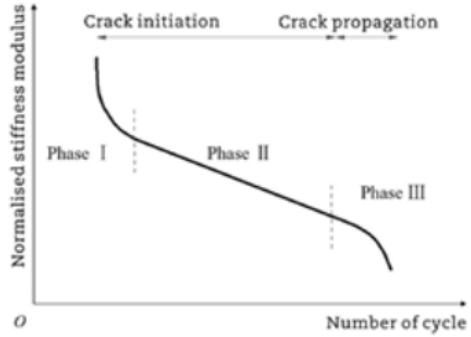


Fig. 14. Typical fatigue curve response.

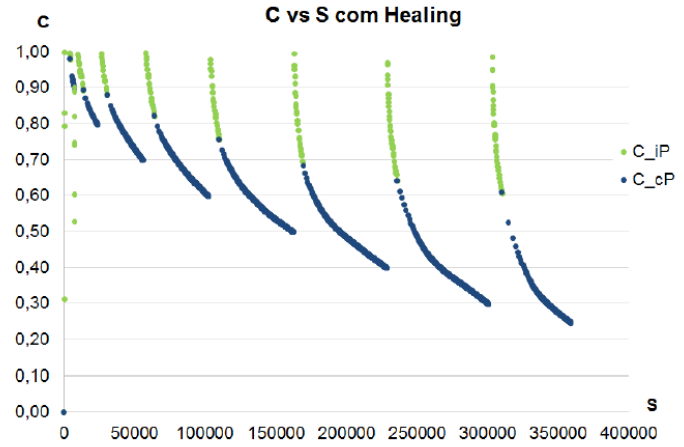
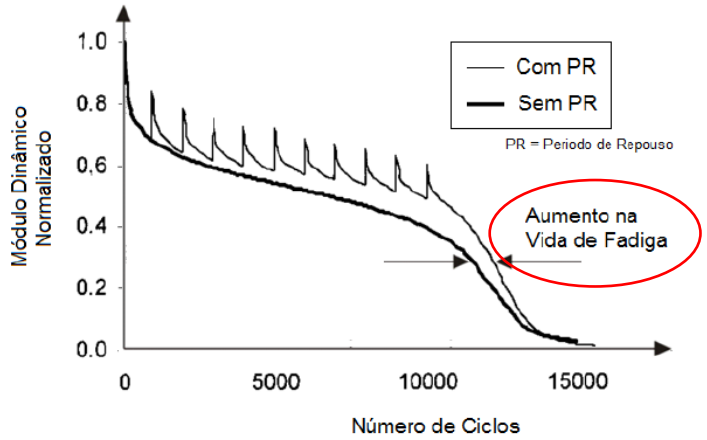


Figura 17 – Resultado do comportamento à fadiga de uma amostra de mastique submetida a períodos de repouso em ensaio de cisalhamento torsional cíclico



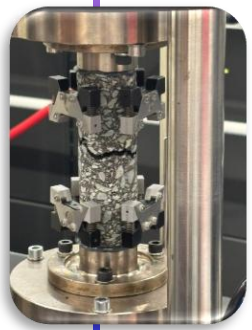
Pivetta F. C. 2018

COMPORTAMENTO MECÂNICO DE MISTURAS ASFÁLTICAS

S-VECD (Simplified Viscoelastic Continuum Damage - Dano Contínuo Viscoelástico Simplificado



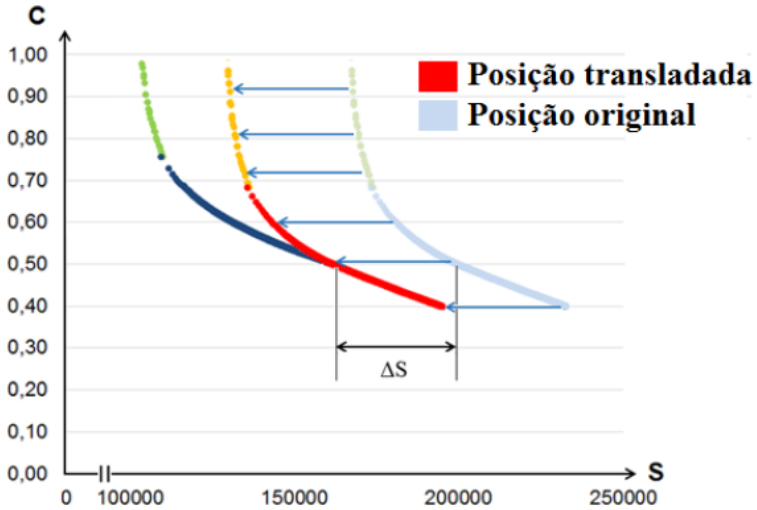






Considerando self realing

Figura 36 – Exemplo de deslocamento de trecho da curva de dano característico com regeneração.



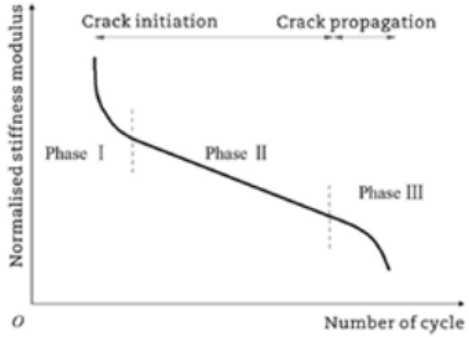
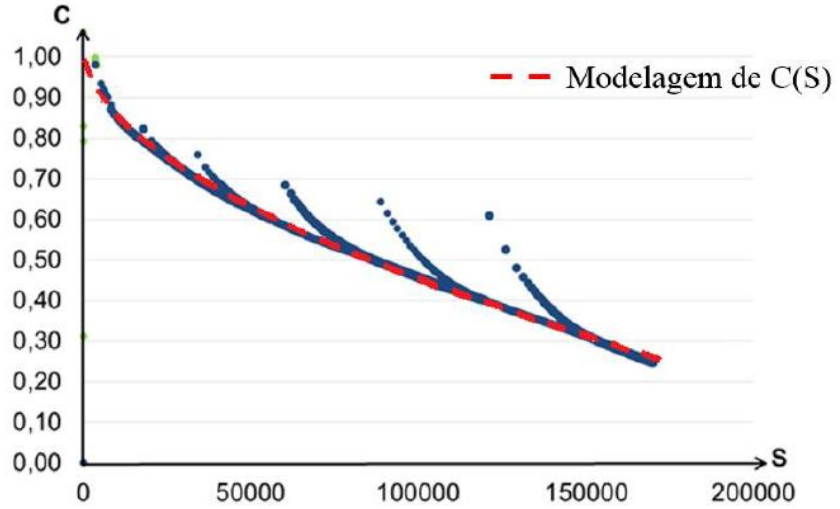


Fig. 14. Typical fatigue curve response.

