

## Article

# Evaluation of Anti-Aging Effect in Biochar-Modified Bitumen

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**Abstract:** Increasing environmental awareness has led to a great research effort towards the formulation of increasingly sustainable pavements, mainly by developing bituminous mixtures incorporating waste materials. Furthermore, some waste materials have been proved to be useful for enhancing the performance of road bitumen and bituminous products, so their use is a potential solution for ensuring environmental, economic, and also technical benefits. Amongst the different wastes to be used for bitumen modification, a possible one is that obtained via the pyrolysis of biomass, named biochar. In the research reported here, a selected biochar was added to bitumen to verify the possibility of improving bitumen performance in terms of photo-oxidation resistance, which is a major problem in urban areas where black flexible pavements contribute to the urban heat island effect. Different biochar amounts were selected, and two different aging methods were performed: short-term aging and UVB aging resistance; they were monitored using rheological and spectroscopic analysis. The structural changes in bitumen in terms of carbonyl and hydroxyl accumulation were observed at various UV irradiation times. All the experimental data indicate that the use of biochar can have a positive effect on the UV resistance of bitumen, lowering its photo-oxidation tendency. This may lead to reductions in use of natural, non-renewable materials, since intervention maintenance may be scheduled at longer terms.

**Keywords:** biochar; biochar-modified bitumen; aging performance; short-term aging; rheology; UV irradiation; FTIR analysis



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## 1. Introduction

In recent years, there has been an increase in CO<sub>2</sub> emissions due to the growth of industry, which has led to an increase in the amount of waste of various kinds [1,2].

The scientific world focuses on reuse of these wastes, including organic waste, to avoid its incineration or accumulation in landfills. Nowadays, the road paving sector is increasingly focused on developing sustainable pavements in order to replace conventional materials with waste materials, while maintaining or even improving the original performances. Indeed, the interest is extremely high, due to the huge amount of virgin materials involved in pavement construction and maintenance activities. Therefore, great attention has been paid in investigating possible wastes to be used in pavement construction and maintenance activities, as well as for road and railway embankment construction, not only as a soil/aggregate replacement but also as a soil stabilizer [3].

On the other hand, great volumes of wastes are often incinerated or buried in landfills, producing a negative effect both in terms of the environment-related issues and human health. A valid alternative for the treatment of organic waste is to subject it to a pyrolysis process, reducing the emissions attributable to the incineration process and obtaining biochar as a product, which is socially sustainable and widely used in different sectors, as seen previously. A widely used technique to exploit organic waste is pyrolysis, achieving not only a decrease in CO<sub>2</sub> emissions compared to incineration but also a product widely used in different areas [4,5].

Through rapid decomposition of materials in the absence of oxygen, biomass is converted into a liquid product (bio-oils), a solid residue (biochar), and various gas products. Several studies have been conducted on the application of biochar in various uses [5–9], which also include road pavements [10,11].

Biochar is composed primarily of carbon atoms and is characterized by its porous nature. Numerous sources, including agricultural straw, animal waste, industrial organic waste, and municipal sludge, can yield biochar [12,13].

Studies have shown that biochar reveals good compatibility with asphalt binders: Zhao et al. [7] investigated the production of asphalt modified with biochar considering different parameters of production, in terms of processing temperature, pressure, and heating velocity; in every case examined, biochar had positive effects in terms of durability, reductions in temperature sensitivity of asphalt binder [14], and, in general, increment in final properties. Xinxing et al. [15] proved that biochar added to asphalt binder has great potential to be used as volatile organic compound (VOC) inhibitors. Indeed, VOC adsorption was influenced by different types of biochar in terms of nature, dimensions, and compositions.

Recently, several studies have also investigated use of biochar in road pavements construction, for porous asphalt in order to reduce pollution from runoff on site [16,17], in agriculture to improve the contribution of nutrients to soil, or as a stabilizer in peatlands [3,12,18].

