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Dissipated Energy Analysis of Four-Point Bending Test on Asphalt Concretes made with Steel Slag and RAP

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Keywords: Asphalt concrete, Reclaimed Asphalt Pavement, steel slag, stiffness modulus, fatigue resistance, dissipated energy.

Abstract. The paper discusses the results of an experimental study and a statistical analysis on the stiffness and the fatigue performance of recycled asphalt concretes, evaluated by the four-point bending test, at 20°C and 10 Hz. The laboratory study was conducted on five different base-binder bituminous mixtures, made with recycled aggregates, namely Reclaimed Asphalt Pavement aggregate (RAP) and Electric Arc Furnace (EAF) steel slag, up to 70% by weight of the aggregate. In order to evaluate statistically the influence of the recycled aggregates on the stiffness of the mixes, the analysis of variance (ANOVA) has been performed on the modulus data. The fatigue tests were performed in stress and strain control mode, in order to describe completely the fatigue properties of the mixes. A dissipated energy method, based on the internal damage produced within the asphalt concretes, was used for the fatigue analysis. The damage curves, expressed in terms of the Plateau Value of the Ratio of Dissipated Energy Change, for both the stress and the strain control mode, were elaborated and statistically analyzed in order to unify the fatigue analysis. Compared to the control asphalt concrete, made exclusively with natural aggregate, the mixes with RAP and EAF slag resulted characterized by improved stiffness and fatigue performance.

1. Introduction.

Laboratory fatigue and stiffness investigations on bituminous mixtures for road pavements can be based on several type of tests: two-point bending tests on trapezoidal and prismatic specimens, three-and four-point bending tests on prismatic beam specimens, as well as repeated indirect tensile strength tests on cylindrical specimens, are some of the most used test protocols in the road laboratories, all over the world [1, 2, 3, 4, 5]. For each one of the above mentioned tests, two different loading modes can be adopted, namely based on controlled stress or controlled strain.

Using the conventional methodology in the fatigue analysis, based on the correlation between the initial strain values and the number of cycles to failure, as well as on the 50% reduction of the initial Stiffness of the mix, two different fatigue life evaluations can be obtained, according to the loading mode [6]. The stress control mode is commonly adopted in order to evaluate the fatigue resistance of stiff materials and thick pavements, while the strain control mode is used in case of conventional bituminous mixtures and flexible pavings [7]. However a complete fatigue analysis should provide a unique value of the fatigue resistance, irrespective of the loading mode, in order to effectively support the rational design of a road pavement. In the present experimental and theoretical study, the fatigue resistance of high performance asphalt concretes for base courses of road pavement, produced using artificial and recycled aggregates (EN 13242 and 13043), was evaluated by means of both the "stress control" and "strain control" four-point bending test (4PBT), following the methodology originally proposed by Carpenter [8, 9] for the analysis of the laboratory data, in order to identify a unique fatigue law, irrespective of the loading mode.

The stiffness properties have been also determined, according to EN 12697-26 Standard, Annex B and statistically analyzed by means of the ANOVA method. The stiffness modulus represents a fundamental mechanical parameter which expresses synthetically the structural properties of a bituminous mix. It is determined by means of non-destructive tests and it is very useful in order to perform statistical evaluations about the effect of one or more components in the mechanical response of the mix [10].

2. Materials and Methods.

2.1 Materials.

2.1.1 Aggregates and bitumen. For the aggregate skeleton of the asphalt concretes, three granular materials have been considered: Reclaimed Asphalt Pavement (RAP) aggregate, steel slags, as well as conventional aggregates, i.e. crushed limestone and sand. The RAP materials have been recovered from the milling of an Italian highway pavement, in the North-eastern part of Italy. The steel slags considered represent a production waste of an Italian steel industry, characterized by the electric arc furnace (EAF) technology. Both the by-products were supplied by Italian private companies, based in the province of Padua (Northeastern area of Italy, Veneto Region), devoted to the recovery, valorisation and re-utilization of industrial wastes, for road pavements. Both the natural aggregates were provided by a local quarry located in the above-mentioned region.

