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Correlating creep properties of bituminous binders with anti-rutting performance of corresponding mixtures

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Abstract

In the experimental study described in this paper, rutting properties of different bituminous binders and those of corresponding mixtures characterized by common composition and volumetrics were investigated and compared. Single shear creep-recovery (SSCR) tests were carried out on binders for the determination of their creep compliance rate (CCR), whereas bituminous mixtures were evaluated by referring to their Flow Number (FN), derived from repeated compressive loading tests. Analysis of experimental data revealed the existence of a strong correlation between rutting parameter of binders and permanent deformation response of mixtures. This confirmed the potential of the proposed testing procedure of being adopted for the evaluation of rutting properties of bituminous binders and for their consequent performance-related ranking.

Keywords: Rutting; Bituminous binders; Bituminous mixtures; Creep; Flow Number

1. Introduction

Formation of ruts in asphalt pavements resulting from accumulation of permanent deformation under repeated traffic loading is significantly affected by the rheological properties of bituminous binders [1,2]. Due to the thermal susceptibility and viscoelastic behaviour of these materials, rutting is greatly promoted at high in-service temperatures and in presence of heavy slow-moving vehicles. The use of binders characterized by enhanced properties in terms of permanent deformation resistance is thus essential in preventing such a phenomenon, which generally leads to a reduction of comfort and safety perceived by road users. To achieve this goal, materials need to be properly selected by referring to the results of reliable laboratory tests, capable of evaluating their non-reversible strain response under loading and of yielding a truly performance-related ranking.

The traditional SHRP parameter $G^*/\sin\delta$ [3,4] adopted in performance grading has been demonstrated to be inadequate in evaluating the real anti-rutting potential of binders, especially in the case of polymer-modified products [5,6]. Limits of the SHRP approach are mainly related to the fact that the abovementioned parameter is determined from small-strain oscillatory loading in the linear viscoelastic domain, far away from actual damage conditions.

A number of studies [5,7–11] have been carried out to overcome these limitations, leading to the development of several standard methods to be used for the assessment of rutting properties of bituminous binders [12,13]. Among these, the Multiple Stress Creep-Recovery (MSCR) test [14]

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has held a prominent role due to its aptitude in simulating the intermittent nature of traffic loading and the stress-dependency of materials. Some authors, however, have questioned the use of 1 second creep followed by 9 second recovery prescribed by the current MSCR protocol since it may not allow the material to reach steady-state flow conditions under loading and may not ensure the complete recovery of deformation at the end of unloading, especially for cross-linked binders characterized by a pronounced delayed elastic strain component [15,16]. A further criticism questions the use of non-recoverable creep compliance (J_{nr}) for binder performance characterization, due to the fact that it is a mechanical parameter not univocally connected with non-reversible deformation [17].

More recently, Santagata et al. [18] proposed a novel test procedure consisting in single shear creep-recovery (SSCR) tests carried out at different temperatures and at predefined loading and recovery times. Results obtained on a wide set of materials indicated the effectiveness of the procedure in discriminating high-temperature characteristics of bituminous binders of different types and origin. Moreover, synthetic information on resistance to flow was obtained by referring to a new control parameter, the so-called creep compliance rate (CCR), which was found to be adequate for the purpose of performance-related ranking.

In order to further corroborate the validity of the method and in accordance with a multi-scale approach, the research scope was extended by including the evaluation of rutting properties of bituminous mixtures. In particular, the aim of the investigation reported in the paper was to correlate results obtained from rheological tests carried out on several bituminous binders with those derived from permanent deformation tests carried out on corresponding mixtures. Data gathered from testing were analysed with the specific goal of verifying the existence of relationships to be used for materials performance prediction.

2. Materials

The set of bituminous binders employed in the experimental investigation was selected in order to cover a wide spectrum of viscoelastic properties. It included two unmodified bitumens (A and B) sampled from two refineries which operate on crudes of different source and origin, one polymer-modified binder (C) containing a high percentage (ranging in the interval 4–5% by weight of base bitumen) of styrene–butadienestyrene co-polymer (SBS), and one asphalt rubber (D) containing 18% crumb rubber (by weight of base bitumen) derived from the grinding of end-of-life tyres. Binders C and D were supplied by specialized manufacturers that did not provide specific information on the adopted production schemes.

