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RILEM TC REPORT

Article of RILEM TC 278-CHA: evaluation of self-healing properties of asphalt binders—outcomes and challenges

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Abstract This paper describes part of the activities conducted by RILEM Technical Committee 278-CHA (Crack-Healing of Asphalt Pavement Materials) Task Group 2a. The main objective of the TG2a was to explore and evaluate the experimental methods and criteria for the assessment of self-healing of asphalt binders. The work was developed in two phases. In the first phase, various existing healing test protocols were scrutinized, encompassing time-sweeps with single rest periods (TS-SRP), time-sweeps with multiple rest periods (TS-MRP), and linear amplitude sweeps with rest periods LASH). The protocols were evaluated and compared across different laboratories. The outcomes of interlaboratory testing led to the selection of the LASH-based approach. However, it was acknowledged that new insights and modifications were necessary due to the possible occurrence of biasing effects during the amplitude sweep. Such issues were addressed in the second phase of research, in which a modified LASH-based procedure underwent further investigation using various methods for data analysis, including approaches based on dissipated energy and the viscoelastic continuum damage model.

Keywords Self-healing · Fatigue damage · Asphalt binder · Dynamic Shear Rheometer · Linear amplitude sweep

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1 Introduction

Fatigue cracking is one of the main distress types affecting asphalt pavements. Under the repeated actions of traffic loading, microcracks may form in asphalt mixtures and eventually coalesce into larger cracks that propagate on the pavement surface [1–3]. Severe cracking can result in structural and functional pavement failures, diminishing safety for motorists and escalating the demand for expensive maintenance and rehabilitation measures.

Fatigue properties of asphalt binders and mixtures are commonly investigated by subjecting them to accelerated testing and monitoring the loss in their mechanical properties like stiffness or strength [4]. Fatigue damage can occur inside the binder phase (cohesive) or between the binder/aggregates interface (adhesive) [5]. Asphalt materials are recognized to have the interesting ability to restore stiffness or strength lost during repeated loading when allowed to rest for a given time interval in the absence of external actions [6–9]. This ability, associated with damage repair, is commonly referred to as self-healing. Self-healing can be intrinsic (i.e., inherent to the material itself) or extrinsic (i.e., induced by added phases or technologies designed to promote crack healing and significantly delay crack propagation; these technologies may or may not be externally triggered) [10]. Therefore, understanding the self-healing properties of materials is crucial for improving long-term fatigue predictions and fostering the development of more durable and sustainable pavements.

Despite intrinsic cohesive self-healing of binders having been widely studied for a long time and a variety of testing methods having been proposed, researchers have no consensus on a possible standardized protocol to be used for the assessment and ranking of binder self-healing potential [11]. This is mainly due to the inherent complexity of self-healing mechanisms and the possible occurrence of many biases in laboratory measurements associated with reversible phenomena unrelated to micro-damage [3, 4]. Separating such biasing effects from accelerated testing is a non-trivial process [2, 12, 13]. Moreover, healing properties are influenced by various factors, including time, temperature, aging, moisture, and the eventual presence of modifiers [14–18].

In literature, the majority of proposed methods for the evaluation of self-healing properties of asphalt binders entail inserting rest periods in cyclic fatigue tests. The Dynamic Shear Rheometer (DSR) is the most used device to perform fatigue-healing tests through time sweeps or amplitude sweeps. Time-sweep healing tests generally include either a single or multiple rest periods [19–23]. These rest periods are designed to simulate field conditions, such as intermittent loading or continuous unloading periods. However, time-sweep healing tests often require long durations, depending on the rest period length and strain amplitude. While extended duration is manageable in research settings, it poses a significant challenge for practical adoption, particularly for mechanistic pavement design or quality assurance purposes. To overcome such limitations, amplitude-sweep testing has gained popularity due to significantly shorter testing times. Alongside the increasing use of the Linear Amplitude Sweep (LAS) test, the LAS-based healing method proposed by Xie et al. (2017) has also been adopted by various researchers [24–30].

The healing indicators commonly derived from healing tests are expressed in terms of the ratio of a material's property before damage (i.e., initial state) and after resting. Parameters used in the literature include stiffness modulus, number of cycles to failure, dissipated energy, pseudo-stiffness, continuum damage and fracture energy [19, 20, 24, 31, 32]. Although some studies have addressed the issue of incorporating elements such as thixotropy and internal heating [9, 33], most healing indices have been relatively simple without taking into account possible biases in measurements. Moreover, in addition to material-specific effects intrinsic to asphalt binders, artifacts in DSR testing due to the constraints of standard plate-plate configuration (e.g., edge fracture/instability, wall slippage, adhesion issues) may play a role in healing properties assessment [34, 35].

The exploration of test methodologies and criteria for the assessment of self-healing in asphalt binders delves into the objectives and challenges of Task Group 2a (TG2a) of RILEM TC 278-CHA. The present paper describes the experimental work conducted by active task group members to this end.

2 Research outline

The work of TG2a was conducted in two phases (Phase 1 and Phase 2).

Phase 1 was motivated by the need, discussed among members of RILEM TC 278-CHA TG2a, to evaluate and compare the aptitude of existing methods in discriminating and ranking asphalt binders in terms of their self-healing properties. To this purpose, TG2 launched an interlaboratory testing program in which three different protocols were scrutinized across different laboratories. The protocols were used to test a common array of materials sourced from distinct suppliers. To ensure consistency, each binder was sourced as a single batch from the corresponding supplier and distributed to all participating laboratories. Based on the outcomes and considerations that emerged from Phase 1, a single protocol was selected for the subsequent phase of the investigation.

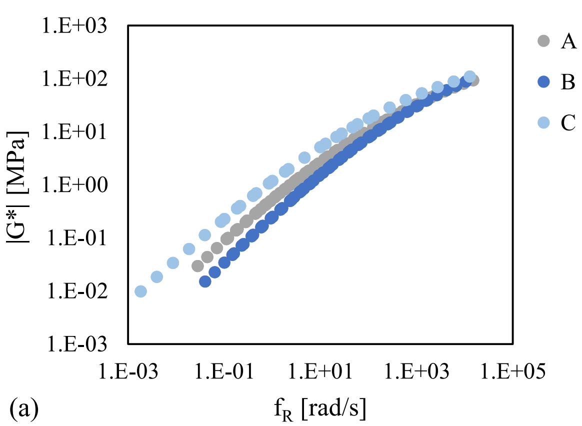
Phase 2 was aimed at gaining more insights into the selected protocol. To this purpose, the original version of the protocol was revised by introducing procedural changes to address three main aspects: i) Loading Scheme Adjustment—The mode of load application during the second loading phase was refined to improve reproducibility and decrease the viscoelastic ringing effect; ii) Rest Period Modification—A no-rest condition was incorporated to help differentiate between damage and other reversible non-linear effects; iii) Supplementary Rest Periods—supplementary tests with increasing rest times were integrated into the protocol to account for potential effects, such isothermal hardening, that could influence the measured self-healing response.