The bitumen content of the RAP material, determined by cold extraction (centrifugation method; EN 12697-1) resulted equal to 4.3% by weight of the aggregate. The recovered binder presented a penetration of 15 0.1xmm at 25 °C (EN 1426) and a softening point of 74 °C (Ring & Ball Method; EN 1427). A standard bitumen (50/70 penetration grade), with a Ring & Ball softening point of 62°C (EN 1427), has been adopted as virgin binder for all the asphalt concretes in the investigation.

2.1.2 Asphalt concretes. The composition of the aggregate skeleton of the asphalt concretes is reported in Table 1. The corresponding grading curves are shown in Figures 1-2. Five non-conventional aggregate skeletons were studied, characterized by different combinations and contents of RAP, steel slag and limestone (S0R2, S0R4, S3R0, S3R2, S3R4: S0 and R0 mean no slag and no RAP; S3, 30% slag; R2 and R4, 20% and 40% RAP). One further asphalt concrete, made with a conventional lithic skeleton (S0R0) was studied and considered as a control mix.

Table 2 presents the design binder percentage (by weight of the granular material), bulk density, Indirect Tensile Strength (ITS), for the bituminous mixtures. The bitumen percentage reported in Table 2 concerns the virgin binder added to the asphalt concretes. For the asphalts made with RAP material, assuming a complete blending condition between the aged RAP bitumen and the virgin one, the total bitumen percentage is determined as the sum of the aged binder of RAP and the Optimum Bitumen Content (OBC). The virgin bitumen has been mixed simultaneously with the RAP, the limestone and the steel slags, in a heated lab mixer, for one minute. The RAP aggregates have been preheated for 2 hours, at 90°C, before to be mixed with the other materials.

A detailed discussion of the chemical, physical and geotechnical properties of all the granular materials, the mix design and some performance test results were previously presented by the authors [11, 12] in other papers.

2.2 Methods.

2.2.1 Stiffness Modulus tests. The Stiffness Modulus of the mixtures has been evaluated by means of Four Point Bending tests (4PBT), according to the Annex B of the European EN 12697-26 Standard, with a controlled strain equal to 50 μm/m, at a temperature of 20°C and frequency of 10Hz. A stand-alone four-point bending test apparatus, characterized by a digital servo-controlled pneumatic actuator with a 5 kN load cell capacity, has been used for the stiffness evaluation (Figure 3); the equipment was hosted in a dedicated climatic chamber. The beam specimens used for the 4PBT, were characterized by a size of 400 x 50 x 60 mm. They have been obtained by cutting 300 x 400 x 50 mm slabs, prepared using an electromechanical laboratory compactor, characterized by a vertical load and/or displacement control of the roller segment by a stepper motor, measured directly by a linear transducer (Figure 4), according to the EN 12697-33 Standard. The target bulk density was assumed equal to that of gyratory specimens involved in the mix design phase, outlined in previous works [11, 12]. Four beam specimens were prepared for each asphalt concrete.

In order to evaluate statistically the level of significance of the effect induced by the marginal aggregate on stiffness of the mixes, a multiple factors ANOVA has been applied [10, 13] to the modulus data, assuming a normal distribution. The RAP, as well as the steel slag quantities have been considered as factors (a and b, respectively) and their interaction was also analyzed. The response is the Stiffness Modulus.

2.2.2 Fatigue tests. The fatigue study was based on the four-point bending test, assuming as reference the protocol described in Annex D of the European EN 12697-24 Standard; therefore, the loading condition was based on a continuous sinusoidal waveform. The fatigue investigation was conducted at 20˚C and 10 Hz, using both strain and stress controlled tests. Different loading conditions were used: 1, 1.25, 1.5 MPa under controlled stress, whereas the strain amplitude was within the range from 200 to 500 μm/m for the strain control mode. The main test variables, namely stress, strain, phase angle and dissipated energy, were determined and recorded automatically by the testing apparatus, which was the same already used for the stiffness modulus tests. The beam specimens already fabricated for the stiffness evaluation, have been subsequently tested for the fatigue study.