Although many studies report the benefits of using biochar in road engineering, there are only a few that deal with the oxidative aging of bitumen–biochar mixtures. This is a fundamental aspect to be deepened as oxidative aging is an inevitable process that damages the long-term performance of asphalt binders [19]. The aim of this study was to evaluate if the addition of biochar to road bitumen can improve the behavior of the modified binder produced, in terms of aging resistance and mechanical performances. Therefore, the properties of bitumen–biochar mixtures at different percentages of biochar were investigated; the properties of mixtures produced before and after short-term aging were evaluated in terms of conventional test and rheological properties. In addition, the samples produced were subjected to photo-oxidative aging, to investigate their anti-aging behavior using spectroscopic analysis. Indeed, photo-oxidation resistance is a major problem for flexible pavements in general and for paved urban areas where the dark surface contributes to the urban heat island effect [20].

## 2. Materials and Methods

### 2.1. Materials

#### Biochar-Modified Bitumen

A 50/70 penetration-grade bitumen for road application was used in this research: the general properties and grade of the bitumen used are summarized in Table 1. A commercial biochar powder used in the food industry was selected as an additive. Specifically, as indicated in the technical dossier, this biochar was obtained from pyrolysis of birch and beech wood. Table 2 shows the chemical–physical properties of the commercial biochar powder used.

**Table 1.** Characteristics of pure bitumen.

Characteristics	Standard	Unit	50/70
Penetration at 25 °C, pen	[21]	0.1*mm	52.25
Ring and ball softening point, T <sub>R&amp;B</sub>	[22]	°C	52.6
Penetration at 25 °C, pen (After short-term aging, according to EN 12607-1)	[21]	0.1*mm	39.3
Ring and ball softening point, T <sub>R &amp; B</sub> (After RTOFT according to EN12607-1)	[22]	°C	56
Viscosity at 100 °C	[23]	Pa*s	2.20
Viscosity at 135 °C	[23]	Pa*s	0.29

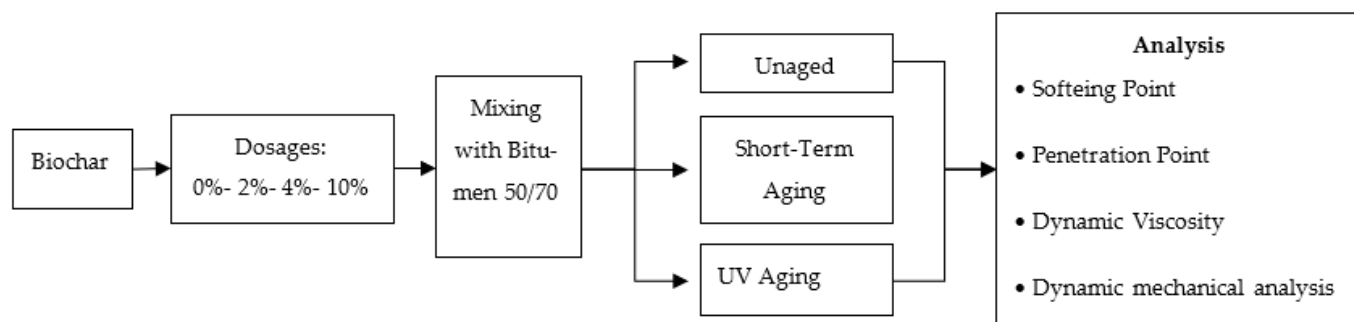
**Table 1.** *Cont.*

Characteristics	Standard	Unit	50/70
Viscosity at 150 °C	[23]	Pa*s	0.15
Viscosity at 180 °C	[23]	Pa*s	0.1

**Table 2.** Properties of biochar powder.

Chemical-Physical Characteristics	
Parameter	Tolerance
Humidity	12.0% max
Ashes	4.0% max
Benzopyrene	10 µg/kg max
Arsenic	3 mg/kg max
Cadmium	1 mg/kg max
Mercury	1 mg/kg max

The biochar-modified bitumen samples for this research were created by subjecting them to a high-shear mixer from Silverson, operating at 3000 rpm and a temperature of 180 °C for a period of 2 h. Modified biochar–bitumen blends were prepared with the addition of 3 different percentages of biochar: 2% wt/wt (named 2% Biochar), 4% wt/wt (named 4% Biochar), and 10% wt/wt (named 10% Biochar). For content higher than 10%, it was not possible to produce, at laboratory scale, a homogenous blend to be tested for rheological characterization. All sample products were subjected to the same characterization, as shown in Figure 1.