3 Materials

The set of asphalt binders considered in the experimental study included two neat binders and an SBS polymer-modified binder. The neat binders were provided by two refineries located in Ireland (Binder A, 40/60 pen grade) and Italy (Binder B, 70/100 pen grade); the polymer-modified binder was provided by a private company operating in France (Binder C, 30/45 pen grade). These binders were chosen to represent a wide spectrum of characteristics with two primary purposes: (1) to establish a baseline for future studies using broadly available materials and (2) to facilitate interlaboratory testing by using materials that may effectively allow the participants to distinguish their respective restoration and self-healing potentials.

All binders were subjected to a preliminary rheological characterization to determine their visco-elastic properties at various frequencies and temperatures. To this purpose, they were tested using frequency sweeps in the frequency range from 0.1 to 100 rad/s and in the intermediate temperature range between 5 and 35 °C. Measurements were carried out on unaged samples to avoid additional effects introduced by laboratory aging. The test data were fitted using the Christensen-Anderson-Marasteanu (CAM) model [36] to generate master curves of stiffness modulus (|G*|) and phase angle (δ) as a function of reduced frequency (f_R).

As shown by the results depicted in Fig. 1, Binder C exhibited the highest values of |G*| and lowest values of (δ) over the whole considered frequency



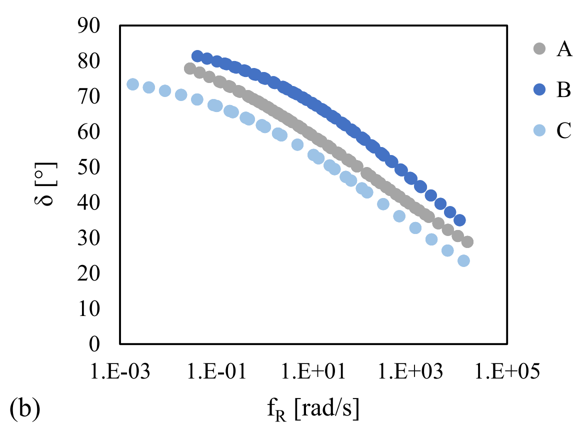


Fig. 1 Intermediate temperature master curves, at a reference temperature of 20 °C, of stiffness modulus (**a**) and phase angle (**b**)

interval, followed in the order by Binder A and Binder B. This outcome is fully coherent with expectations since it reflects the differences in type and penetration grade of the binders.

4 Phase 1—interlaboratory testing on healing protocols

Healing test protocols considered in the first phase of the experimental work included time-sweeps with a single rest period (TS-SRP), time-sweeps with multiple rest periods (TS-MRP), and linear amplitude sweeps with rest periods (LASH). All protocols entailed using DSR with 8-mm parallel plates and a 2-mm gap between plates. They were applied to test all the considered asphalt binders (A, B and C).

Results obtained from Phase 1, along with a full description of the protocols and the interlaboratory testing program, have been published by Baglieri et al. (2022) [37]. A summary of the main findings and observations that emerged from the investigation is reported below.

4.1 Findings from Phase 1

As discussed in previous work by TG2a, the comparison of healing performance (HI) derived from the TS-SRP, TS-MRP, and LASH protocols (summarized in Fig. 2 and Table 1) revealed significant variability. Although all tests were conducted in oscillatory shear strain mode under standardized conditions (20 °C and 10 Hz), the rankings obtained from these methods were inconsistent. The polymer-modified binder (Binder C) ranked highest in TS-MRP tests. However, it exhibited comparable healing to a neat binder (Binder B) in TS-SRP tests and performed the worst in the LASH test. Similarly, Binder B displayed conflicting behavior, demonstrating the highest restoration potential based on TS-SRP and LASH protocols but ranking the lowest in TS-MRP tests. Notably, Binder A exhibited considerably lower restoration potential than Binders B and C in TS-SRP tests but ranked second in the LASH and TS-MRP protocols. These outcomes highlighted the influence of protocol design and experimental conditions on the self-healing characterization of binders.

Table 1 Binder rankings for healing tests conducted in Phase 1

Method	Binder ranking
TS-SRP	Binder B > Binder C > Binder A
TS-MRP	Binder C > Binder A > Binder B
LASH	Binder B > Binder A > Binder C

In the continuation of the experimental work, it was decided to focus on a single method among those considered in the first phase. In this regard, the LASH-based approach was selected as the preferred one for evaluating self-healing in asphalt binders. Despite the challenges and limitations of the original procedure, the LASH test demonstrated notable advantages in efficiency and practicality compared to other test types. It offered a simpler and faster tool for healing assessment, addressing the challenges posed by the resource-intensive nature of time-sweep-based healing tests. Limited laboratory resources and time constraints further reinforced the decision to prioritize the LASH-based approach for Phase 2 of the experimental plan.

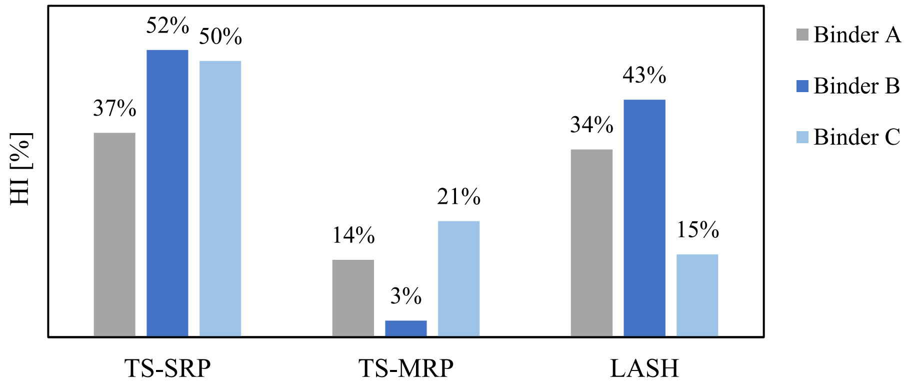


Fig. 2 Healing indicators for the testing protocols used in Phase 1 (adapted from [37])

4.2 Observations on the LASH test

The first issue faced by participants during LASH testing was the inconsistency and inaccuracy in the ramp to the initial strain of the second loading phase. In fact, during the transition from rest to the desired strain amplitude, data points were imprecise, with some DSR systems requiring several seconds to stabilize (Fig. 2). The problem was found to vary depending on the DSR's model, spindle geometry, and binder type. The inconsistency may stem from inertia-elastic or viscoelastic ringing, a known artifact in high-frequency oscillatory shear and stepped amplitude sweeps tests [38]. To address this issue, operators removed "outlier" data points at the start of the second loading phase, beginning the analysis only once the DSR readings stabilized (Fig. 3).

Another issue that may arise in amplitude sweep-based healing tests is the possible presence of edge effects during loading. Several studies have shown the impact of edge effects on modulus loss for asphalt binders during time-sweeps [40]. These edge effects, promoted by shear rate increases at the sample's periphery, cause instability flow and deformation ("necking") under excessive non-homogeneous forces. The result is a non-uniform deformation and partial immobilization of the sample, complicating the interpretation of test results. Other studies have demonstrated that amplitude-sweep tests are not immune to these effects [22, 34, 41, 42]. In the work by Safaei and Castorena (2016), three failure modes were identified (adhesive failure, cohesive cracking, and instability flow) across varying temperatures. Their findings indicated that an intermediate PG temperature minus 4 °C would be the appropriate testing temperature to ensure damage accumulation occurs without significant flow or adhesion issues.