Figura 37 – Curva C *vs* S com períodos de repouso após translação.



Pivetta F. C. 2018

COMPORTAMENTO MECÂNICO DE MISTURAS ASFÁLTICAS

S-VECD (Simplified Viscoelastic Continuum Damage - Dano Contínuo Viscoelástico Simplificado

Considerando self realing : Tempos de descanso variados !!





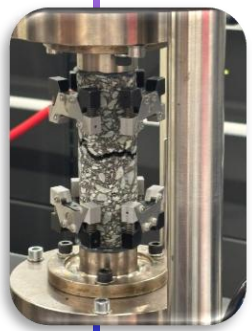
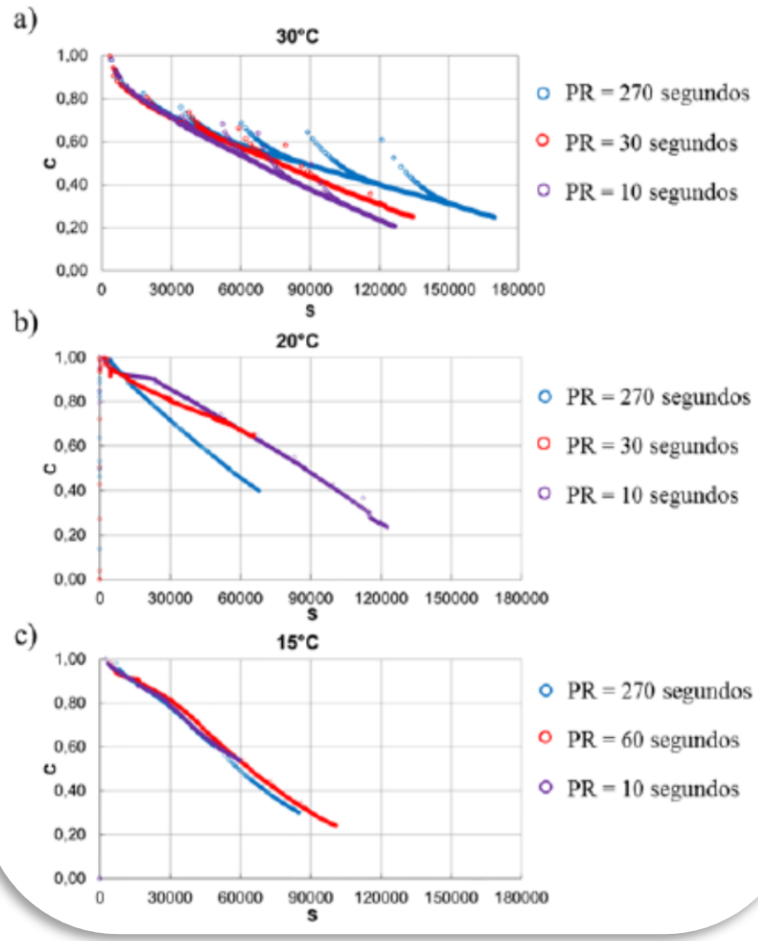




Figura 43 – Resultados de ensaio de curvas características de dano deslocadas a partir de variações de dano - mistura 10148.
a) Períodos de Repouso de 270, 30 e 10 segundos em 30° C;
b) Períodos de Repouso de 270, 30 e 10 segundos em 20° C;
c) Períodos de Repouso de 270, 60 e 10 segundos em 15° C.



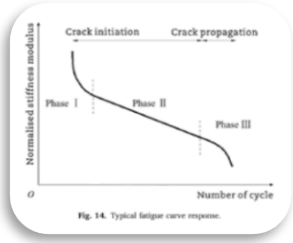
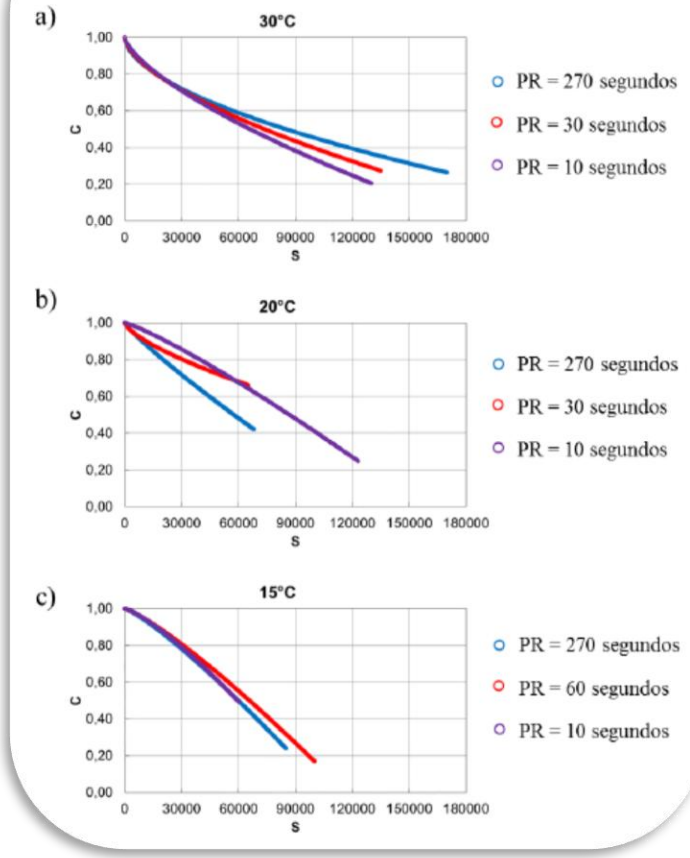


Fig. 14. Typical fatigue curve response.

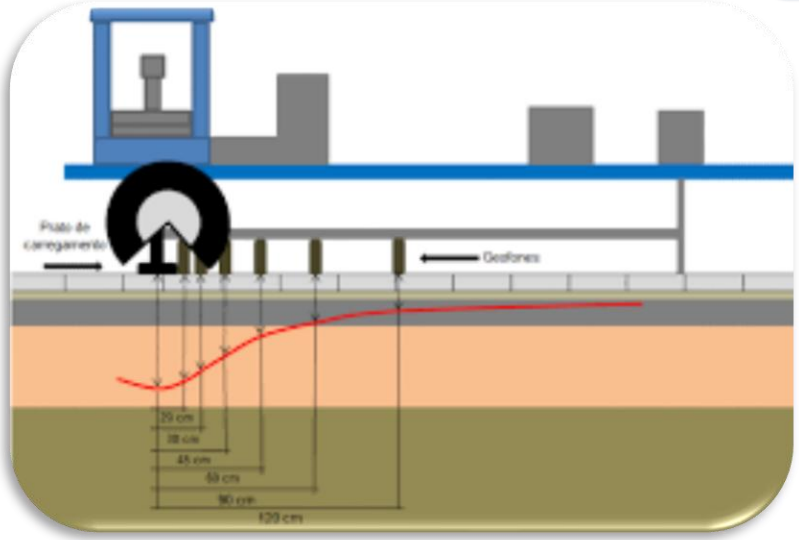
Fonte: Pivetta F. C. 2018

Figura 46 – Resultados da modelagem das curvas características de dano deslocadas - mistura 10148. a) Períodos de Repouso de 270, 30 e 10 segundos em 30° C;
b) Períodos de Repouso de 270, 30 e 10 segundos em 20° C;
c) Períodos de Repouso de 270, 60 e 10 segundos em 15° C.