The analysis of the fatigue data has been conducted by means of the dissipated energy method originally developed by Carpenter et al. [8, 9]. In such approach, the Plateau Value (PV) of the Ratio of Dissipated Energy Change (RDEC) is considered the main parameter for the fatigue evaluation of asphalt concretes. The RDEC is determined using the following expression:

$$RDEC = \frac{DE_{n+1} - DE_n}{DE_n} \quad (1)$$

where DE_n and DE_{n+1} represent the dissipated energy generated in the load cycle n and n+1, respectively. The RDEC is considered an effective parameter, determined as a function of the damage underwent within the mix, between two subsequent cycles, and the dissipated energy generated in the previous loading cycle [8, 9]. Moreover, according to previous investigations it has been pointed out that RDEC does not depend from other types of dissipated energy, related to mechanical work or heat generation [8, 9]. Hence, RDEC is a proper engineering parameter, representative of the internal damage developed within the bituminous mixture during loading; its evolution over the test can be represented by a curve, which presents three different phases [8, 9]. The first phase is characterized by a sharp reduction of RDEC, whereas it is substantially constant with the load cycles in the second phase. Therefore, in such part of the test, a constant rate of input energy is dissipated into internal damage. The transition between the second phase and the third one, denoted by a high rate of the RDEC with the number of cycles, allows to identify the fatigue failure of the asphalt concrete. In the Carpenter's approach the fatigue analysis has to be focused on the second phase; the RDEC value that characterizes such phase is named Plateau Value (PV) of RDEC. The PV is the ultimate parameter of the dissipated energy approach of Carpenter; it allows to compare the fatigue behaviours of different bituminous mixtures, under a rational framework. The higher the PV, the lower the fatigue life of the asphalt concrete [8, 9, 14, 15, 16, 17]. Shu et al. [14] have already compared the damage resistance of different hot mix asphalts, in terms of PV levels; however, they used controlled strain tests only and moreover, they worked exclusively with a single strain level. Vice versa, in the present research the PV values were determined for both stress and strain control mode. Furthermore, a range of stress/strain levels has been used to determine the damage curves (PV curves – PVC); such curves, defined in the plan PV - N_f (being the latter equal to the load repetitions associated to a reduction of 50% of the initial stiffness) substitute the conventional fatigue curves, in order to evaluate the fatigue behaviour of the asphalt concretes. The analytical interpolation of the PV - N_f data pairs has been based on the use of a power law model:

$$PV = aN_f^{\,b} \tag{2}$$

where a and b represent interpolation coefficients associated to the type of mix.

2.2.2 Statistical analysis of the damage curves. For each asphalt concrete, in order to verify from a statistical point of view the equality of the damage curves at constant stress and constant strain, the method proposed by Shen and Carpenter [8] has been used. The hypothesis H_0 that two damage curves can be considered statistically the same is initially assumed; then the procedure can be summarized in the following steps:

1. Fitting of the full model, to determine the error sum of squares SSE(*F*) = SSE_1 + SSE_2. SSE_1 and SSE_2 are the error sum of squares for the regression curves of the controlled stress data and the controlled strain data, respectively. The total degrees of freedom can be computed as df(*F*)

= $df_1 + df_2$, where df_1 and df_2 are the degrees of freedom for the controlled stress data and the controlled strain data regressions, respectively.

2. Fitting of the reduced model, combining both data set into one comprehensive data set, admitting the H_0 hypothesis (i.e. the pair of individual stress and strain damage curves can be statistically taken in consideration as a unique curve), to determine the error sum of squares SSE(*R*) as well as the degrees of freedom df(*R*), for the reduced model.

3. Calculation of the *F** statistic by means of the subsequent formula:

$$F^{*} = \left(\frac{SSE(R) - SSE(F)}{df(R) - df(F)} \right) \Bigg/ \left(\frac{SSE(F)}{df(F)} \right) \qquad (3)$$

4. Determination of the *p-value* (namely the level of statistical significance), by means of the Excel® function of *F* probability distribution (F_{DIST}), for the stress control data set and strain control data set:

$$p - value = F_{DIST}\left(F^*, df_a, df_b\right) \qquad (4)$$

where df_a = df(R) - df(F), whereas df_b = df(F).