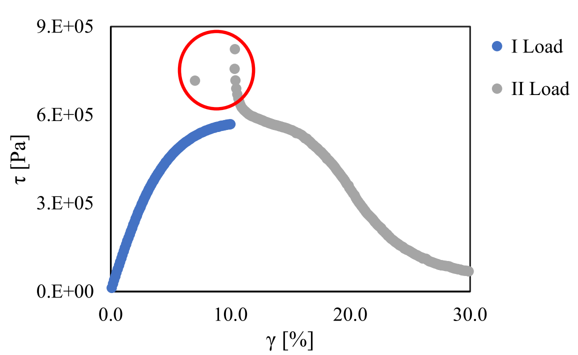


Fig. 3 Inaccurate zone of measurement (circled in red) in LASH test second loading phase. Due to viscoelastic ringing, it is demonstrated that a DSR may require additional time to stabilize ramping from 0.1% to the desired strain amplitude [39]

To comprehend the issue of instability flow as well as equipment-specific artifacts, inspections with video analysis tools were conducted as part of the interlaboratory tests to monitor deformations and geometric changes of samples during DSR measurements. To this purpose, samples made with the considered binders were subjected to amplitude sweeps and filmed to verify when sample geometry changed during the test. Videos were processed using commercial software to enhance brightness and contrast, and still, frames were extracted at one frame per second and binarized. A manually selected region of interest (ROI) representing the "undamaged" sample area (Fig. 4, presented by way of example for the unmodified Binder A) served as the basis for analysis. Four regions were defined: Regions 1 (R1) and Region 4 (R4) measured changes outside the sample area, while Regions 2 (R2) and Region 3 (R3) quantified changes inside the sample area. The white pixel areas in each region were averaged and normalized to assess geometric changes. This operation facilitated determining the flow strain amplitude (FSA), defined as the deviation from the initial linear region of the strain-energy curve before flow occurs; FSAs were determined for both the inner and outer regions [40]. The analysis highlighted the importance of selecting adequate testing temperatures or strain thresholds to minimize edge effects in amplitude sweep-based protocol (Fig. 5).

5 Phase 2—insights into LASH-based testing

5.1 Specimen preparation

The 8-mm diameter and 2-mm gap specimens for LASH-based testing at DSR were fabricated by following a common preparation process based on the use of silicone rubber mold, as shown in Fig. 6. The process consisted of various subsequent steps. Firstly, the binder was placed in a forced draft oven until it reached sufficient fluidity: this typically required 30 min for a 50-g container of material. Oven temperatures were selected to reduce the

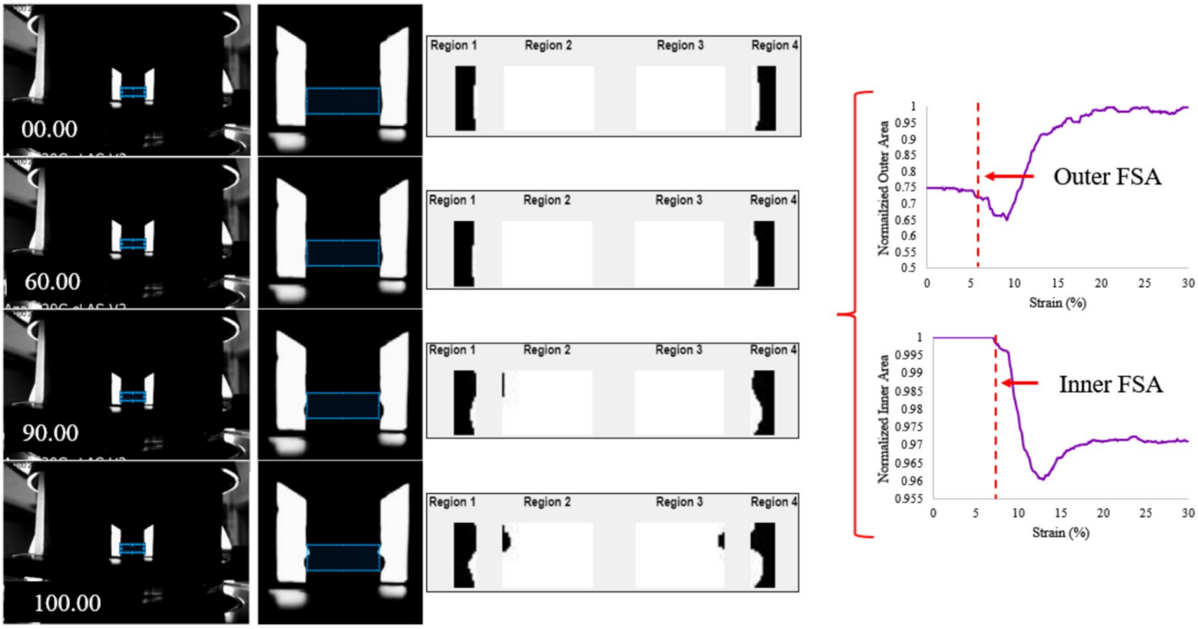
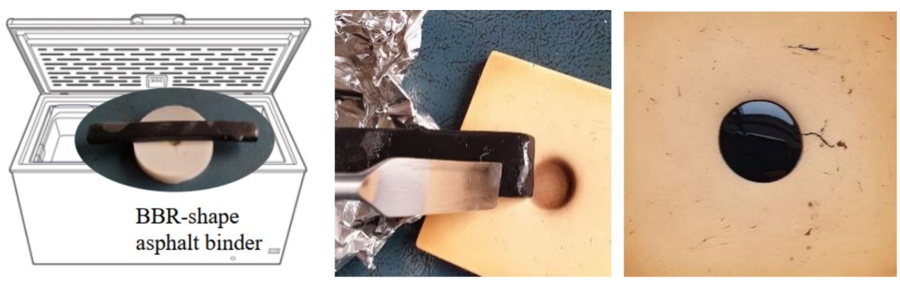


Fig. 4 Example of inner and outer FSA determination using DSR video analysis during the uninterrupted amplitude sweep [39]

Fig. 5 DSR sample preparation (left to right): BBR-shaped asphalt binder beam placed in a freezer, specimen dissection from asphalt beam and homogenized specimen after heating



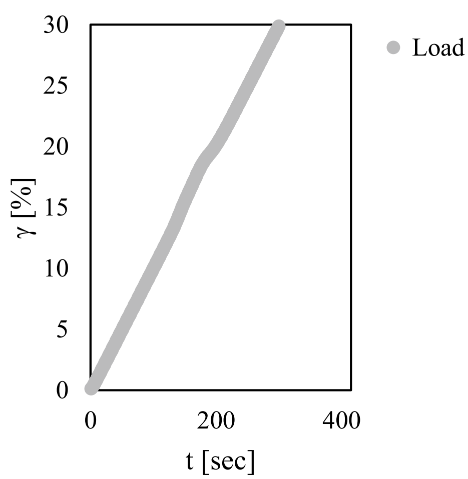


Fig. 6 Loading pattern of LAS test

potential overheating and premature aging (i.e., 130 and 150 °C for the neat and polymer-modified binder, respectively). After heating, the binder was poured into a pre-prepared frame typically used for bending beam rheometer. The reason is related to the need of preparing each specimen immediately before testing. After the beams were de-molded, the specimens were carefully wrapped in aluminum foil and stored at freezing temperatures (15 to − 20 °C). Before preparing for DSR testing, the beams were removed to room temperature and a small portion was dissected and placed into the silicone rubber mold using a heated spatula. To de-mold the specimen, it was put into a freezer at − 5 °C for 2 to 5 min with an aluminum foil cover; then, it was placed on the pre-heated DSR plates (45 or 50 °C for the neat binder and polymer-modified binder, respectively). The upper plate was moved to the trimming position, and the sample was trimmed according to AASHTO T 315–12 to be prepared for measurement.