All binders were investigated in short-term aged conditions simulated by means of the Rolling Thin Film Oven (RTFO) in accordance with AASHTO T240 [19]. Basic dynamic shear tests were carried out in order to determine upper limiting performance grade (PG) temperatures (T_{PG-U}, corresponding to $G^*/\sin\delta$ equal to 2.2 kPa). Moreover, in the preliminary characterization phase, binders were also subjected to MSCR tests with the consequent evaluation of non-recoverable creep compliance parameters ($J_{nr0.1}$ and $J_{nr3.2}$ corresponding to applied stress levels of 0.1 and 3.2 kPa, respectively).

Obtained results are synthesized in Tables 1 and 2.

For each type of binder, a corresponding mixture (named, in the order, MA, MB, MC and MD) was manufactured in the laboratory by making use of mineral aggregates provided by a local contractor in four different size fractions (sand 0–5 mm, fine gravel 3–8 mm, medium gravel 8–12 mm and Portland cement filler). Aggregate gradation of the mixtures was defined according to Italian technical specifications for standard wearing courses [20], characterized by a maximum aggregate size of 16 mm (Fig. 1). Reconstruction of the target gradation curve was made by subjecting available fractions to washed sieve separation and by thereafter combining single-size fractions in the needed quantities. Binder dosage was set at 5.5% by weight of dry aggregates.

Loose blends were analysed in order to determine their Theoretical Maximum Density (TMD) to be used for the evaluation of air voids of compacted specimens. TMD values reported in Table 3 were obtained by means of the pycnometer method according to EN12697-5 [21].

3. Methods

Rutting potential of bituminous binders considered in this paper was investigated by adopting the SSCR test protocol mentioned above. For the purposes of the research, analysis of experimental data was limited to the creep phase, from which values of the CCR parameter were determined.

The apparatus employed for testing was a stress-controlled dynamic shear rheometer (DSR), equipped with a permanent magnet synchronous drive (minimum torque = 0.1 μNm, torque resolution <0.1 μNm) and an optical incremental en-coder for the measurement of angular rotation (resolution <1 μrad). The standard 25 mm parallel plates geometry was used with 1.0 mm gap.

Measurements were performed at four temperatures (ranging from 46 to 64 °C in the case of binder A and B, from 58 °C to 76 °C in the case of binders C and D) at a single stress level (equal to 100 Pa). Conditioning of binder specimens was carried out until target test temperature was stable for at least 15 min. At least two replicates were run at each temperature and average data were considered in the analysis.

Table 1
T_{PG-U} values obtained from dynamic shear tests.

Binder code	A	B	C	D
T_{PG-U} [°C]	68.3	66.0	81.7	101.5

Table 2
$J_{nr0.1}$ and $J_{nr3.2}$ values obtained from MSCR tests.

Binder code	T [°C]	$J_{nr0.1}$ [kPa^{-1}]	$J_{nr3.2}$ [kPa^{-1}]
A	52	0.276	0.281
	58	0.748	0.814
	64	1.935	2.176
	70	4.614	5.250
	76	10.308	11.539
B	46	0.182	0.181
	52	0.516	0.523
	58	1.374	1.411
	64	3.420	3.564
	70	7.927	8.252
C	64	0.142	0.170
	70	0.320	0.515
	76	0.760	1.340
	82	1.530	3.330
	88	2.519	8.225
D	64	0.013	0.050
	70	0.020	0.162
	76	0.040	0.478
	82	0.087	1.267
	88	0.259	3.704
	94	1.027	9.361

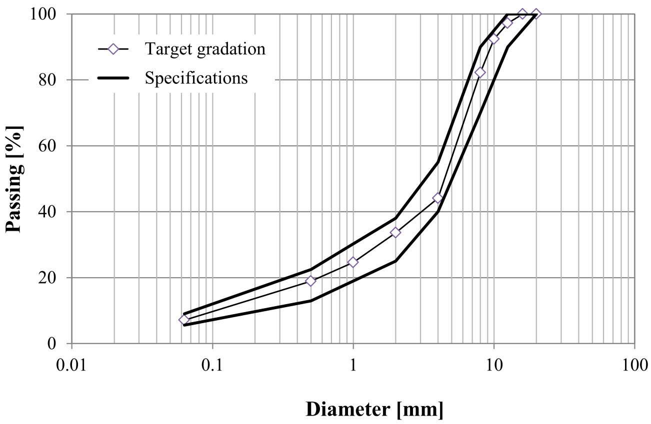

Fig. 1. Target gradation and specifications for standard wearing course mixture.