Comparison of the *p-value* with a conventional α-value of 0.05 in order to reject or to accept the H_0 hypothesis. If *p-value* $\leq \alpha$, then H_0 is rejected and it can be concluded that the two damage curves are statistically different. Otherwise the null (H_0) hypothesis is accepted and the couple of data sets analyzed can be fitted as a unique damage curve for the asphalt concrete considered.

3. Results and discussion.

3.1 Stiffness Modulus results. According to the data reported in Table 3, the Stiffness Modulus was higher for the asphalt concretes containing recycled aggregates rather than that of the reference mix (S0R0). The contribution of the RAP material to the increase of the stiffness of the mixes, is basically due to the age hardening effect of the RAP bitumen [10]. Increasing the use of RAP, the quantity of aged bitumen integrated in the asphalt concrete increased as well, with the result of higher stiffness modulus of the mixes. Furthermore, the asphalt concretes with EAF slags showed always higher Stiffness Modulus values than the corresponding mixtures without them, independently of the RAP content, as already noted in previous experimental investigations [18].

The output of the multiple factors ANOVA are reported in Table 4. At the 95% confidence level, both the factors resulted to be statistically significant, given that the p-values were equal to 0. However, the RAP quantity was the most significant variable, as a result of its higher F-value (133.16). Also the interaction among the factors resulted statistically significant (p-value lower than 5%), even if its influence on the Stiffness Modulus has to be considered less relevant than that of each individual factor. In fact, the p-value associated to the interaction between the factors (0.006), resulted higher than that of the RAP or steel slag content (both equal to 0); moreover the F-value of the interaction was the lowest (6.97). Therefore, the ANOVA method has allowed to clarify statistically the actual influence of the RAP and the steel slag on the structural response of the mixes considered; this aspect represents a substantial step forward in the rational understanding of the mechanical behavior of such materials, with respect to previous investigations [11].

3.2 Fatigue tests results. The damage curves obtained for the controlled strain and the controlled stress mode are presented in Figures 5 and 6, respectively. The coefficients of regression and determination (R^2) are reported in Tables 5-6; R^2 resulted extremely high for all the cases considered. According to the results presented in Table 7, the damage curves obtained according to the controlled stress and controlled strain mode can be considered statistically the same, because the p-value was greater than the α-value, for each of the asphalt concrete considered.

Therefore, it is possible to fit both the controlled stress and the controlled strain data with a unique regression curve, that characterizes completely the fatigue behavior of each mixture; the results of the unified fitting analysis are presented in Figures 7 to 12. The unified damage curves, are characterized by satisfactory coefficients of determination, within the range from 0.7639 to 0.9822.

The unified damage curves have been used in order to compute, for each asphalt concrete, the PV value for a 1,000,000 loading cycles (PV_6), in order to synthetically analyze and compare the fatigue performance of the mixtures, regardless of the loading mode; however, it has to be pointed out that not all the mixes achieved a fatigue resistance equal or greater than 1,000,000 loading cycles. Table 8 reports the results obtained by means of the regression curves indicated in Figures 7 to 12.

The PV_6 values resulted lower for the asphalts with EAF slag and RAP aggregate; thus, the use of the marginal materials investigated leads to a considerable increment of the fatigue resistance. The rough texture of the EAF grains led to an improved adhesion of the bitumen film and moreover the steel slag mixtures are characterized by a higher bitumen content (Table 2) with respect to the asphalt concrete without EAF aggregates; therefore, the ductility and the fatigue resistance of the EAF mixes resulted higher, confirming previous results [11, 19, 20]. The aged binder of the RAP aggregates could increase the brittleness of the mixtures, with detrimental effect for the fatigue resistance, but the strong affinity between the virgin bitumen and the RAP binder, allows an improved adhesion between the RAP grains and the virgin bitumen film, with positive effects in terms of fatigue resistance. Nevertheless, it is the simultaneous and combined use of EAF slag and RAP aggregate that minimizes the values of PV_6; more precisely the lowest damage has been determined for S3R2. These findings confirm the ranking of the mixtures, in terms of fatigue resistance, already outlined in previous studies [11], based on the conventional approach related to the 50% reduction of the initial Stiffness Modulus. However, the possibility to obtain a unique estimation of the fatigue life of the mixes, instead of the two different predictions provided by the conventional approach, for the controlled stress and the controlled strain tests, represents a very important goal; it is the second major novelty of the present research. The actual possibility to unify the fatigue analysis under controlled stress and controlled strain conditions, allows to overcome the intrinsic ambiguity of the empirical approach, enabling an ultimate ranking of the fatigue resistance of the mixes, on the basis of more rational and scientific concepts, in contrast to previous investigations [11].