AEROPORTO : PISTA DE POUSO E DECOLAGEM

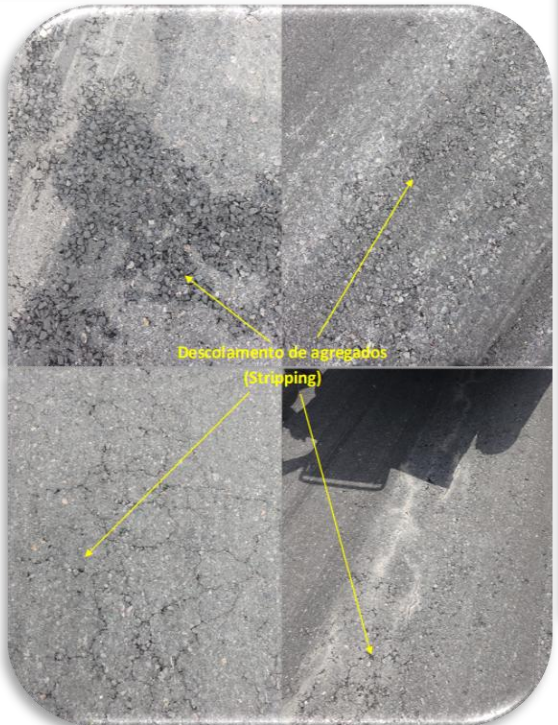
ESTUDO DE CASO: BR-230

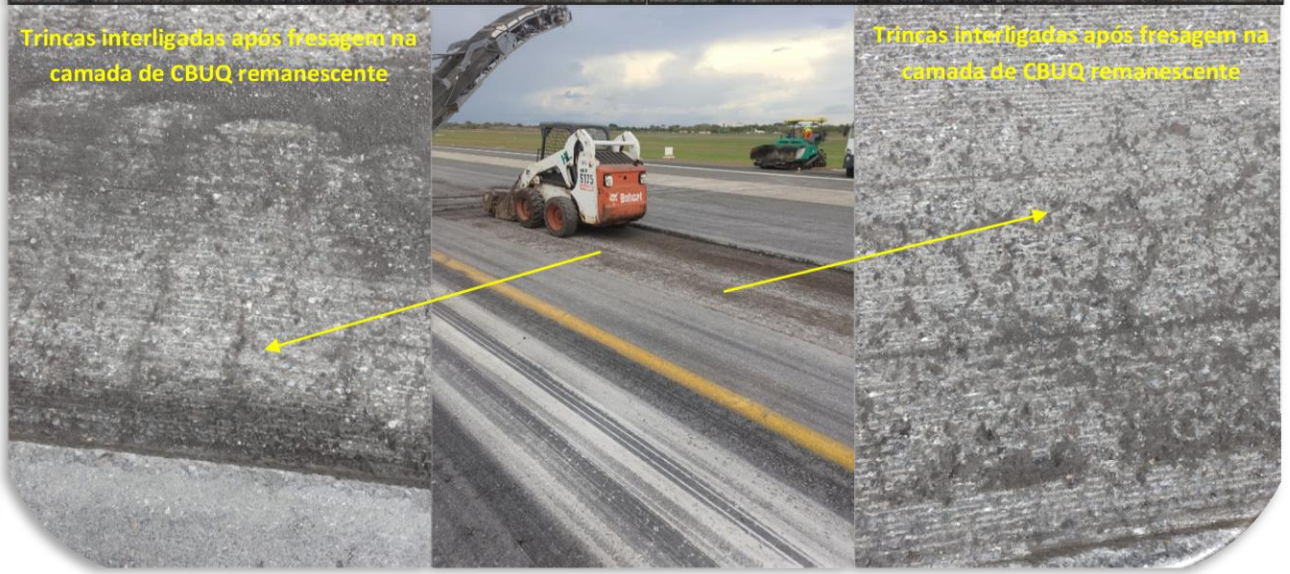






CBUQ: SBS
BASE: BGS





AEROPORTO : PISTA DE POUSO E DECOLAGEM

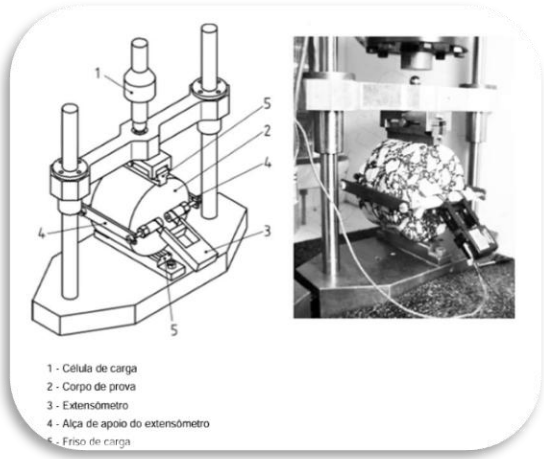
ESTUDO DE CASO: BR-230

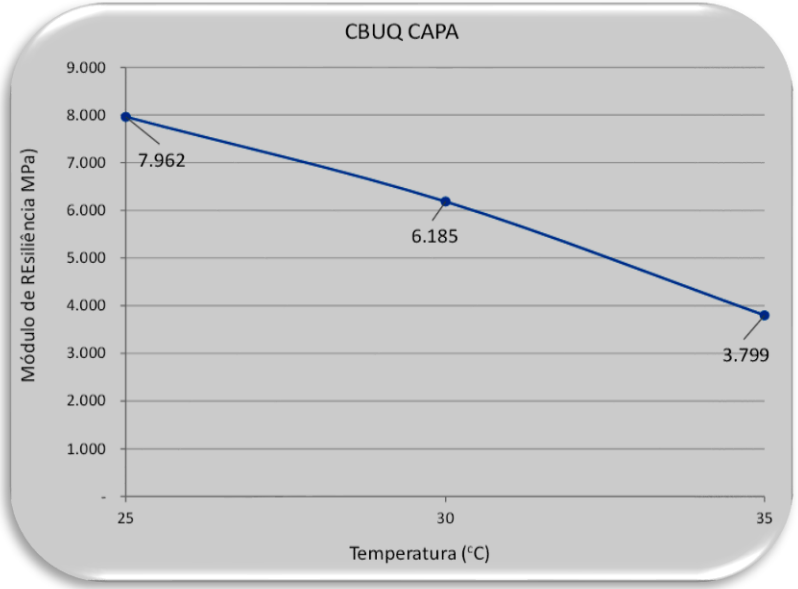












Fadigas : Classe 4 – Nascimento (2015)