Table 3
TMD values of bituminous mixtures.

Mixture code	MA	MB	MC	MD
TMD [kg/m^3]	2514	2504	2519	2580

Duration of the creep phase was established on the basis of past experience gained by the Authors [18], with the purpose of allowing materials to reach steady-state flow conditions under loading. Adopted values, summarized in Table 4, are consistent with the fact that unmodified binders (A and B) were expected to flow quite quickly at the selected test temperatures, whereas in the case of the polymer-modified binder (C) and the asphalt rubber (D) it was anticipated that achievement of steady-state conditions would require very long creep time as a result of their internal rubber-like structure.

Table 4
Duration of creep phase adopted at different test temperatures.

Binder code	Temperature [°C]	Duration of creep phase [s]
A, B	46	600
	52	240
	58	180
	64	120
C, D	58	10,800
	64	1800
	70	600
	76	300

Table 5
Average air void content of AMPT specimens.

Mix code	MA	MB	MC	MD
v [%]	5.7	5.6	5.8	5.0

Permanent deformation properties of bituminous mixtures were evaluated by means of Flow Number (FN) tests following AASHTO TP 79 [22]. During these tests, cumulative permanent strains (ε_p) developed in cylindrical specimens as a consequence of repeated compressive loads are recorded as a function of the number of loading cycles (N). FN is defined as the number of loading cycles corresponding to the transition point between the secondary and tertiary creep regions, identified on N-ε_p plots derived from experimental data. On the basis of extensive research carried out under NCHRP project 9–19 [23], such a parameter has been recommended as a valid indicator of the aptitude of bituminous mixtures to resist to rutting [24].

Tests were carried out by means of the Asphalt Mixture Performance Tester (AMPT) at three temperatures (46, 52 and 58 °C) and with a repeated axial stress of 600 kPa. Even though it was proven that lateral confinement provides a better simulation of stress conditions which occur in the field, for practical reasons mainly related to the need of limiting total testing time, in the present study FN values were determined by imposing no confinement to test specimens. In fact, by increasing the level of confining pressure, resistance of mixtures to flow may significantly increase, resulting in very long test durations. Moreover, it was shown that in some cases deformation may not reach the tertiary creep stage, making determination of FN impossible [25]. Finally, it should be mentioned that it was reported that tests carried out in confined conditions may lead to poor repeatability of experimental results, which have also been found to be extremely sensitive to sample preparation [26]. For all mixtures, FN tests were carried out in triplicate repetitions and average results were considered in the analysis.

Specimens used for AMPT testing were cylindrical cores (100 mm diameter, 150 mm height), extracted from the centre of larger gyratory shear compactor samples (150 mm diameter, 170 mm height) and subsequently trimmed by means of a masonry saw in order to obtain smooth and parallel end surfaces. Samples were fabricated with the target void content (v) of their cores set at 5.5 ± 0.5%; actual mean values measured according to EN 12697-8 [27] are reported in Table 5. Before testing, specimens were conditioned at the target test temperature in a climatic chamber for 12 h.

4. Results and discussion

4.1. Creep behaviour of binders

Examples of experimental data gathered from the creep phase of SSCR tests are shown in Fig. 2, obtained by plotting shear strains (γ) measured under loading as a function of time (t). Diagrams provide a comparison between the response of unmodified bitumens (A and B) and that of modified binders (C and D) at a common test temperature (equal to 58 °C).

In the case of unmodified binders, t-γ curves exhibited an almost constant slope throughout the creep phase, indicating the achievement of viscous flow in a very short loading time. On the contrary, curves corresponding to modified binders revealed the existence of an initial curvature (which was found to gradually smoothen out for increasing test temperatures) associated to the presence of an internal rubber-like network. Nevertheless, durations of the creep phase were sufficient to obtain a final linear trend, confirming also for these materials the attainment of steady-state conditions.

From the final linear portion of t-γ loading curves, creep compliance rate (CCR) values were calculated as follows:

$$\mathrm{CCR} = \frac{\mathrm{d}\left(\frac{\gamma}{\tau_0}\right)}{\mathrm{dt}} = \frac{\mathrm{dJ}}{\mathrm{dt}} \qquad (1)$$

where γ is shear strain, τ_0 is applied stress, and J is creep compliance.