5.2 Modified test procedure

The modified procedure for LASH-based testing involved performing shear strain amplitude sweeps under large oscillatory shear conditions using three different testing configurations: linear amplitude sweep (LAS), repeated linear amplitude sweep with a single rest period (R-LASH) and without rest period (R-LAS), and delayed linear amplitude sweep (D-LASH). These configurations were designed to evaluate the self-healing performance of asphalt binders while accounting for possible time-dependent effects. The neat binders (A and B) were exclusively considered for the modified LASH-based procedure of Phase 2 of the research to eliminate potential influences of the elastomer's presence on the results. Moreover, DSR video analysis revealed that neat binders were the most challenging materials to be tested when considering instability flow issues. All tests were carried out in three replicates at a constant temperature of 20 °C and frequency of 10 Hz.

5.2.1 LAS

Amplitude sweeps were used to evaluate the fatigue resistance of materials under incremental loading. They were also considered to select the appropriate damage level for rest periods in healing tests. LAS tests were performed following AASHTO TP 101–12 (2018). According to the standard, the binder was subjected to an initial frequency sweep, during which 0.1% strain was applied over a range of frequencies from 0.2 to 30 Hz. The subsequent linear amplitude sweep was carried out using oscillatory shear in strain-control mode at 10 Hz. The loading scheme consisted of intervals of constant strain amplitude, where each interval was followed by another interval with a 1% increment between intervals. Figure 6 shows the loading pattern imposed on the specimens during the LAS test, with minimum and maximum strain values equal to 0.1 and 30%, respectively.

5.2.2 R-LASH and R-LAS

R-LASH test consisted of two loading phases separated by a single rest period. The first loading phase followed an increasing shear strain pattern, starting from 0.1% and continuing until a specific damage level was reached. The second loading phase was conducted as a standard LAS test.

The damage level imposed in the first loading was established based on the peak in the shear stress (τ) versus shear strain (γ) curve, denoted as $\gamma(\tau_{peak})$. Two levels were considered in this study for R-LASH testing:

- level 1—γ value equal to 50% of $\gamma(\tau_{peak})$
- level 2—γ value equal to $\gamma(\tau_{peak})$.

The duration of the rest period was set to one of four values: 5, 30 min, 2, or 24 h. During the rest period, a low continuous oscillatory shear strain of 0.1% was applied at 10 Hz to monitor material stiffness, with data points recorded every 30 s. It is important to mention that during the application of the increasing shear strains, the occurrence of damage may be superimposed by non-linear effects due to the viscoelastic nature of the binder. Thus, it is of primary importance to verify whether the damage is imparted to the sample or if the response merely reflects the non-linearity of the material. R-LAS tests without a rest period were performed to verify the proper damage level imparted by the first loading. R-LAS tests were also conducted to determine whether damage could occur without healing due to the lack of rest. Figure 7 illustrates the loading patterns imposed on samples during repeated amplitude sweeps without a rest period and with a rest period of a given length.

5.2.3 D-LASH

D-LASH tests were introduced to account for the potential hardening of the material that may take place when it is left idle. This hardening effect could affect the response observed during the second loading phase of the R-LASH test. D-LASH tests involved performing a standard linear amplitude sweep on an undamaged sample after being conditioned with various rest times. An example of the loading pattern applied to the sample during the tests is illustrated in Fig. 8.

5.3 Experimental results

5.3.1 *Stress versus strain curves*

Figure 9a shows an example of shear stress versus shear strain curves derived from LAS test replicates carried out on binder A. Visual inspection of the curves in the figure indicates good repeatability of the test results, as evidenced by the close alignment of the three curves. This is further substantiated by the low coefficients of variation for τ_{peak} and $\gamma(\tau_{peak})$, which ranged between 1.20 and 1.80% for all test

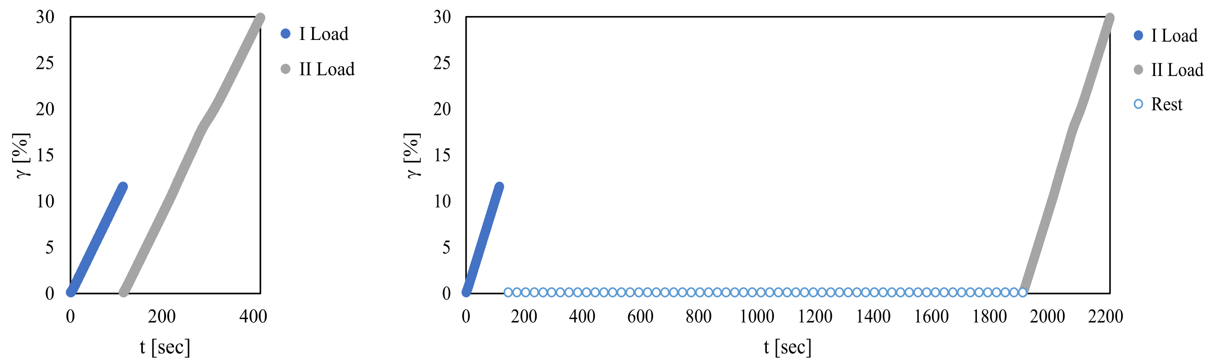
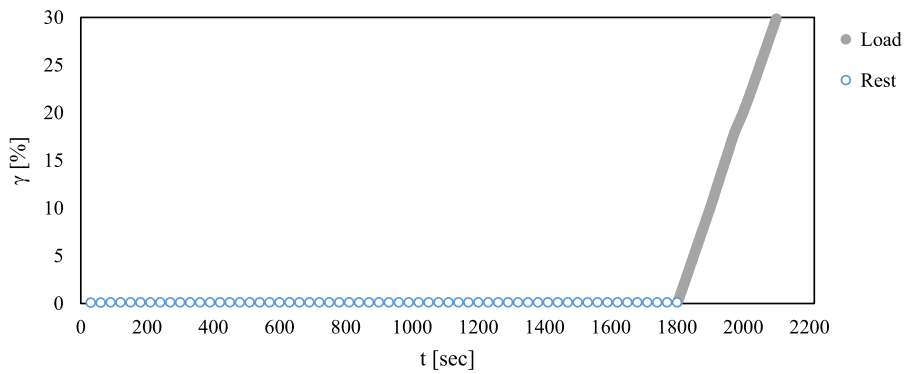


Fig. 7 Loading pattern of R-LAS (left) and R-LASH (right) tests with a rest period of 30