**Figure 1.** Experiment plan.

## 2.2. Methods

To investigate the binders' behavior at both intermediate and high temperatures at different aging conditions, empirical characterization in terms of softening point and penetration tests of untreated bitumen and biochar-modified bitumen was carried out according to [21,22], before and after rolling thin film oven test (RTFOT). Dynamic viscosity was measured at different temperatures for all samples tested, with a Brookfield viscometer (DV-III™ Ultra Rheometer, Middleboro, MA, USA), according to [23].

Dynamical Mechanical Analysis (DMA) was also performed to characterize the rheological properties of the binders studied and, in particular, to examine their visco-elastic properties. According to [24] Anton Paar Physica MCR 10, a dynamic shear rheometer was used in conducting the dynamic mechanical analysis. The frequency sweep tests were performed in a temperature range from −10 to 180 °C, with a plate–plate geometry, using two plates with different diameters: an 8 mm diameter plate was used for low temperatures, and a 25 mm diameter plate for high temperatures. Preliminary strain sweep tests were conducted too, in order to define the linear viscoelastic region for all the materials studied, and, consequently, the strain level to be applied for the frequency sweep was set equal to 1% for all the binders, in order to operate within the linear viscoelastic range. The

master curves for the viscoelastic functions were generated using  $T = 30\text{ }^{\circ}\text{C}$  as a reference temperature by shifting the experimental isotherms horizontally, taking into consideration the WLF (Williams–Landel–Ferry) shift factors. [25]. Different parameters were measured, such as complex shear modulus,  $G^*$ , storage modulus,  $G'$ , loss modulus,  $G''$ , and phase angle,  $\delta$ . All samples were subjected to two different aging processes: thermal aging and photo-oxidation aging. More precisely, thermal aging was performed, in accordance with [26], using the RTFOT procedure at a constant airflow of 4000 mL/min and a rotation speed of 15 rpm for 75 min at  $163\text{ }^{\circ}\text{C}$ .

For real-scale production, storage stability was also evaluated according to [27] on modified blends prepared with the addition of 2%, 4%, and 10% biochar. The test was carried out by storing the samples poured in an aluminum tube at high temperature in an oven set at  $180\text{ }^{\circ}\text{C}$  for 72 h. After high-temperature storage, the upper and lower outer layers of the blends were extracted for testing, including penetration, softening point, and elastic recovery, each performed in duplicate.

In order to evaluate the photo-oxidative aging of the biochar-modified bitumen, an accelerated aging test was carried out using a Q-UV chamber (by Q-LAB, USA) supplied with UVB-313 nm fluorescent lamps, at  $70\text{ }^{\circ}\text{C}$ .

Attenuated Total Reflectance–Fourier Transformation Infrared Spectroscopy (ATR-FTIR) with a Spectrum One spectrometer from PerkinElmer, Waltham, MA, USA was employed to track photo-degradation. This involved performing 16 scans with a resolution of  $4\text{ cm}^{-1}$ . The ATR-FTIR spectra displayed were selected based on the normalized results obtained from at least three samples. For each sample, ATR-FTIR analyses were performed at various points until overlapping spectra were identified. UV irradiation aging was studied by observing the variations collected at various exposure times, especially those related to two characteristic bands: carbonyl peak (centered at ca.  $1700\text{ cm}^{-1}$ ) and hydroxyl peak (at ca.  $3600\text{--}3200\text{ cm}^{-1}$ ).

Based on the literature, the alterations in the structure of both unaltered and biochar-modified bitumen are determined through the following calculations [28]:

$$I(\text{OH}) = \frac{\text{Area of the hydroxyl band centred between } 3600 - 3200\text{ cm}^{-1}}{\text{Area of the CH}_2 \text{ centred at ca. } 1455\text{ cm}^{-1} + \text{Area of the CH}_3 \text{ band centred at ca. } 1376\text{ cm}^{-1}} \quad (1)$$

$$I(\text{CO}) = \frac{\text{Area of the carbonyl band centred at ca. } 1700\text{ cm}^{-1}}{\text{Area of the CH}_2 \text{ centred at ca. } 1455\text{ cm}^{-1} + \text{Area of the CH}_3 \text{ band centred at ca. } 1376\text{ cm}^{-1}} \quad (2)$$