CCR represents a material property that does not depend upon time and that provides a measure of the resistance to flow. From a rheological point of view, it corresponds to the inverse of zero-shear viscosity [18].

Obtained CCR values plotted against test temperature in the semi-logarithmic scale are displayed in Fig. 3. It is clearly observed that, with such a representation, experimental data can be approximated by linear functions. Moreover, a clear distinction can be made between unmodified (A and B) and modified (C and D) binders, with first ones exhibiting higher CCR values than second ones at all test temperatures. In terms of ranking, the asphalt rubber (D) yielded the highest resistance to flow, which corresponds to the highest anti-rutting potential. In addition, small differences were detected when comparing the two unmodified binders to each other, with slightly lower CCR values in the case of binder A, associated to a higher $T_{PG\text{-}U}$ value (Table 1). Scatter of experimental results was assessed by referring to percent relative error values (E_{CCR}%) which are listed in Table 6 together with measurement ranges. It was thus observed that data repeatability was overall acceptable for the unmodified and polymer-modified binders (E_{CCR}% values in most cases below 5%), while a greater dispersion was recorded for the intrinsically non-homogeneous asphalt rubber binder (E_{CCR}% values of the order of 10–20%).

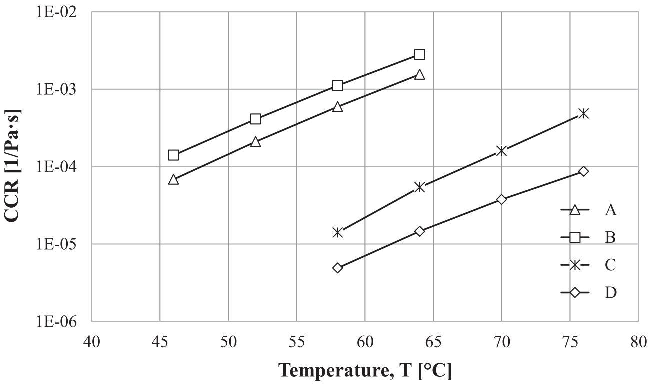

Fig. 3. Variation of CCR as a function of test temperature.

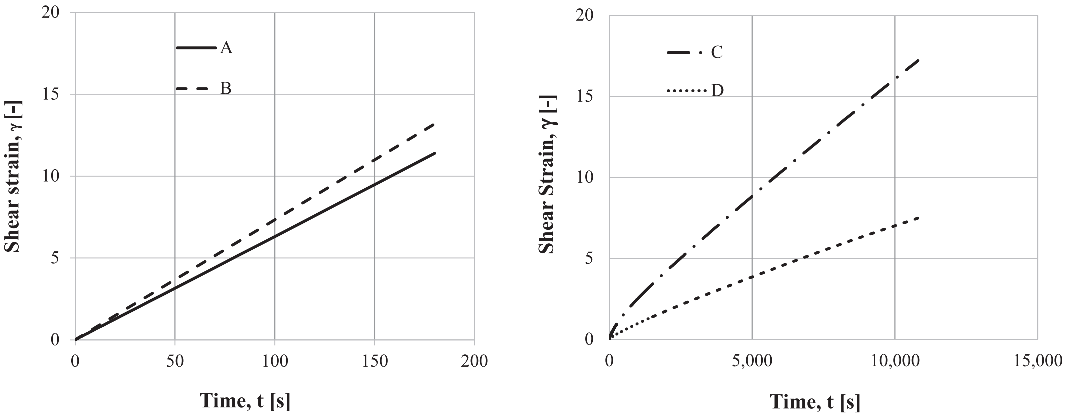

Fig. 2. Results obtained from the creep phase of SSCR tests at 58 °C: (a) unmodified bitumens A and B, (b) modified binders C and D.

Table 6
Measured ranges and percent relative errors of CCR.