Fig. 8 Loading pattern of D-LASH test with a rest period of 30 min



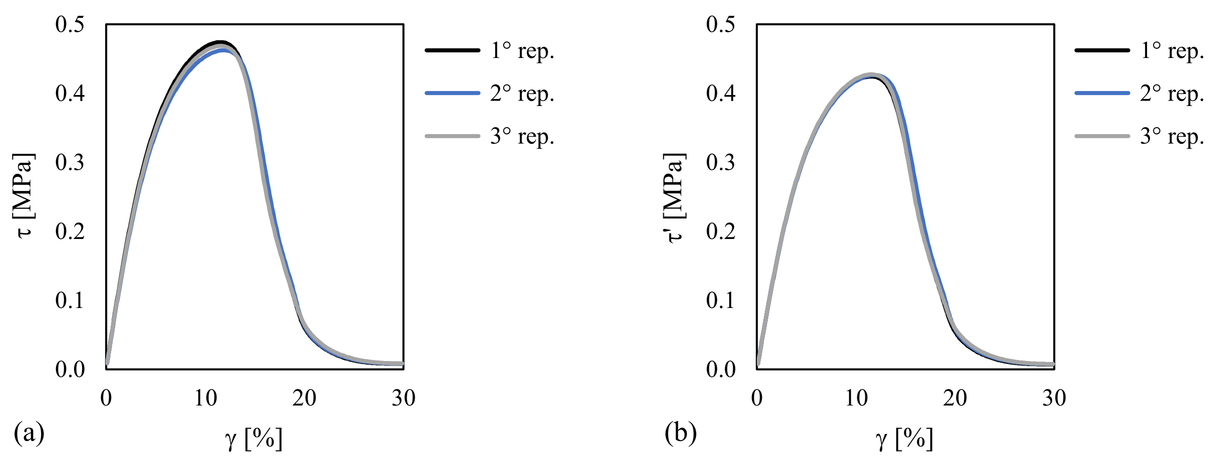


Fig. 9 τ versus γ (**a**) and τ' versus γ (**b**) curves derived from LAS tests on Binder A

conditions and materials considered in the study. In Fig. 9b, τ' represents the measured τ normalized with respect to the Dynamic Modulus Ratio (DMR) factor. This factor is the ratio of the initial norm of the complex modulus, which indicates the stiffness of the undamaged specimen under low strain conditions, to the linear viscoelastic norm of the complex modulus of the material. τ' was used instead of the measured τ to eliminate differences due to specimen-to-specimen variability. This adjustment reduced the coefficient of variation to values below 0.5%, as visually demonstrated in the graph where the results from the three repetitions collapsed on top of each other.

Figure 10 presents the results from R-LASH tests with no rest and 30-min rest performed on Binder A. In Fig. 10b, which corresponds to damage level 1, it is evident that the second loading phase initially overlaps with the first loading phase and then follows the path (curve defined by points) described by the material in the LAS test (which serves as the reference behavior). This would suggest that full healing occurred after 30 min of rest, as the material behavior in the R-LASH test is the same as that in the LAS test. However, Fig. 10a shows that the behavior of the material during the second loading phase in no-rest conditions is identical to that observed in the LAS

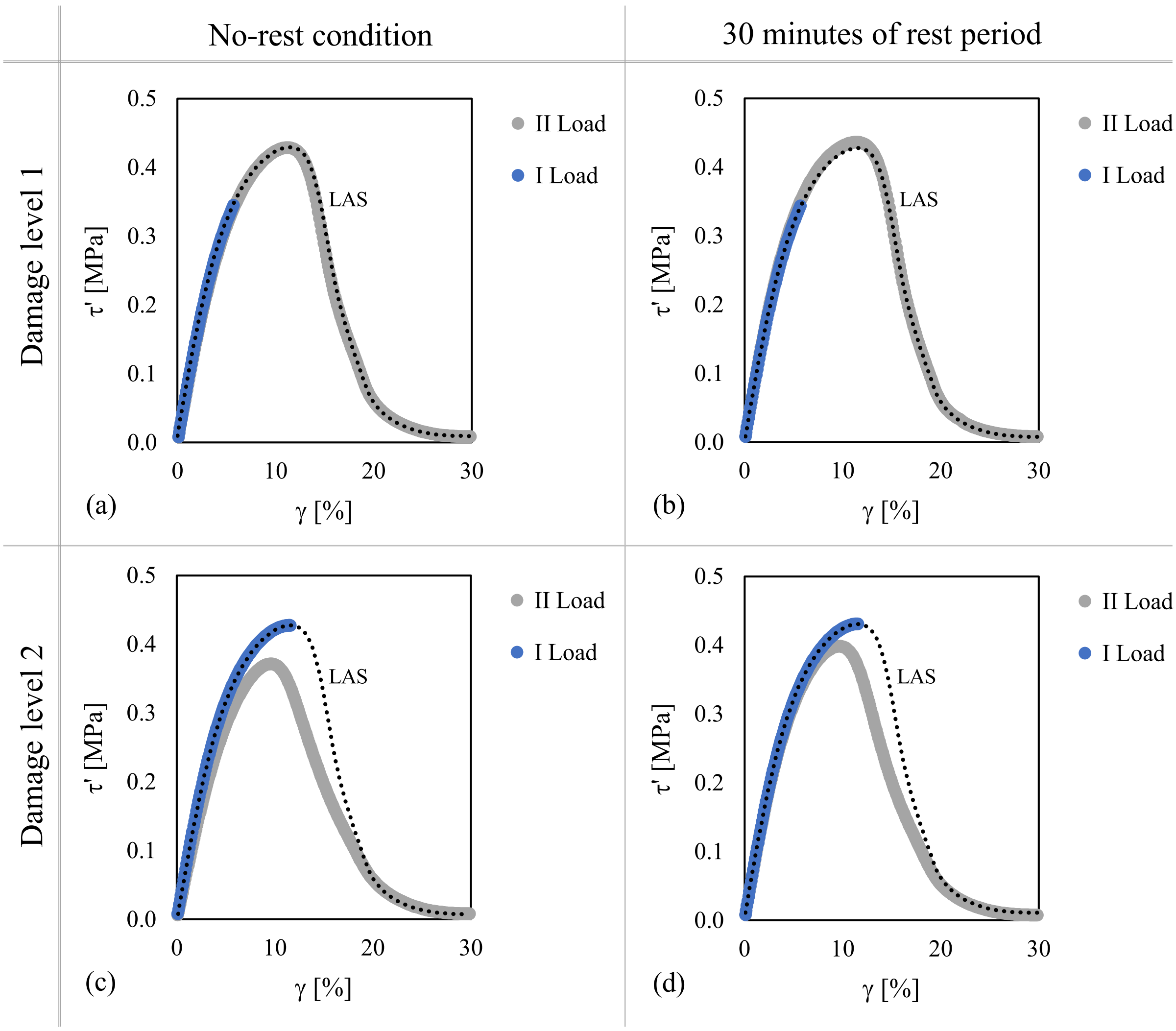


Fig. 10 Example of τ' versus γ outcomes derived from tests on binder A subjected to damage level 1 without rest (**a**) and with 30 min of rest period (**b**) and damage level 2 without rest (**c**) and with 30 min of rest period (**d**)

test. This indicates that no damage occurred in the first phase of loading. Therefore, deviation from linear viscoelastic behavior in the τ' versus γ curve is to be attributed entirely to non-linearity of the material. Figures 10c and d show that actual damage occurred when the strain value reached at the end of the first loading phase was increased to level 2. The occurrence of damage is clearly argued from the evidence that both reloading curves of R-LASH and R-LAS tests follow a different path with respect to the reference LAS curve. By comparing the various τ' versus γ curves, the magnitude of healing gained during the rest period and the remaining damage to be healed can be straightforwardly quantified. The magnitude of healing can be assessed by comparing the reloading curves of R-LASH and R-LAS tests to each other. The remaining unhealed damage can be determined by examining the difference between the τ' versus γ curves of the LAS test and the second loading phase of the R-LAS test.