RESULTADOS DE ENSAIO DE FADIGA

Quadro 09 – Resultados do ensaio de Fadiga

Amostra	Espessura (cm)	Diâmetro (cm)	Nível de Tensão Aproximado (%)	Carga aplicada (N)	Módulo Resiliente Inicial	Deformação Específica Resiliente	Diferença de Tensões (MPa)	Número de Aplicações
CP3B	6,75	10,06	25	1920	3126	0,0000576	0,7	1201362
CP9B	6,39	10,08	25	1821	4686	0,0000384	0,7	1652378
CP7B	8,20	10,09	25	2339	3156	0,0000570	0,7	844476
CP12B	7,34	10,06	30	2505	3182	0,0000679	0,9	600478
CP2B	6,25	10,05	30	2131	3041	0,0000710	0,9	539418
CP24B	6,05	10,09	30	2071	4763	0,0000453	0,9	742599
CP18B	5,98	10,05	35	2379	4259	0,0000592	1,0	246786
CP30B	5,15	10,10	35	2059	3612	0,0000698	1,0	145446
CP22B	6,20	10,03	35	2462	2806	0,0000898	1,0	112776
CP25B	6,34	10,07	40	2888	3887	0,0000741	1,2	85481
CP14B	5,31	10,09	40	2424	3429	0,0000840	1,2	93271
CP21B	5,60	10,06	40	2549	2725	0,0001057	1,2	73226

Figura 13 – Vida de Fadiga *versus* Diferença de Tensões

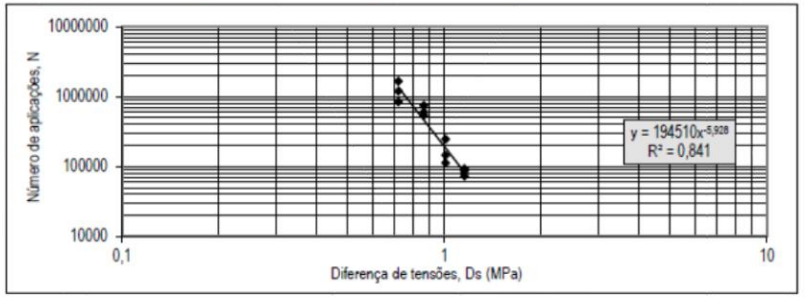
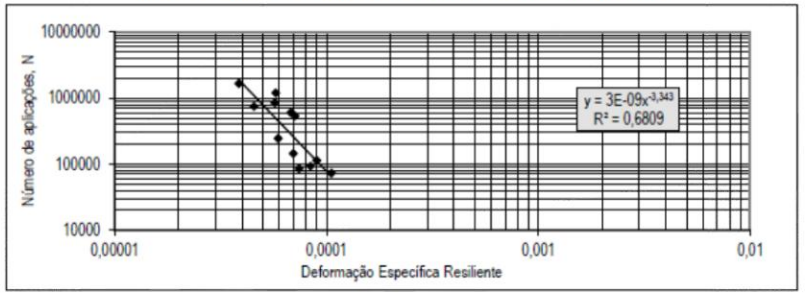


Figura 14 – Vida de Fadiga *versus* Deformação Específica Resiliente



ESTUDO DE CASO: BR-230 João Pessoa - PB

REVESTIMENTO COM 36 ANOS DE USO !!!!







AMOSTRA EXTRAÍDA



IDT



CPs - PRISMÁTICOS EXTRAÍDOS



4PB





Ensaio	Resultado
Extração de ligante	4,85%
Granulometria	-
Volume de Vazios	2,7%
Resistência à Tração	0,71 MPa
Módulo de Resiliência	2956 MPa