Binder code	Temperature (°C)	$CCR_{measured}$ (1/Pa.s)	E_{CCR}% (%)
A	46	$(6.60 \div 7.10)\ 0.10^{-5}$	3,6
	52	$(2.03 \div 2.17)\ 0.10^{-4}$	3,3
	58	$(5.75 \div 6.13)\ 0.10^{-4}$	3,2
	64	$(1.51 \div 1.60)\ 0.10^{-3}$	3,0
B	46	$(1.39 \div 1.42)\ 0.10^{-4}$	1,1
	52	$(4.07 \div 4.15)\ 0.10^{-4}$	1,0
	58	$(1.10 \div 1.12)\ 0.10^{-3}$	1,0
	64	$(2.80 \div 2.81)\ 0.10^{-3}$	0,2
C	58	$(1.40 \div 1.41)\ 0.10^{-5}$	0,4
	64	$(4.50 \div 6.28)\ 0.10^{-5}$	16,5
	70	$(1.54 \div 1.65)\ 0.10^{-4}$	3,4
	76	$(4.60 \div 5.07)\ 0.10^{-4}$	4,9
D	58	$(4.00 \div 5.80)\ 0.10^{-6}$	18,4
	64	$(1.20 \div 1.72)\ 0.10^{-5}$	17,8
	70	$(3.20 \div 4.32)\ 0.10^{-5}$	14,9
	76	$(7.60 \div 9.77)\ 0.10^{-5}$	12,5

4.2. Permanent deformation of mixtures

Experimental curves obtained from FN tests carried out on bituminous mixtures considered in the investigation are represented in Figs. 4 and 5, which show the relationship between the total cumulative permanent axial strain (ε_p) developed in specimens and the number of loading cycles (N). Fig. 4 contains experimental data gathered from tests carried out at 58 °C for all mixtures, whereas Fig. 5 provides a comparison between curves recorded at different temperatures (46, 52 and 58 °C) for mixture MA. In both figures, plotted curves refer to individual repetitions.

From N-ε_p plots, three different zones corresponding to different stages of flow can be clearly identified: a primary zone, in which rate of strain decreases as the number of loading cycles increases; a secondary stage, characterized by a rate of strain that remains almost constant with load repetitions; and a third stage (tertiary flow), in which strain rate rises dramatically, leading to failure.

FN values were derived from experimental curves by adopting the Francken model recently introduced in AMPT data analysis [28–30], due to its effectiveness and consistency in fitting experimental data [25,30]. Results obtained from calculation are summarized in Fig. 6, which also displays error bars corresponding to maximum relative errors.

Consistently with expectations, mixtures containing modified binders (MC and MD) exhibited FN values which are significantly higher than those recorded for mixtures prepared with conventional bitumens (MA and MB). Moreover, the rubberized mixture MD showed a superior performance with respect to mixture MC, produced with the SBS polymer-modified binder, over the whole temperature range explored in the investigation. On the contrary, minor differences were observed when comparing the unmodified mixtures MA and MB to each other, with the first one proving to be slightly more resistant to accumulation of permanent deformation than the second one. Finally, it was noticed that the relative ranking of mixtures determined from FN tests matches that of binders established on the basis of SSCR tests.

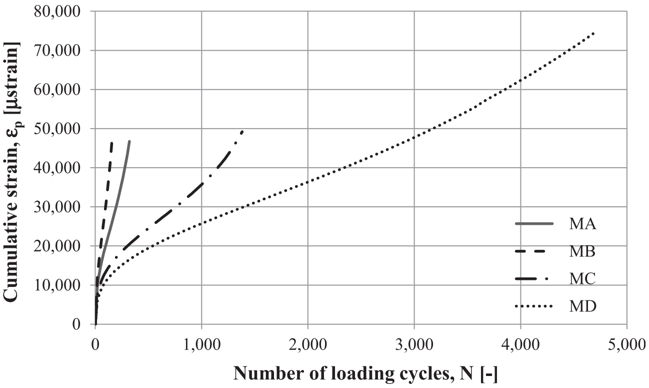

Fig. 4. FN curves obtained at 58 °C for all bituminous mixtures.

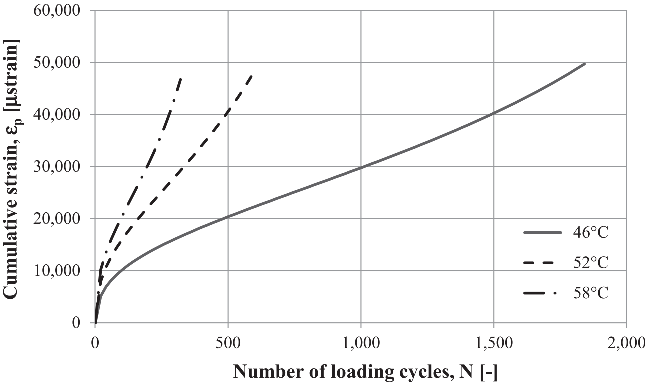

Fig. 5. FN curves obtained at different temperatures for mixture MA.