However, it is important to note that the recovery of mechanical properties of the material during the rest period may be partly attributed to time-dependent effects, such as physical hardening under isothermal conditions. Figure 11, which compares the response of Binder A subjected to R-LASH tests at different rest times, provides evidence of such effects that may yield non-negligible levels. The increase in rest time from 30 min to 24 h resulted in a significant progressive increase in peak value of strain with respect to the no-rest condition. Since R-LASH tests were carried out on undamaged specimens, such an increase cannot reflect any healing but is associated with a time-dependent hardening.

Considerations reported above on the stress versus strain response of Binder A can be extended to Binder B, which exhibited a qualitatively similar behavior under the different types of tests.

5.3.2 *Energy-based analysis*

Dissipated strain energy (*w*) is widely used as a fundamental property to study the behavior of asphalt binders under repeated loading [43]. Pronk and Hopman [44] suggested that the energy dissipated during each loading cycle contributes to fatigue damage. Any change in the material's internal structure due to damage is then reflected in alterations to the energy dissipation process [45, 46].

Examples of *w* values plotted as a function of shear strains gathered from LAS tests on Binders A and B are displayed in Fig. 12.

After the rest period was applied to the materials subjected to a given level of damage in R-LASH tests, cohesive healing contributed to such damage repairing. This was reflected in changes of *w* curves, as shown by diagrams reported in Fig. 13. As expected, the curves corresponding to the first loading phases collapsed on top of the *w* curves of LAS tests because the response was independent of the rest period applied right after loading. As the binders were reloaded, the deviation of *w* values from the reference curves was influenced by the level of damage

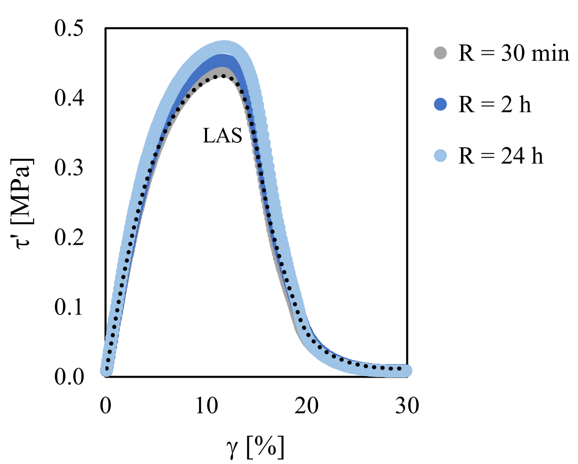


Fig. 11 τ' versus γ curves derived from D-LASH tests on binder A in non-rest conditions and after rest time equal to 30 min, 2, and 24 h

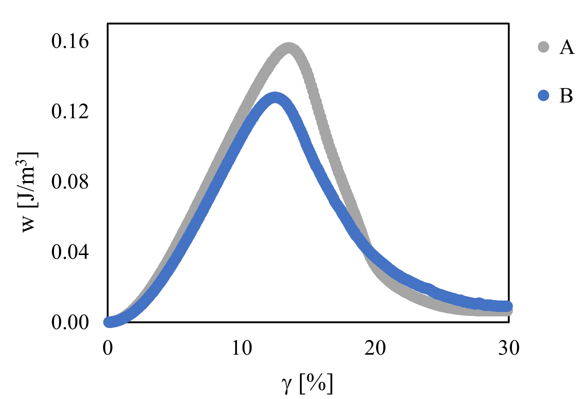


Fig. 12 *w* versus γ curves derived from LAS tests on binders A and B

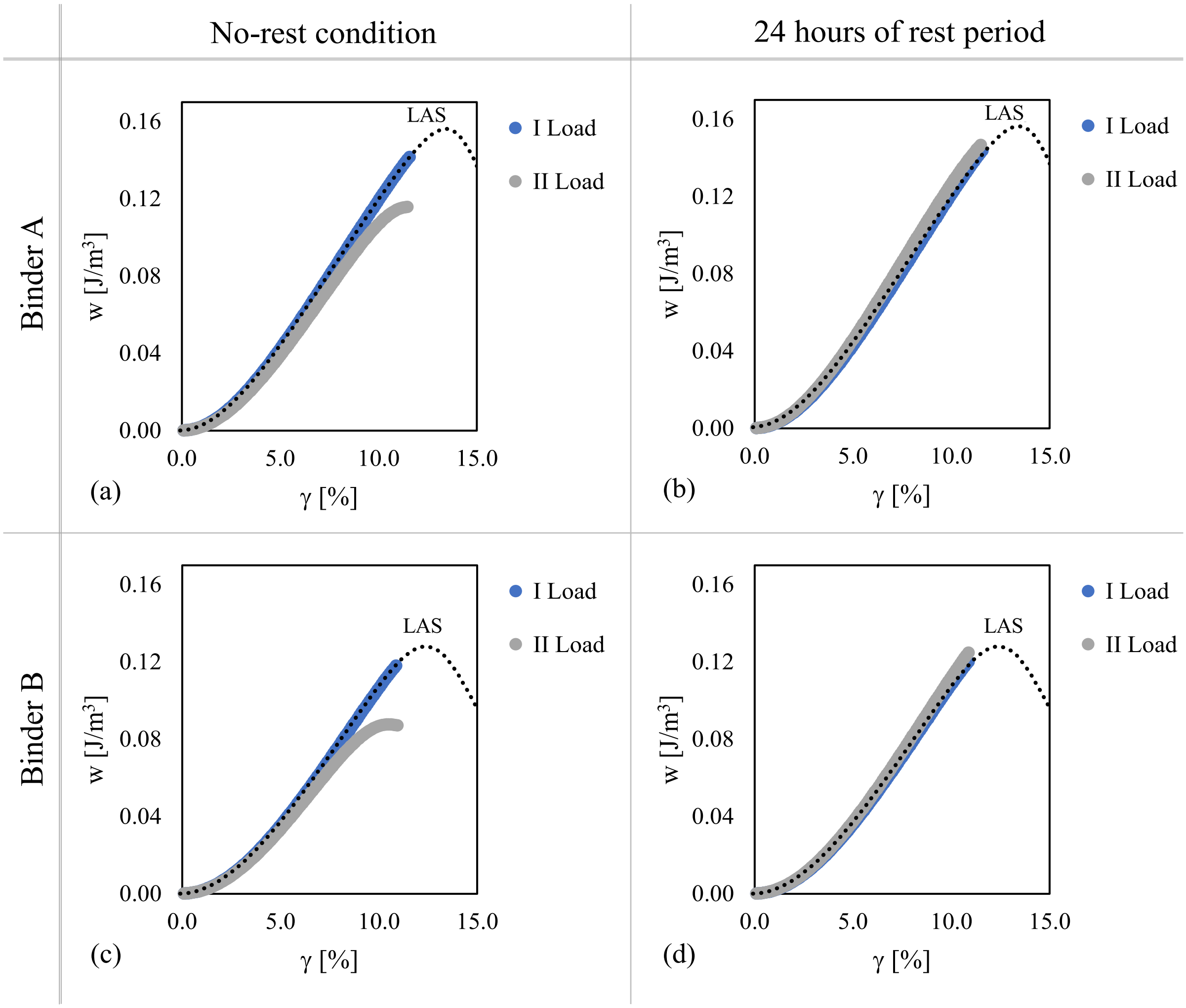


Fig. 13 *w* outcomes derived from R-LASH tests on binders A and C subjected to damage level 1 without rest (**a** and **c**) and with 24 h of rest period (**b** and **d**)