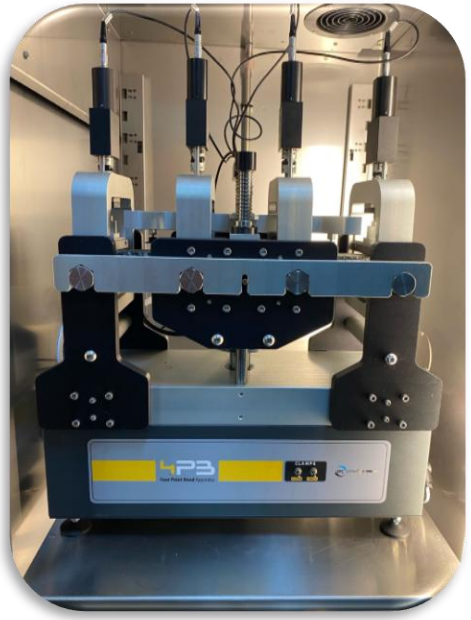
CAP 50/70



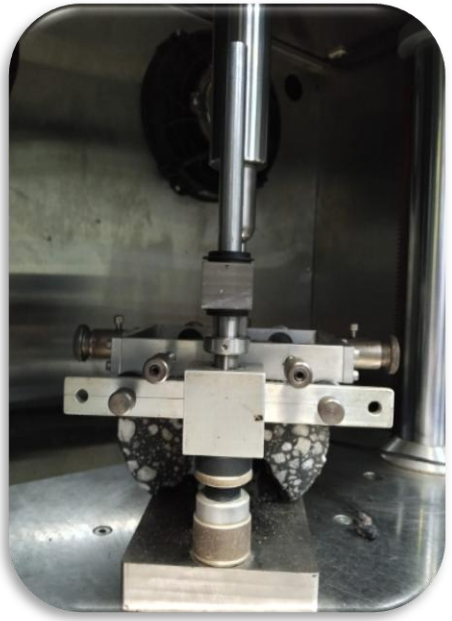
ESTUDO DE CASO: BR-230 – Resultados

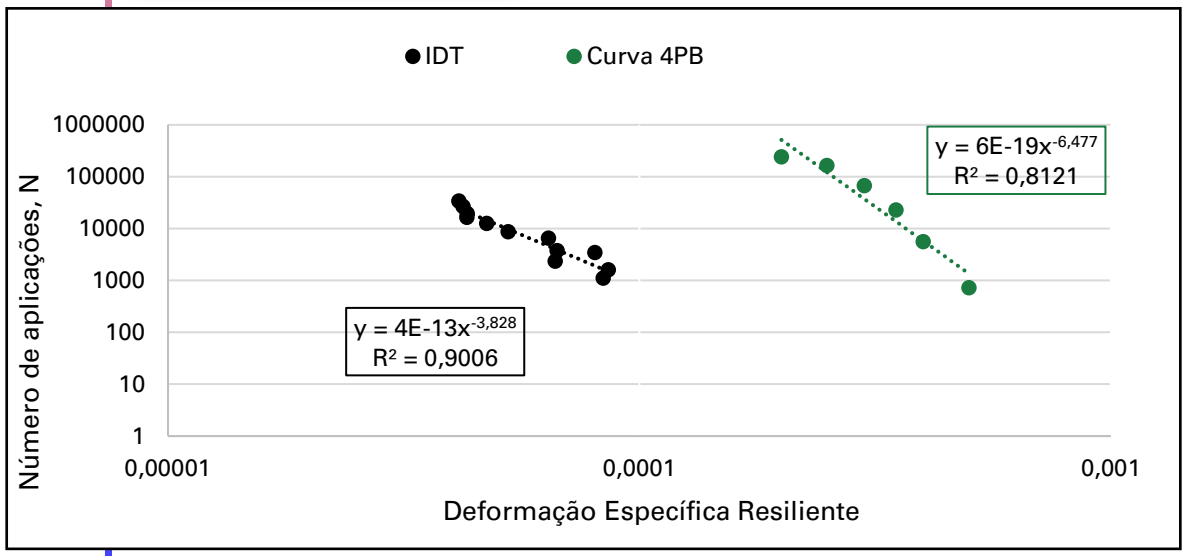
Revestimento com 36 anos de uso !!!!