### 3. Results and Discussion

#### 3.1. Bitumen and Modified Binders' Characterization

The results of the empirical characterization carried out in terms of penetration and softening point tests of unaged and aged bitumen and binders' containing different amounts of biochar are summarized in Figure 2. The results show that biochar, regardless of the percentage added, increases the rigidity of bitumen, as expected. Indeed, with an increase in biochar content, the softening point increases, and the penetration of asphalt binder at  $25\text{ }^{\circ}\text{C}$  decreases. These results highlight a beneficial effect in bitumen resistance against penetration due to the presence of biochar particles.

Dynamic viscosity measurements were carried out on all the samples studied and, for comparison purposes, pure bitumen was also tested. Figure 3 shows the results of the viscosity tests carried out. The viscosity of biochar-modified bitumen increases as the percentage of biochar added increases, in agreement with the results of the empirical tests. It is important to evaluate how much the viscosity increases, because if this parameter increases too much, it compromises the possibility of using modified binders for road applications. Therefore, the viscosity at  $135\text{ }^{\circ}\text{C}$  was evaluated for each sample, and the values are highlighted in Figure 3.

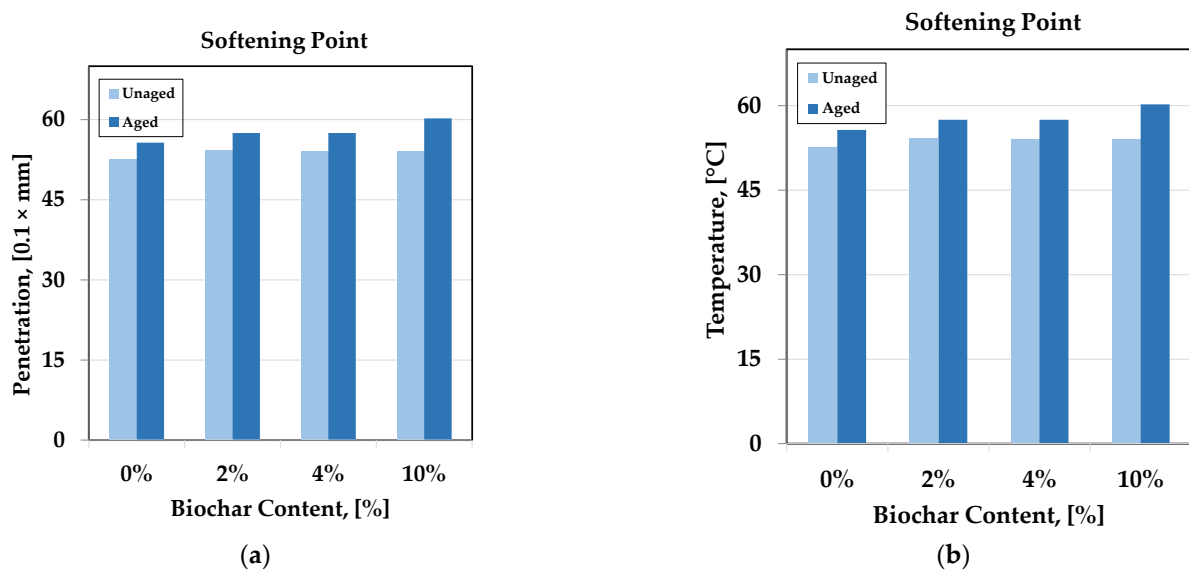


Figure 2. (a) Penetration test of all samples investigated, (b) softening point of all samples investigated.