imposed during the first loading phase. This is displayed in Fig. 13a and c when no rest was applied. The longer the rest period, the closer the reloading *w* curve to that of the first phase. In certain cases, the *w* values during the second loading phase exceeded the values obtained from LAS tests, as shown in Fig. 13b and d for a 24-h rest period. This behavior, observed in the τ versus γ curves, is likely due to effects related to hardening phenomena occurring when the material was left idle under isothermal conditions. Additionally, Fig. 14 presents the *w* curves derived from D-LASH tests conducted with different rest periods. A comparison of the curves reveals that longer rest periods led to increased *w* values, further confirming the effect of rest time on material response.

5.3.3 Simplified viscoelastic continuum damage-based analysis

The simplified viscoelastic continuum damage (S-VECD) model has been adopted to interpret linear amplitude sweep test data. This model allows for the derivation of the damage characteristic curve (DCC), which links material integrity (pseudo-stiffness, C) to damage intensity (internal state variable, S) [34, 41]. Figure 15 displays the DCCs determined from LAS tests for Binders A and B.

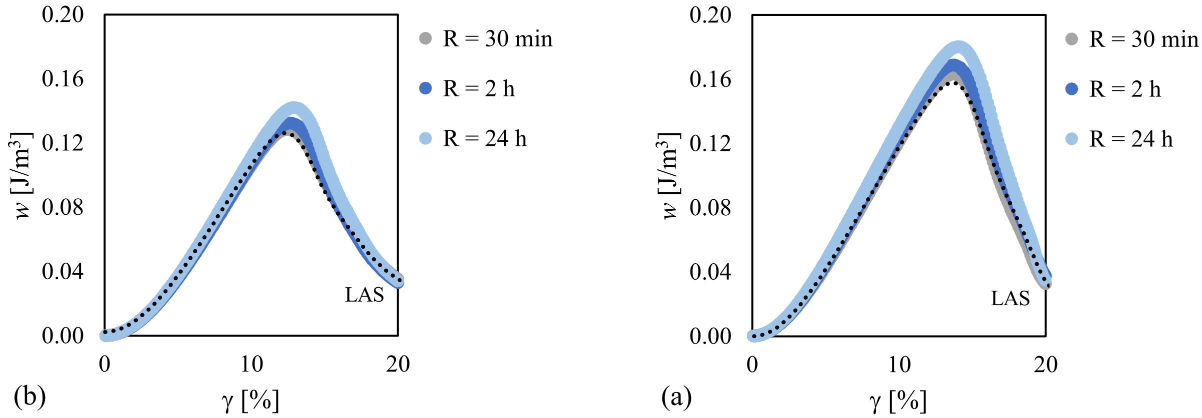


Fig. 14 Comparison of w curves derived from D-LASH tests on Binder A (**a**) and Binder B (**b**) with rest periods of 30 min, 2, and 24 h

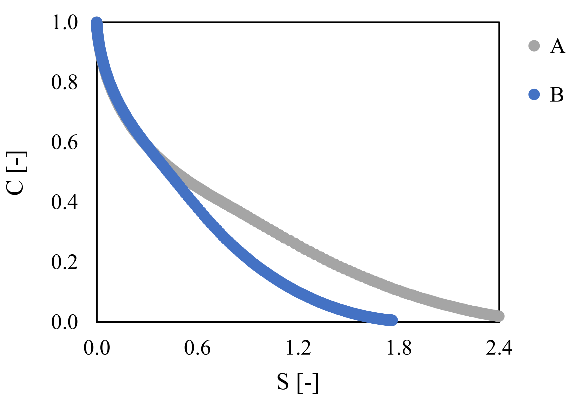


Fig. 15 DCCs derived from LAS tests of binders A and B

When applying the S-VECD analysis to R-LASH data, two DCCs corresponding to the two loading phases of the test can be obtained. This is shown in diagrams reported in Fig. 16, derived from test data measured in the range of γ between 0.1% and $\gamma(\tau_{peak})$. As in the previous case, the first loading phase overlapped with the reference behavior observed during the LAS test, as it was independent of the rest period applied after the first loading. For the reloading phase, the initial value and shape of DCCs were influenced by the extent of the rest period. It is worth noting from Fig. 16b and d that initial values of C recorded in the second loading phases after 24 h of rest were greater than 1, causing the entire DCCs to shift above those of the first loading phase. It is inferred that such an occurrence can also be imputed to hardening effects caused by the microstructural reorganization of material during the rest period. This outcome is further substantiated by the results obtained from D-LASH tests at different rest periods, as displayed in Fig. 17. The comparison of DCCs shows that the adoption of longer rest periods translated into a progressive vertical shift of curves. This implies that for any specific level of material integrity, the binder is able to endure a damage intensity that increases as the rest period is longer.

6 Summary and conclusions

The experimental work carried out by the RILEM TC CHA-278 TG2a aimed at providing new insights into understanding and testing the self-healing properties of asphalt binders.

Multiple self-healing test protocols were evaluated and compared through interlaboratory testing in the first phase of the research. The three proposed protocols—Time-Sweep Single Rest Period (TS-SRP), Time-Sweep Multiple Rest Periods (TS-MRP), and Linear Amplitude Sweep with Healing (LASH)—were used to test a common array of asphalt binders. Results obtained by different laboratories revealed conflicting binder rankings across the three protocols, emphasizing the impact of test design and conditions. The findings from interlaboratory testing also indicated that material-related biasing effects, such as instability flow, viscoelastic ringing, and equipment-specific artifacts limit current fatigue-healing protocols. Incorporating video analysis tools into the