4 P



IDT



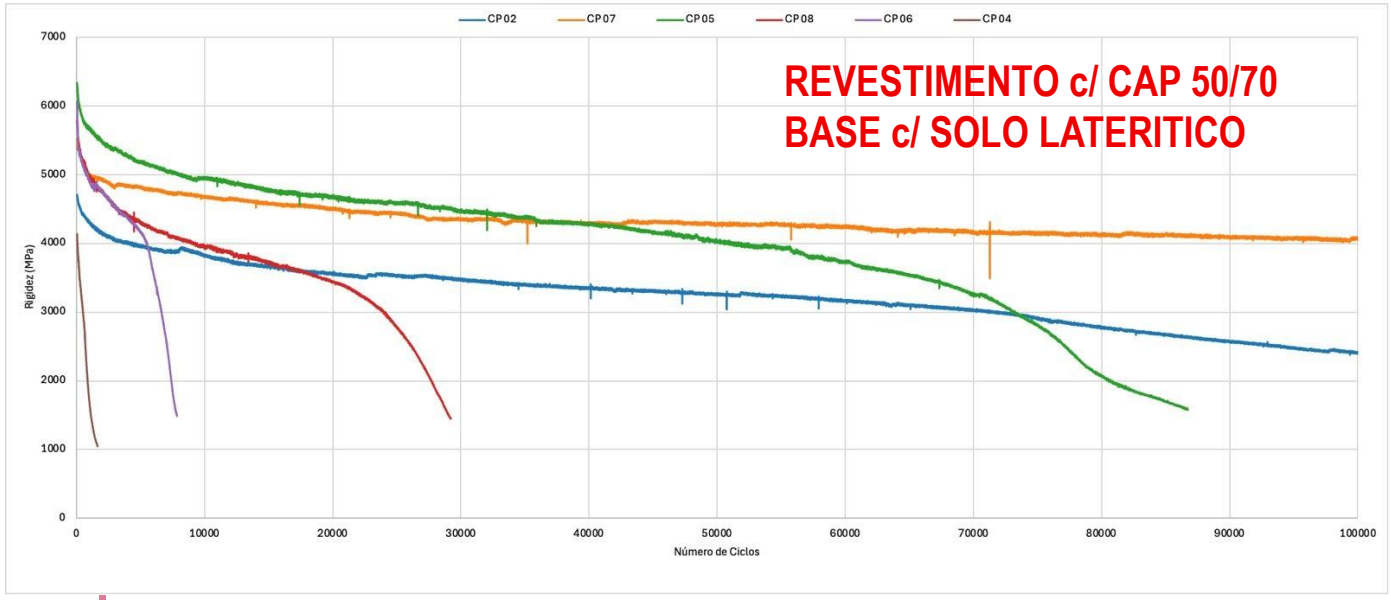


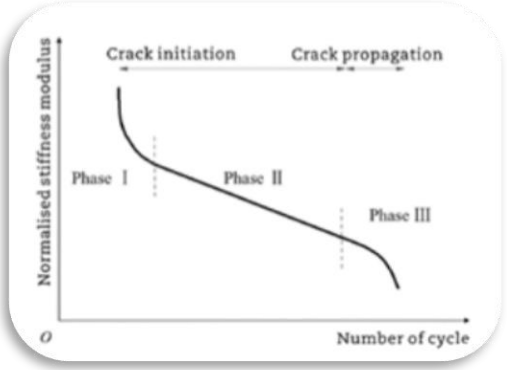
CURVA DE FADIGA

FFM e Classe de Fadiga IDT

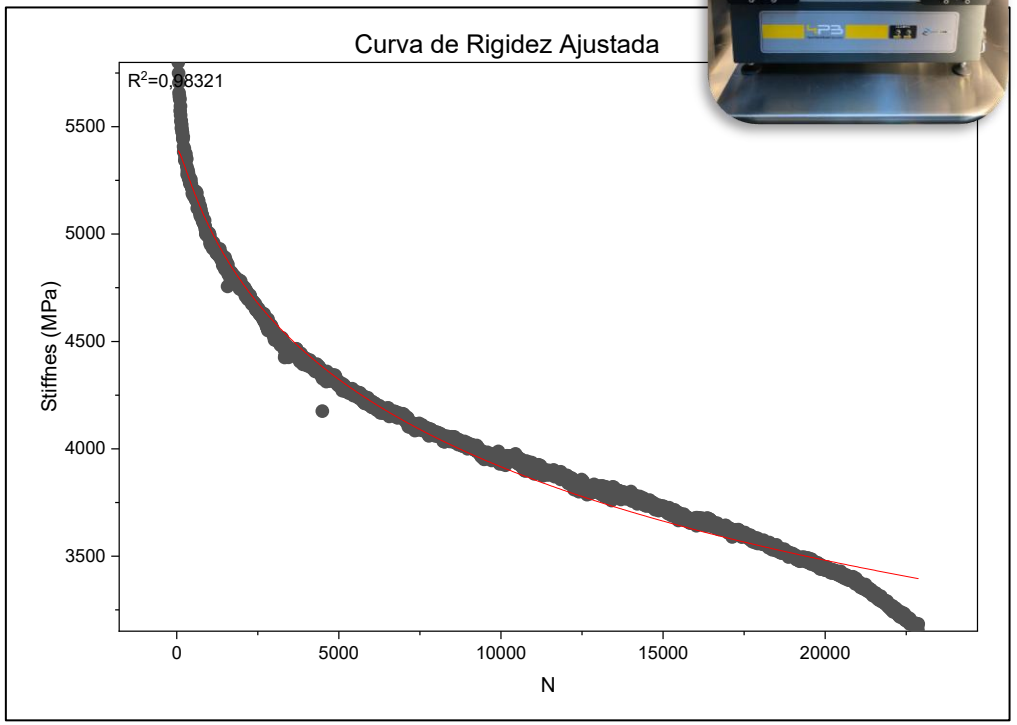
FFM	0,86
Classe	0

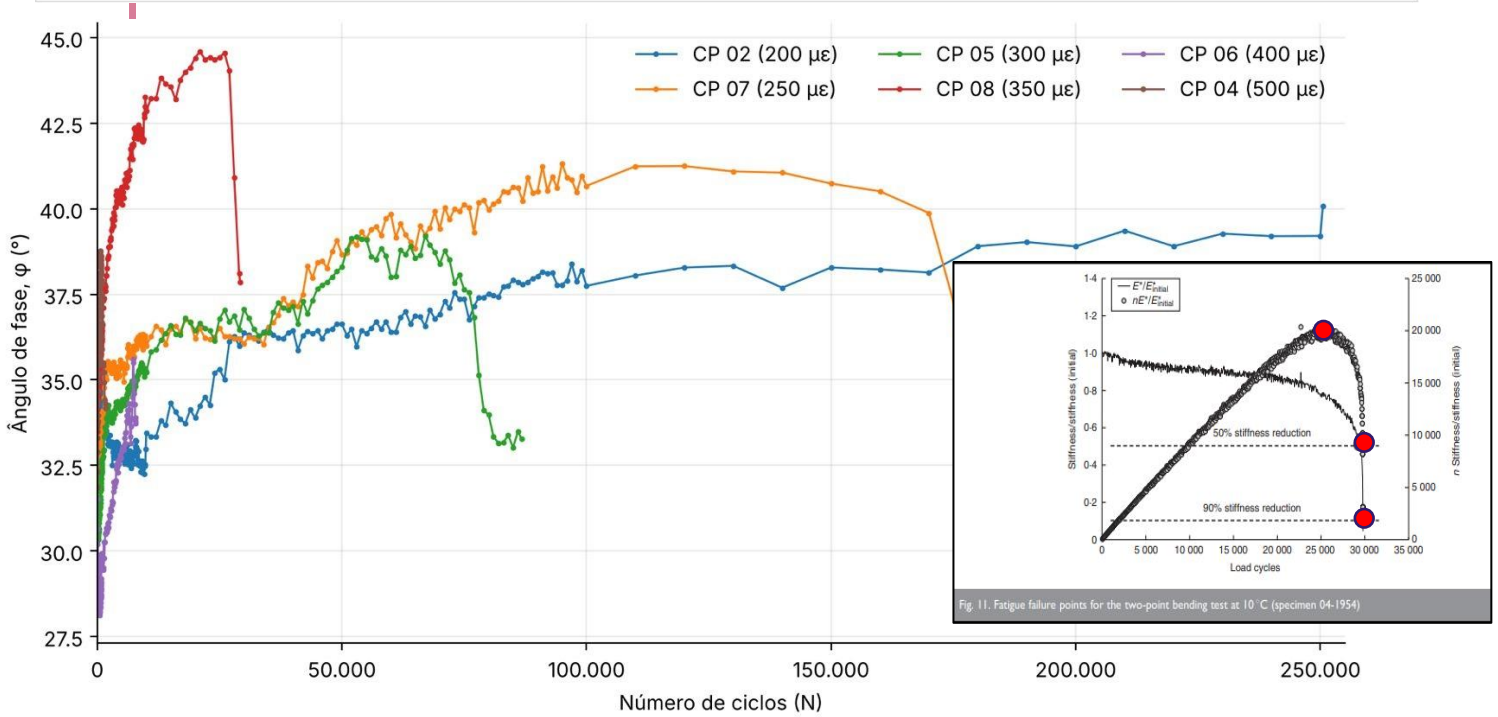
ESTUDO DE CASO: BR-230 – Resultados







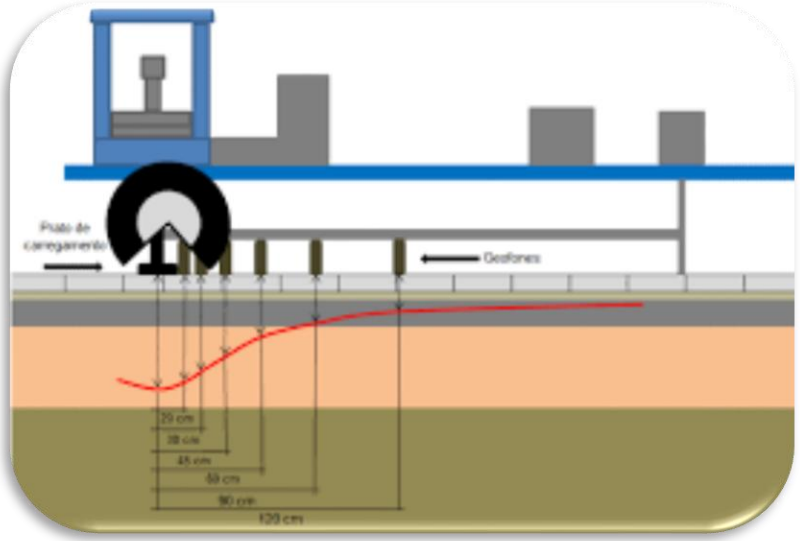


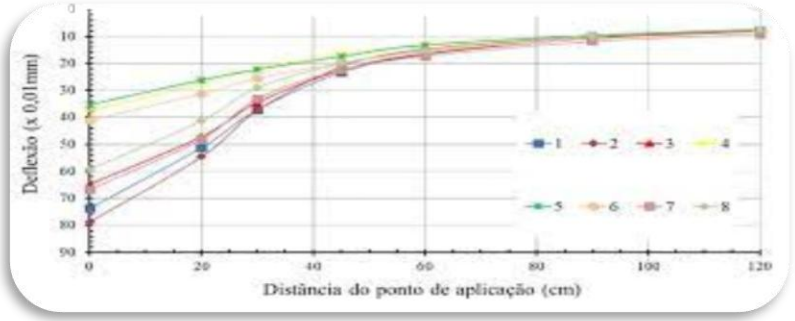


Perda de Rigidez & Número de aplicações

COMPATIBILIDADE DE RIGIDEZ ENTRE CAMADAS !
Níveis de Deflexão & Fases de Vida de Fadiga

“Bacia de deslocamento & vida útil”