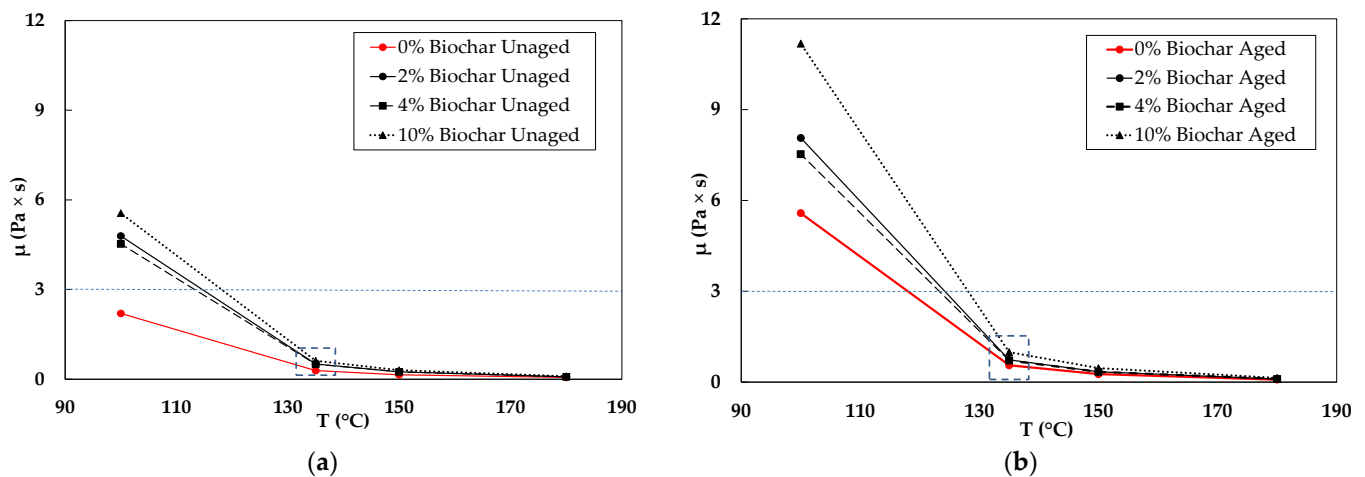


Figure 3. Dynamic viscosity of the binders studied, measured using a Brookfield rotational viscometer: (a) unaged, (b) aged.

The viscosity at 135 °C is a fundamental parameter for determining the feasibility of road bituminous mixtures at the production level. Technical specifications require that the viscosity of the binder at 135 °C must be lower than 3 Pa\*s in order to avoid pumpability problems during production at a large scale in the plant [29,30]. For all investigated samples, this parameter was always less than 3 Pa\*s.

Comparison of the master curves for the complex modulus,  $G^*$ , is depicted in Figure 4, for both unaged (Figure 4a) and aged conditions (Figure 4b). It can be noticed that while the effect of the biochar modification can be neglected, in terms of mechanical properties, in unaged conditions, after aging, the biochar-modified binders prove to have higher mechanical performance (higher moduli), especially at low loading frequencies (i.e., at high temperatures), and this effect is more appreciable for the highest biochar content (10%).

The addition of biochar did not cause significant changes to the rheological behaviour of the material in terms of  $G^*$ , both for the unaged binder and the aged one. Therefore, it was decided to evaluate the behaviour of the elastic and viscous components of the modulus for each formulated binder to investigate the change in each individual contribution.