Lastly, it is worth noting the outmost importance of a direct evaluation of the fatigue behavior, since the ITS results (Table 2) as well as the stiffness characterization (Table 3) revealed a different quality of the mixes.

4. Conclusions.

The experimental and theoretical study discussed in this paper deals with the stiffness and fatigue behavior analysis of road base course asphalt concretes, made with RAP and EAF aggregates.

The statistical analysis conducted on the stiffness modulus data has allowed to verify the significance of the effect on the stiffness properties of the mixes, induced by the inclusion of the marginal aggregates in the asphalt concrete.

The 4PBT fatigue data, recorded at 10Hz and 20°C, have been elaborated according to the energy based methodology of Carpenter, focused on the analysis of the Ratio of Dissipated Energy Change.

A statistical analysis of the fatigue data demonstrated the possibility to unify the fatigue studies performed under controlled stress and controlled strain, by means of the damage parameter PV, namely the Plateau Value of the Ratio of Dissipated Energy Change.

In the present study six different asphalt concretes were considered, but further research, aimed at amplifying the number of asphalt concretes considered, is needed for a robust validation of the Carpenter's approach.

In comparison with the control mix, made integrally with natural materials, all the bituminous mixtures with marginal aggregates were characterized by a strongly improved fatigue behaviour, in terms of the PV computed at 1,000,000 loading cycles.

In order to maximise the environmental sustainability of the road pavement, the use of the highest RAP content (40%) can be recommended, although the best fatigue performance was achieved with 20% RAP.

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Table 1 Aggregate type and composition of the mixtures.

Aggregate type	Grading fraction, mm	Composition, %					
		S3R0	S3R2	S3R4	S0R0	S0R2	S0R4
Limestone	15/20	-	-	-	12	12	11
	10/15	-	-	-	20	20	20
	5/10	29	21	14	25	15	12
Sand	0/2	38	26	12	40	30	13
Filler	-	3	3	4	3	3	4
RAP material	0/10	-	20	40	-	20	40
Steel slag	15/20	20	12	12	-	-	-
	10/15	10	18	18	-	-	-

Table 2 Physical and mechanical properties of the mixes.

Property	Mixtures					
	S3R0	S3R2	S3R4	S0R0	S0R2	S0R4
OBC, %	4.85	4.00	3.10	4.75	3.90	3.00
Bulk density, Mg/m^3	2.626	2.661	2.714	2.410	2.433	2.469
ITS, MPa	1.74	1.90	2.18	1.62	1.88	2.35

Table 3 Stiffness Modulus and standard deviation.

Property	Mixtures					
	S0R0	S0R2	S0R4	S3R0	S3R2	S3R4
Stiffness Modulus (MPa)	5,922±986	9,076±194	11,761±618	8,642±632	10,483±350	12,319±357

Table 4 ANOVA test results.

Source	DF	Adj SS	Adj MS	F-value	P-value
a	1	14632817	14632817	43.00	0.000
b	2	90624469	45312235	133.16	0.000
a*b	2	4744697	2372348	6.97	0.006

Table 5 Regression coefficients of the damage curves for the strain control tests.