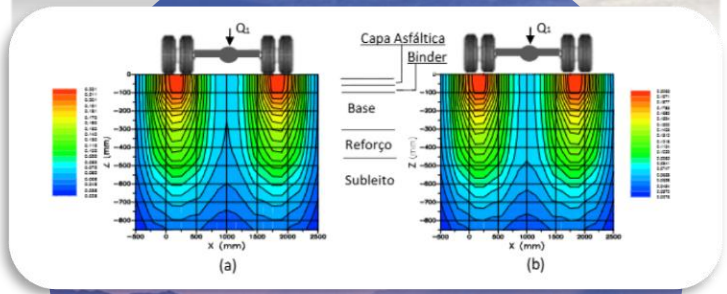












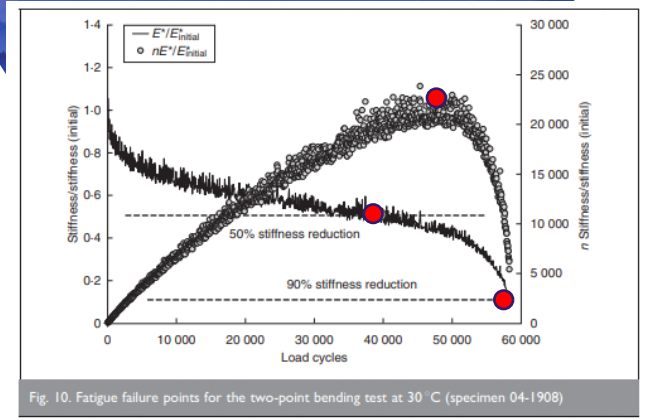
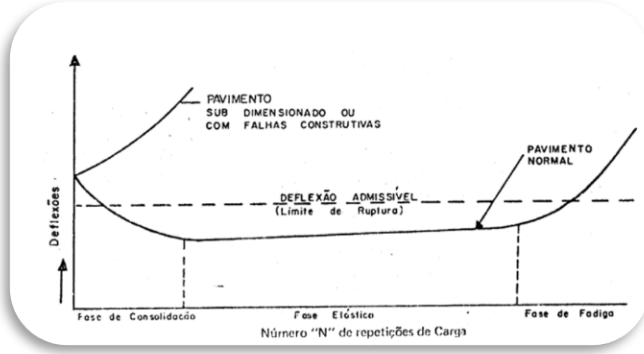
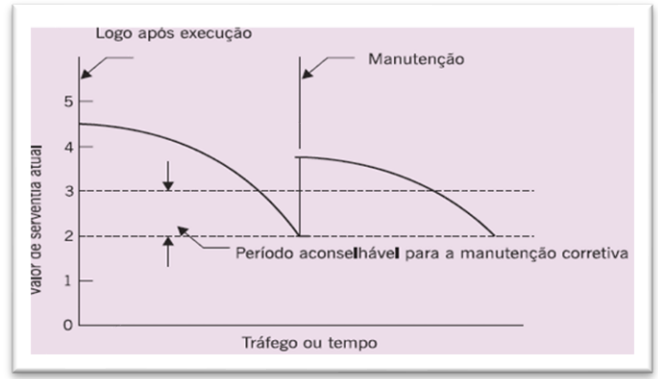


Fig. 10. Fatigue failure points for the two-point bending test at 30 °C (specimen 04-1908)



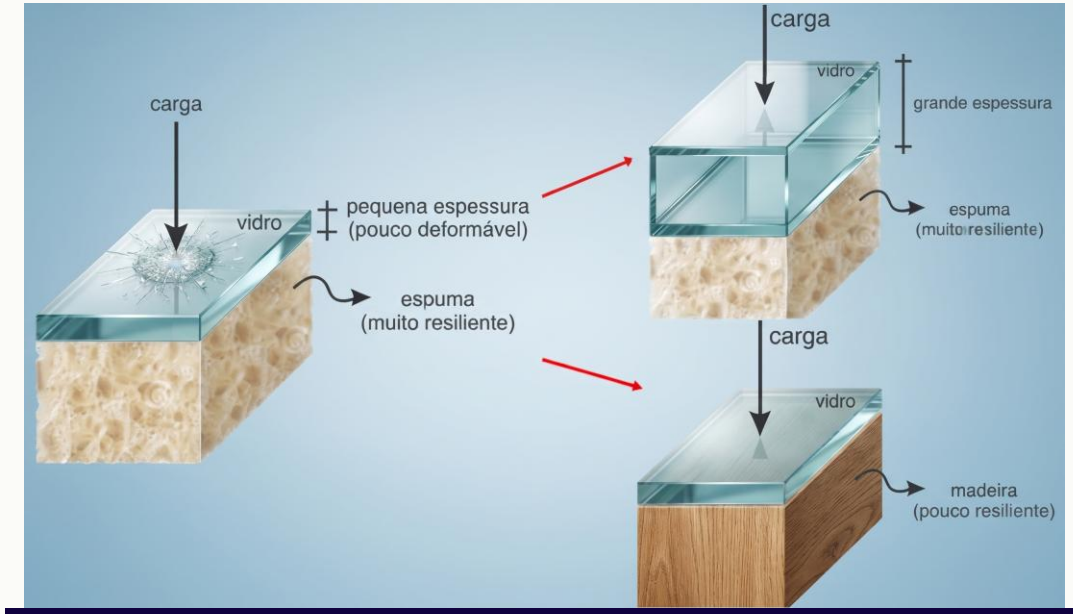




Índice de Serventia

A INVERSÃO

Mudar o alvo: controlar a entrada, não prever a saída!



AS DUAS ALAVANCAS DA COMPATIBILIZAÇÃO

A camada rígida só não trinca se a razão de rigidezes entre ela e o suporte for compatível com a solicitação

— ou espessa a camada rígida, ou enrijece o suporte —

PREDIÇÃO DE TRINCAMENTO

Carga → **Deformação** → **Lei lab** → **Shift factor** → **Dano** → **Área trincada**

Mesmo em passo mensal (MeDiNa, MEPDG), cada integração herda a dispersão do shift factor.