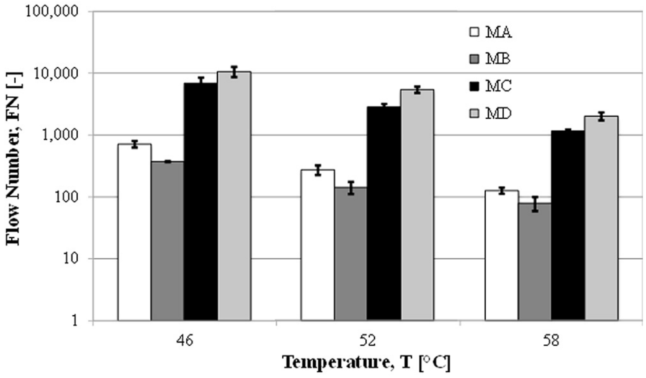

Fig. 6. FN values as a function of test temperature.

4.3. Relationship between binder and mixture data

Moving from the observations reported in previous sections, the following step of the analysis consisted in correlating creep behaviour of binders with permanent deformation response of corresponding mixtures. The relationship which stemmed from analysis is represented in Fig. 7, in which CCR values are plotted as a function of FN values obtained at the same test temperatures.

It should be underlined that SSCR tests were not carried out on binders C and D at 46 °C and 52 °C as a result of the unpractical, too long loading duration which would be necessary to reach flow conditions. Thus, corresponding CCR values were extrapolated from those registered at higher temperatures (58 °C, 64 °C, 70 °C and 76 °C) by fitting a linear relationship to temperature-CCR data represented in the semi-log scale (Fig. 3).

Fig. 7 highlights the existence in the log–log scale of a unique linear decreasing trend not depending upon binder origin and type. Such an occurrence demonstrates that the anti-rutting potential of bituminous mixtures considered in this study is strongly governed by the viscoelastic properties of the binder phase as measured by SSCR tests. A single power-law function, characterized by a very high regression coefficient R2, can therefore be used to fit experimental data.

The finding discussed above confirms the validity of the proposed SSCR method, which is capable of capturing relevant aspects of binder rheology and of providing a true performance-related ranking [31]. Furthermore, as reported by Santagata et al. [31], the CCR-FN relationship can be used for the prediction of the flow number of a bituminous mixture of given composition and volumetric characteristics from the results of binder testing. This is shown in Table 7, where measured FN values are compared to those calculated by means of the power-law function displayed in Fig. 7, with the corresponding evaluation of prediction errors (ΔFN%). Table 7 also lists ranges of measured FN values and the consequent percent relative errors (E_{FN}%). It is thus observed that in most cases prediction errors are comprised in the range of variability of Flow Number test results ($|\Delta FN\%| < E_{FN}\%$), indicating model estimates to be reasonably accurate.

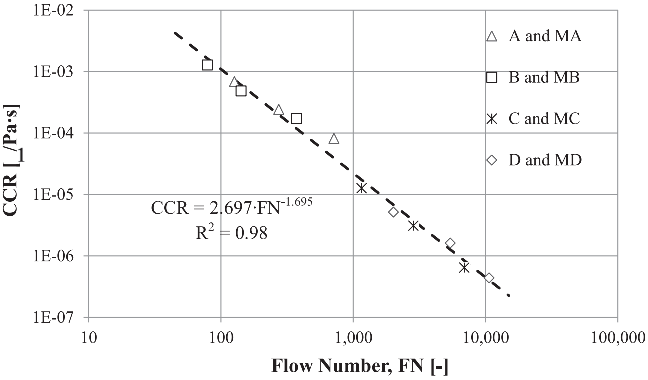

Fig. 7. Relationship between CCR and FN values.

5. Conclusions

In the research study presented in the paper, single shear creep-recovery (SSCR) tests were used to evaluate rutting properties of several bituminous binders at various temperatures. Experimental data were compared with those derived from Flow Number (FN) tests carried out on corresponding bituminous mixtures characterized by same composition (aggregate gradation and binder dosage) and target void content.