Mixture	a (μm/m)	b (-)	R^2 (-)
S0R0	3.4391	-1.071	0.9715
S0R2	0.7453	-1.177	0.9930
S0R4	0.1538	-0.997	0.9959
S3R0	0.1156	-0.862	0.8975
S3R2	0.9242	-1.223	0.9963
S3R4	0.4679	-1.130	0.9960

Table 6 Regression coefficients of the damage curves for the stress control tests.

Mixture	a (μm/m)	b (-)	R^2 (-)
S0R0	1.9517	-1.134	0.9942
S0R2	2.1379	-1.137	0.9998
S0R4	4.1237	-1.184	0.9969
S3R0	1.1593	-1.086	0.9998
S3R2	1.8164	-1.108	0.9997
S3R4	2.3313	-1.134	0.9967

Table 7 Statistical analysis of the equality of the controlled stress and controlled strain damage curves.

Mixture	S0R0	S0R2	S0R4	S3R0	S3R2	S3R4
df_1	2	2	2	2	2	2
SSE_1	1.50405	0.751402	2.17439	0.294176	1.38775	1.42228
df_2	2	2	2	2	2	2
SSE_2	0.631352	0.65765	1.16421	0.90193	2.82369	1.75972
df_F	4	4	4	4	4	4
SSE_F	2.135402	1.409052	3.3386	1.196106	4.21144	3.182
df(R)	5	5	5	5	5	5
SSE(R)	6.00826	2.40852	3.43237	3.49366	6.70014	3.34405
df_a	1	1	1	1	1	1
df_b	4	4	4	4	4	4
F*	7.254574	2.837278	0.112346	7.683446	2.363752	0.203708
p-value	0,054464	0.167384	0.754329	0.050233	0.199001	0.675132

Table 8 PV_6 computed by means of the unified damage curves.

Mixture	S0R0	S0R2	S0R4	S3R0	S3R2	S3R4
PV_6	3.53691E-06	8.06954E-08	3.84956E-07	3.90735E-07	7.13444E-08	2.15815E-07

Figure's captions:

Fig. 1 Design grading curves of the mixes S0R0, S0R2, S0R4.

Fig. 2 Design grading curves of the mixes S3R0, S3R2, S3R4.

Fig. 3 Four-point bending test apparatus.

Fig. 4 Laboratory compactor.

Fig. 5 Plateau Value (PV) versus cycles to failure (N_f) for the strain control tests.

Fig. 6 Plateau Value (PV) versus cycles to failure (N_f) for the stress control tests.

Fig. 7 Unified fitting analysis for mix S0R0.

Fig. 8 Unified fitting analysis for mix S0R2.

Fig. 9 Unified fitting analysis for mix S0R4.

Fig. 10 Unified fitting analysis for mix S3R0.

Fig. 11 Unified fitting analysis for mix S3R2.

Fig. 12 Unified fitting analysis for mix S3R4.