COMPATIBILIZAÇÃO DE RIGIDEZ

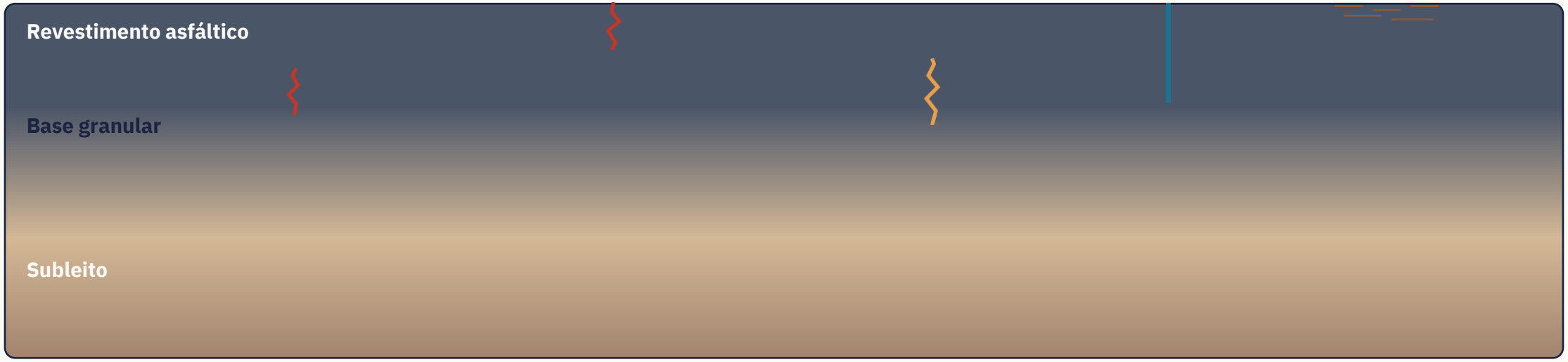
Carga → **Deformação** → **εt < endurance?**

Verificação geométrica no projeto. Sem shift factor.

A analogia pedagógica: o vidro só não se parte sobre a espuma se for grosso o suficiente (↑ h_1) ou se a espuma for substituída por madeira (↑ E_2, MR). O pavimento segue a mesma lógica.

A ONTOLOGIA DO FENÔMENO

"Trincamento" não é um fenômeno — é um estado terminal de cinco fenômenos



Bottom-up
Fadiga por flexão repetida da fibra inferior

Top-down
Tração em superfície sob rodas pesadas

Reflexão
Propagação de trinca de camada inferior

Térmica
Retração em climas frios ou gradiente diurno

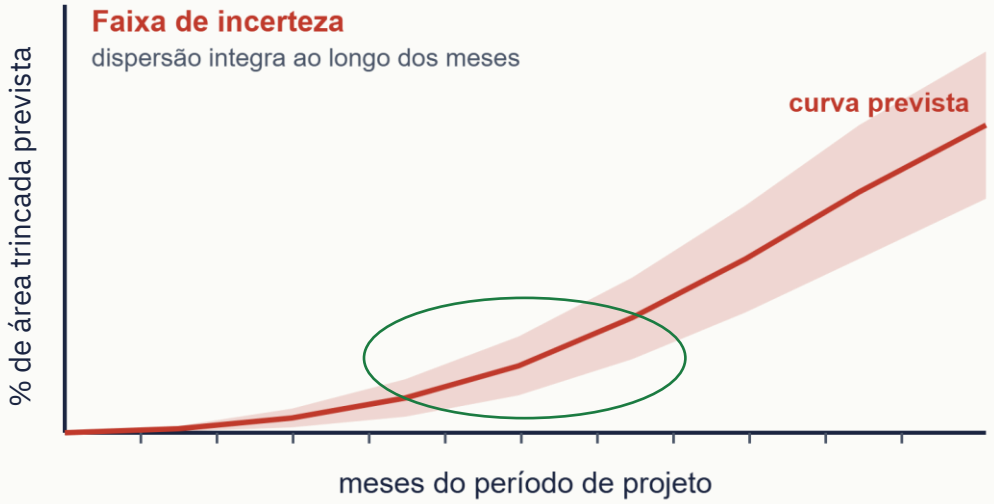
Envelhecimento
Oxidação do ligante, perda de coesão

Nenhuma função de transferência unificada captura cinco cinéticas com drivers independentes. Calibrar uma lei contra área observada confunde causas.

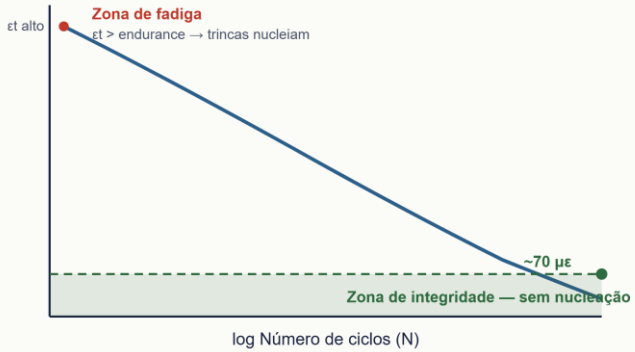
COMPATIBILIZAÇÃO DE RIGIDEZ ENTRE CAMADAS

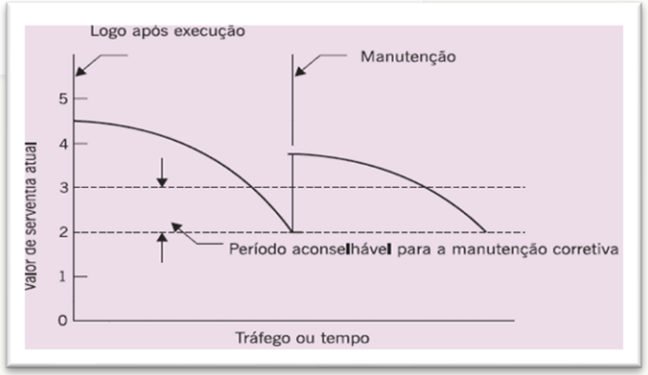
MeDiNa, FlexPAVE, MEPDG: computam dano por fadiga mês a mês acumulando por Miner — a saída é uma curva evolutiva de área trincada, não um número único no fim do período.

Considerações Finais !!!!









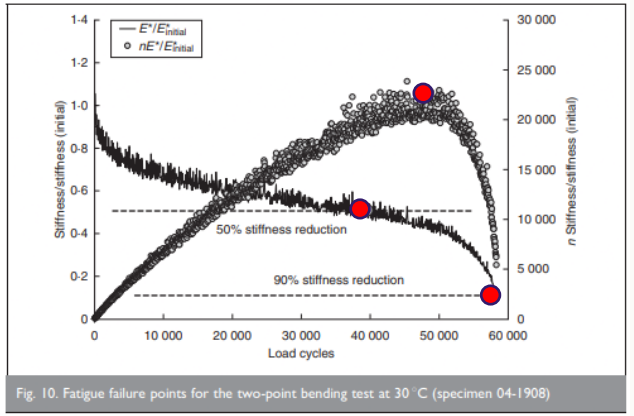


Fig. 10. Fatigue failure points for the two-point bending test at 30 °C (specimen 04-1908)

A compatibilização somando-se ao prognóstico paramétrico por uma indução de compatibilidade de rigidez sobre o campo de deformações — que não depende de integração temporal nem de calibração empírica.

OBRIGADO !



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PaveSym



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