Analysis of results showed that binders and mixtures were identically ranked in terms of their potential rutting performance. In particular, the superior performance of asphalt rubber and of its corresponding mixture was clearly highlighted.

A single relationship independent from binder origin and type was found between CCR binder parameter and FN, thus confirming the effectiveness of the SSCR test protocol in capturing the contribution of the binder phase to accumulation of permanent deformation in considered mixtures. Moreover, the potential of employing CCR values for the prediction of FN was explored with a satisfactory outcome.

Based on obtained results, it is envisioned that future research will focus on the validation and generalization of the abovementioned relationship and by extending

Table 7
Measured and predicted FN values of bituminous mixtures.

Mixture code	Temperature (°C)	$FN_{measured}$	$FN_{predicted}$	ΔFN% (%)	FN range	E_{FN}%
MA	46	715	464	−35.0	626 ÷ 795	11,8
	52	274	244	−10.8	226 ÷ 323	17,7
	58	126	132	4.5	112 ÷ 140	11,1
MB	46	374	299	−20.1	368 ÷ 384	2,1
	52	142	163	14.3	121 ÷ 184	22,1
	58	79	91	15.7	62 ÷ 102	25,3
MC	46	6914	8071	16.7	5833 ÷ 8969	22,7
	52	2851	3191	11.9	2453 ÷ 3128	11,8
	58	1160	1396	20.3	1105 ÷ 1236	5,6
MD	46	10649	10135	−4.8	8560 ÷ 12589	18,9
	52	5412	4696	−13.2	4693 ÷ 5975	11,8
	58	2017	2366	17.3	1752 ÷ 2358	15,0

testing from the laboratory to the field by considering the rutting performance of full-scale sections.

References

[1] K.E. Cooper, S.F. Brown, G.R. Pooley, The design of aggregate gradings for asphalt base course, J. Assoc. Asphalt. Pav. 54 (1985) 324–346.

[2] J.B. Sousa, J. Craus, C.L. Monismith, Summary Report on Permanent Deformation in Asphalt Concrete, SHRP Report A/IR-91-104, Strategic Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., 1991.

[3] E.T. Harrigan, L.B. Leahy, J.S. Youtcheff, The Superpave mix Design System. Manual of Specifications, Test Methods, and Practices, SHRP Report A-379, Strategic Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., 1994.

[4] D.A. Anderson, D.W. Christensen, H.U. Bahia, R. Dongre, M.G. Sharma, C.E. Antle, Binder Characterization and Evaluation. Volume 3: Physical Characterization, SHRP Report A-369, Strategic Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., 1994.

[5] H.U. Bahia, D.I. Hanson, M. Zeng, H. Zhai, M.A. Khatri, R.M. Anderson, Characterization of modified asphalt binders in Superpave mix design, NCHRP Report 459 National Cooperative Highway Research Program: Transportation Research Board, National Research Council, Washington, D.C., 2010.

[6] J. D'Angelo, R. Dongre, Superpave binder specifications and their relationship to modified binders, in: 47th Canadian Technical Asphalt Association Annual Meeting, Calgary, Canada, November, 18–20, 2002.

[7] J. D'Angelo, R. Kluttz, R. Dongre, K. Stephens, L. Zanzotto, Revision of the Superpave high temperature binder specification: the multiple stress creep recovery test, J. Assoc. Asphalt Pav. 76 (2007) 123–162.

[8] E. Masad, C.-W. Huang, J. D'Angelo, D. Little, Characterization of asphalt binder resistance to permanent deformation based on nonlinear viscoelastic analysis of multiple stress creep recovery (MSCR) test, J. Assoc. Asphalt Pav. 78 (2009) 535–562.

[9] N. Saboo, P. Kumar, Analysis of different test methods for quantifying rutting susceptibility of asphalt binders, J. Mater. Civil Eng. 28 (7) (2016) 04016024.

[10] M.D.I. Domingos, A.L. Faxina, Susceptibility of asphalt binders to rutting: Literature review, J. Mater. Civil. Eng. 28 (2) (2016) 04015134.

[11] E. Santagata, O. Baglieri, D. Dalmazzo, L. Tsantilis, Evaluation of anti-rutting potential of polymer modified binders by means of creep-recovery tests, Mater. Struct. 46 (10) (2013) 1673–1682.