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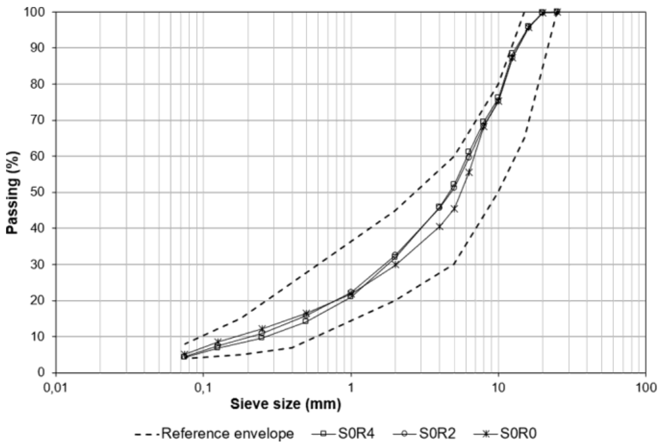
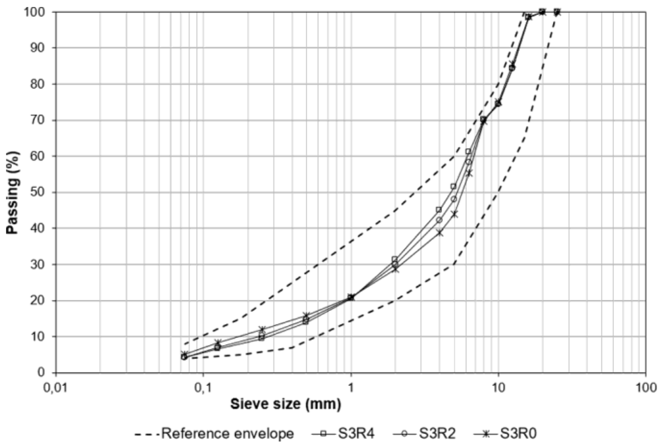
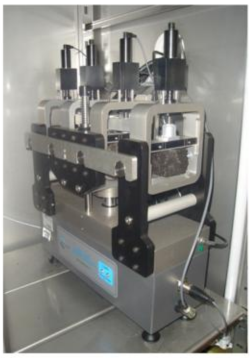
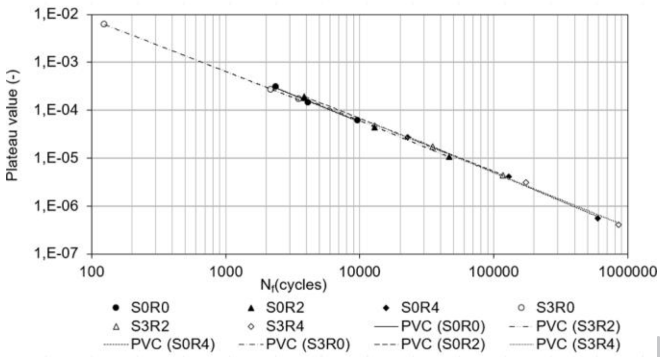


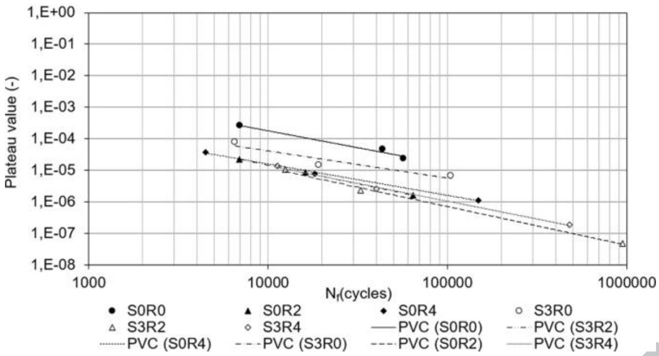
100
90
80
70
60
50
40
30
20
10
0
Passing (%)
0,01
0,1
1
10
100
Sieve size (mm)
Reference envelope
S0R4
S0R2
S0R0

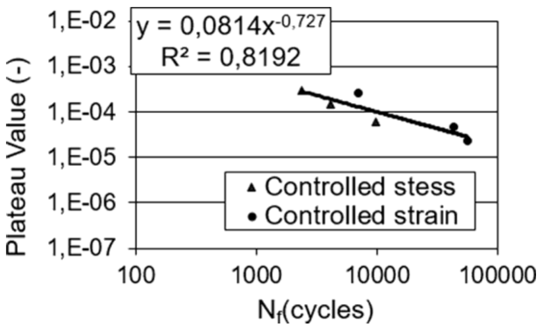


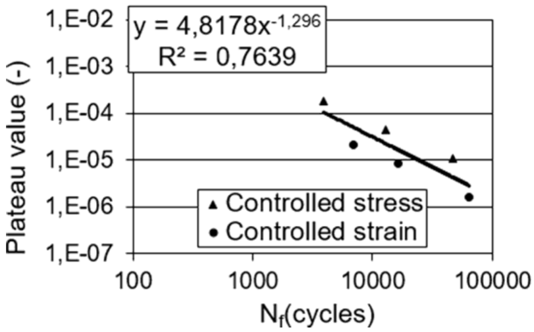
Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0,01
0,1
1
10
100
Sieve size (mm)
Reference envelope
S3R4
S3R2
S3R0