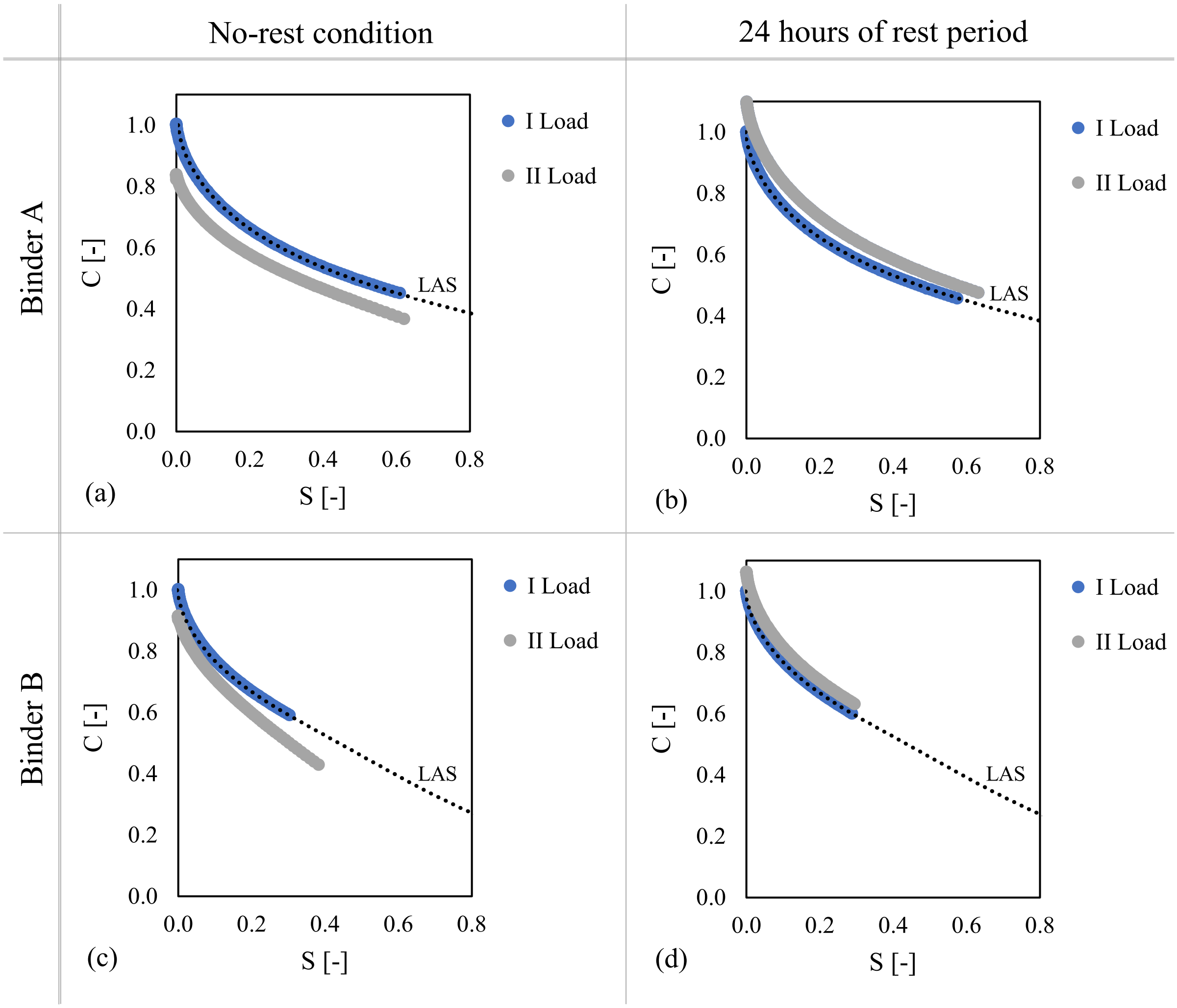


Fig. 16 DCCs derived from R-LAS tests on Binders A and B subjected to damage level 1 without rest (**a** and **c**) and with 24 h of rest period (**b** and **d**)

protocols offered practical criteria for identifying failure points and improving data reliability.

Among the three protocols, the LASH test was selected as the preferred and most practical choice for the second testing phase. The original version of the protocol underwent some modifications to address some specific aspects, as: (1) the loading scheme was adjusted to refine load application during the second loading phase, reducing viscoelastic ringing and improving reproducibility; (2) a no-rest condition was introduced to distinguish damage from non-linear effects; and (3) supplementary tests with increasing rest periods were added to account for hardening effects. The outcomes of the second phase of experimental work demonstrated that the rest periods' duration significantly influenced the materials' response, as observed through dissipated energy and continuum damage metrics. The dissipated energy w proved to be a reliable indicator of changes in the specimen's damage level, effectively linking R-LASH and D-LASH tests through damage accumulation and hardening phenomena. Applying the simplified viscoelastic continuum damage (S-VECD) model further revealed that longer rest periods impacted the restoration of material, with some samples achieving pseudo-stiffness values exceeding their initial states.

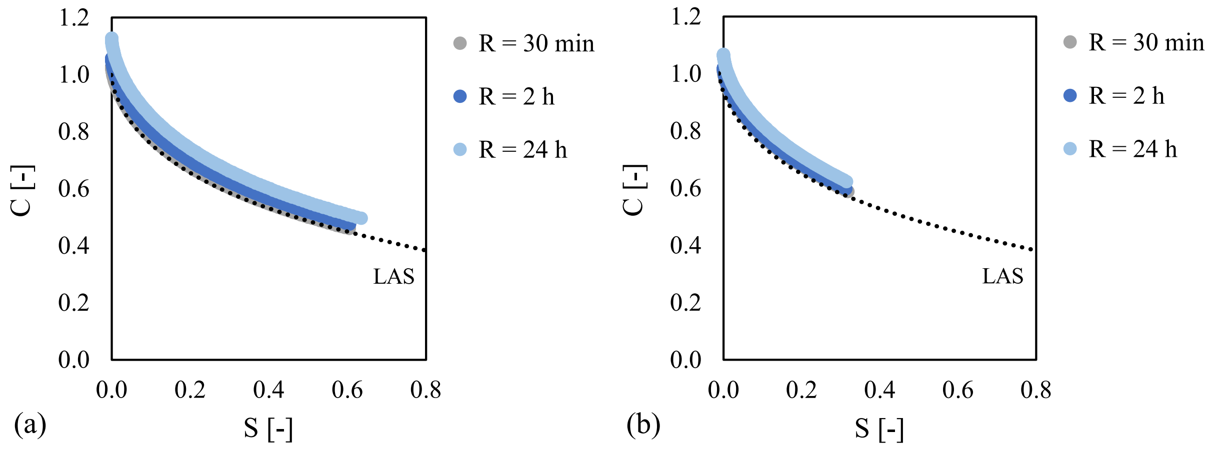


Fig. 17 Comparison of DCCs derived from D-LASH tests at increasing rest periods on Binder A (**a**) and Binder B (**b**)

Further investigation of D-LASH tests suggests that microstructural reorganization during rest time enhances the material's ability to endure subsequent damage, leading it to be a source of bias in healing assessments. By leveraging insights from D-LASH tests, it may be possible to isolate these hardening effects, enabling a more accurate evaluation of actual healing mechanisms.

The work done by the task group is deemed to have produced useful strides in the study and characterization of self-healing properties of asphalt binders; however, several areas require further exploration. One key focus is the impact of aging factors such as thermo-oxidative, moisture-related, and UV-induced aging—on binder healing behavior, as these factors are critical to understanding long-term performance. Additionally, the role of additives, including recycling agents and antioxidants, should be evaluated to determine their effects on binder performance. Finally, extending laboratory findings to field applications is essential to validate the protocols and assess their ability to predict in-service performance accurately. Such research areas could fall within the objectives and scope of a new RILEM TC that would continue investigating this topic.

Author contributions O. Baglieri: Conceptualization, Writing—original draft, Writing—review and editing, Supervision R.M. Aurilio: Formal analysis, Investigation, Writing—original draft, Visualization F. Miglietta: Formal analysis, Investigation, Writing—original draft, Visualization L. Tsantilis: Investigation, Writing—review and editing, Visualization H. Baaj: Conceptualization, Writing—review and editing, Supervision.

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