[12] CEN/TS 15325, Bitumen and bituminous binders. Determination of Zero Shear Viscosity (ZSV) using a shear stress rheometer in creep mode, European Committee for Standardization, Brussels, Belgium.

[13] CEN/TS 15324, Bitumen and bituminous binders. Determination of equiviscous temperature based on low shear viscosity using dynamic shear rheometer in low frequency oscillation mode, European Committee for Standardization, Brussels, Belgium.

[14] AASHTO TP 70, Multiple stress creep recovery (MSCR) test of asphalt binder using dynamic shear rheometer (DSR), American Association of State Highway Transportation Officials, Washington, D.C.

[15] F. Merusi, F. Giuliani, Intrinsic resistance to nonreversible deformation in modified asphalt binders and its relation with specific criteria, Constr. Build. Mater. 25 (2011) 3356–3366.

[16] S.E. Zoorob, J.P. Castro-Gomesb, L.A. Pereira Oliveirab, J. O'Connellc, Investigating the multiple stress creep recovery bitumen characterisation test, Constr. Build. Mater. 30 (2012) 734–745.

[17] F. Merusi, Delayed mechanical response in modified asphalt binders. Characteristics, modeling, and engineering implications, Road Mater. Pav. 13 (2012) 321–345.

[18] E. Santagata, O. Baglieri, M. Alam, D. Dalmazzo, A novel procedure for the evaluation of anti-rutting potential of asphalt binders, Int. J. Pav. Eng. 16 (4) (2015) 287–296.

[19] AASHTO T240, Effect of heat and air on a moving film of asphalt binder (Rolling Thin-Film Oven Test), American Association of State Highway Transportation Officials, Washington, D.C.

[20] CIRS, Performance-related technical specification for the construction and maintenance of road pavements, Inter-University Road Research Center, Ancona, Italy (in Italian), 2001.

[21] CEN 12697–5, Bituminous mixtures - Test method for hot mix asphalt. Determination of the maximum density, European Committee for Standardization, Brussels, Belgium.

[22] AASHTO TP79, Standard method of test for determining the dynamic modulus and flow number for hot mix asphalt (HMA) using the asphalt mixture performance tester (AMPT), American Association of State Highway Transportation Officials, Washington, DC.

[23] M.W. Witczak, K.E. Kaloush, T. Pellinen, M. El-Basyouny, H. von Quintus, Simple Per-formance Tests for Pavement Superpave mix design, NCHRP Report 465 National Cooperative Highway Research Program Transportation Research Board, National Research Council, Washington, D.C., 2002.

[24] M.W. Witczak, Simple Performance Tests: Summary of Recommended Methods and Database, NCHRP Report 547 National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., 2005.

[25] R. Bonaquist, Ruggedness Testing of the Dynamic Modulus and Flow Number Tests with the Simple Performance Tester, NCHRP Report 629. National Cooperative Highway Research Program Transportation Research Board, National Research Council, Washington, D.C., 2008.

[26] R. Bonaquist, Wisconsin Mixture Characterization using the Asphalt Mixture Performance Tester (AMPT) on Historical Aggregate Structure, WHRP Report 09–03, Wisconsin Highway Research Program, Wisconsin Department of Transportation, Madison, WI, 2010.

[27] CEN 12697–8, Bituminous mixtures - Test methods for hot mix asphalt. Determination of void characteristics of bituminous specimens, European Committee for Standardization, Brussels, Belgium.

[28] K.P. Biligiri, K.E. Kaloush, M.S. Mamlouk, M.W. Witczak, Rational modeling of tertiary flow for asphalt mixtures, Transport. Res. Rec. 2007 (2001) 63–72.

[29] R. Dongré, J. D'Angelo, A. Copeland, Refinement of flow number as determined by asphalt mixture performance tester, Transport. Res. Rec. 2127 (2009) 127–136.

[30] N. Roy, A. Veeraragavan, J. Murali Krishnan, Interpretation of flow number test data for asphalt mixtures, Proceedings of the Institution of Civil Engineers: Transport, 168(3) (2015), 191–199.

[31] E. Santagata, O. Baglieri, M. Alam, P.P. Riviera, Evaluation of rutting properties of bituminous binders by means of single shear creep-recovery (SSCR) tests and correlation with mixture performance, RILEM Bookseries (2016) 745–756.