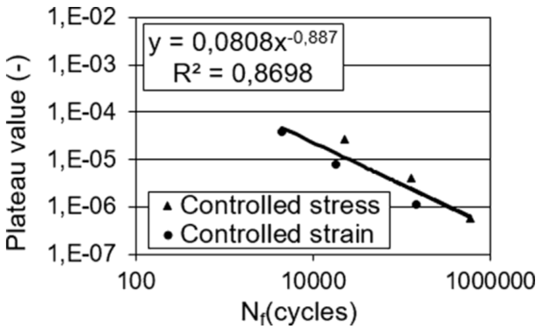


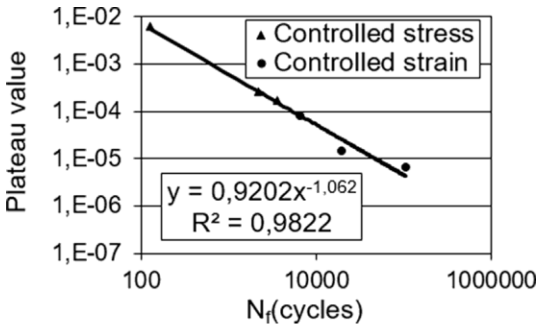

1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
Plateau value (-)
100
1000
10000
100000
1000000
N_f(cycles)
S0R0
S0R2
S0R4
S3R0
S3R2
S3R4
PVC (S0R0)
PVC (S3R2)
PVC (S0R4)
PVC (S3R0)
PVC (S0R2)
PVC (S3R4)

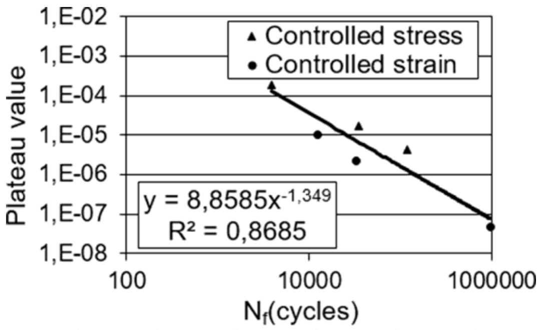

1,E+00
1,E-01
1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
1,E-08
Plateau value (-)
1000
10000
100000
1000000
N_f(cycles)
S0R0
S0R2
S0R4
S3R0
S3R2
S3R4
PVC (S0R0)
PVC (S3R2)
PVC (S0R4)
PVC (S3R0)
PVC (S0R2)
PVC (S3R4)

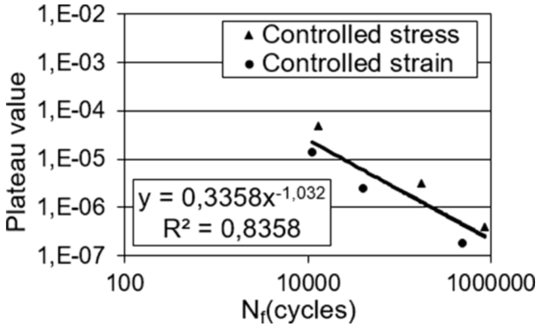

y = 0,0814x$^{-0,727}$
R² = 0,8192
Plateau Value (-)
1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
Controlled stess
Controlled strain
100
1000
10000
100000
N_f(cycles)


y = 4,8178x-1,296
R² = 0,7639
1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
Plateau value (-)
Controlled stress
Controlled strain
100
1000
10000
100000
Nf(cycles)


1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
Plateau value (-)
y = 0,0808x-0,887
R² = 0,8698
Controlled stress
Controlled strain
100
10000
1000000
Nf(cycles)


1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
Plateau value
Controlled stress
Controlled strain
y = 0,9202x^-1,062
R² = 0,9822
100
10000
1000000
Nf(cycles)


1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
1,E-08
Plateau value
Controlled stress
Controlled strain
y = 8,8585x-1,349
R² = 0,8685
100
10000
1000000
Nf(cycles)


1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
Plateau value
Controlled stress
Controlled strain
y = 0,3358x-1,032
R² = 0,8358
100
10000
1000000
Nf(cycles)