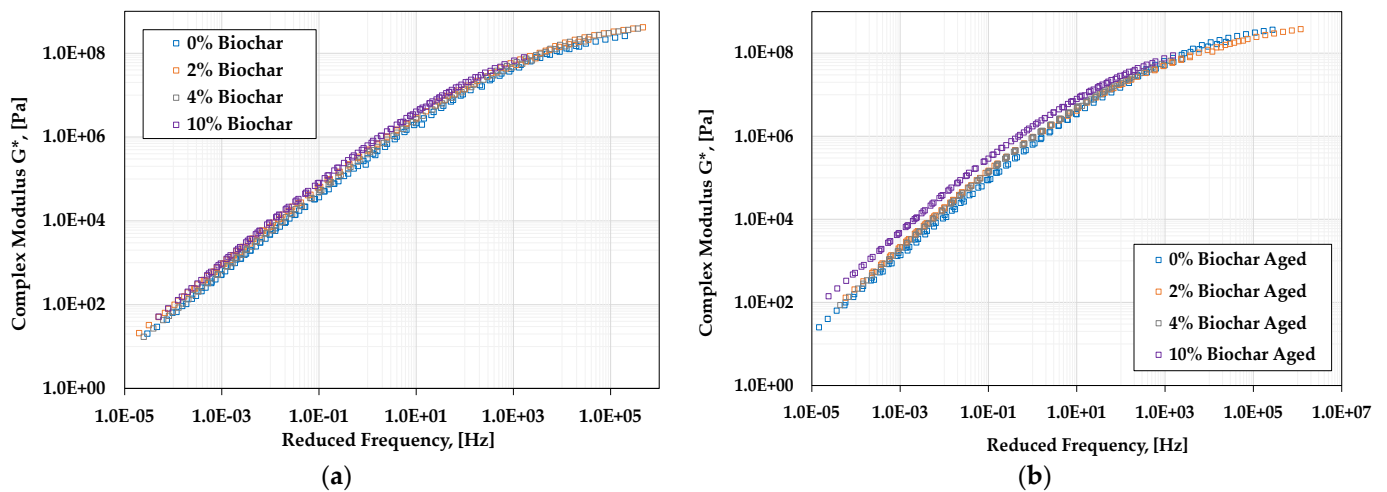


Figure 4. Master curves of  $G^*$  and  $G^*$  for binders studied, in unaged (a) and aged conditions (b).

Figure 5a–h show the results in terms of the master curves of biochar-modified bitumen according to DSR tests at 30 °C for all the binders studied. Loss and storage modulus values at different frequencies were determined by horizontally shifting the experimental isotherms using WLF shift factors, assuming a reference temperature of 30 °C.

To better evaluate the effect of the additive, in terms of aging resistance of bitumen, the crossover frequency values were studied considering unaged bitumen and short-term aging. The Aging Index (AI) was calculated using Equation (3) (see Equation (3) below), according to the literature [31], and the results are shown in Figure 6. The results obtained prove that the addition of biochar reduces the aging process of bitumen in terms of rheological properties. Indeed, for all modified binders, the Aging Index (AI) proves to be lower than for the neat unmodified bitumen, as shown in Figure 6. In detail, the aging index is reduced from 43.5% to 36.5% when 10% biochar is dispersed into the neat bitumen. So, it can be concluded that biochar has a protective effect in terms of short-term aging.

$$AI = \frac{\text{Unaged crossover frequency} - \text{aged crossover frequency}}{\text{unaged crossover frequency}} \times 100 \quad (3)$$

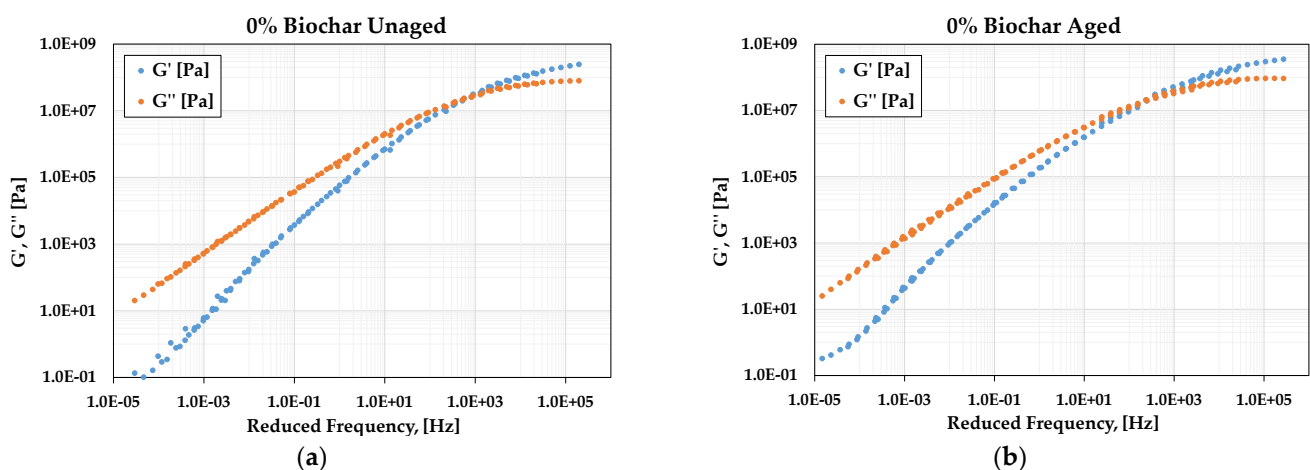
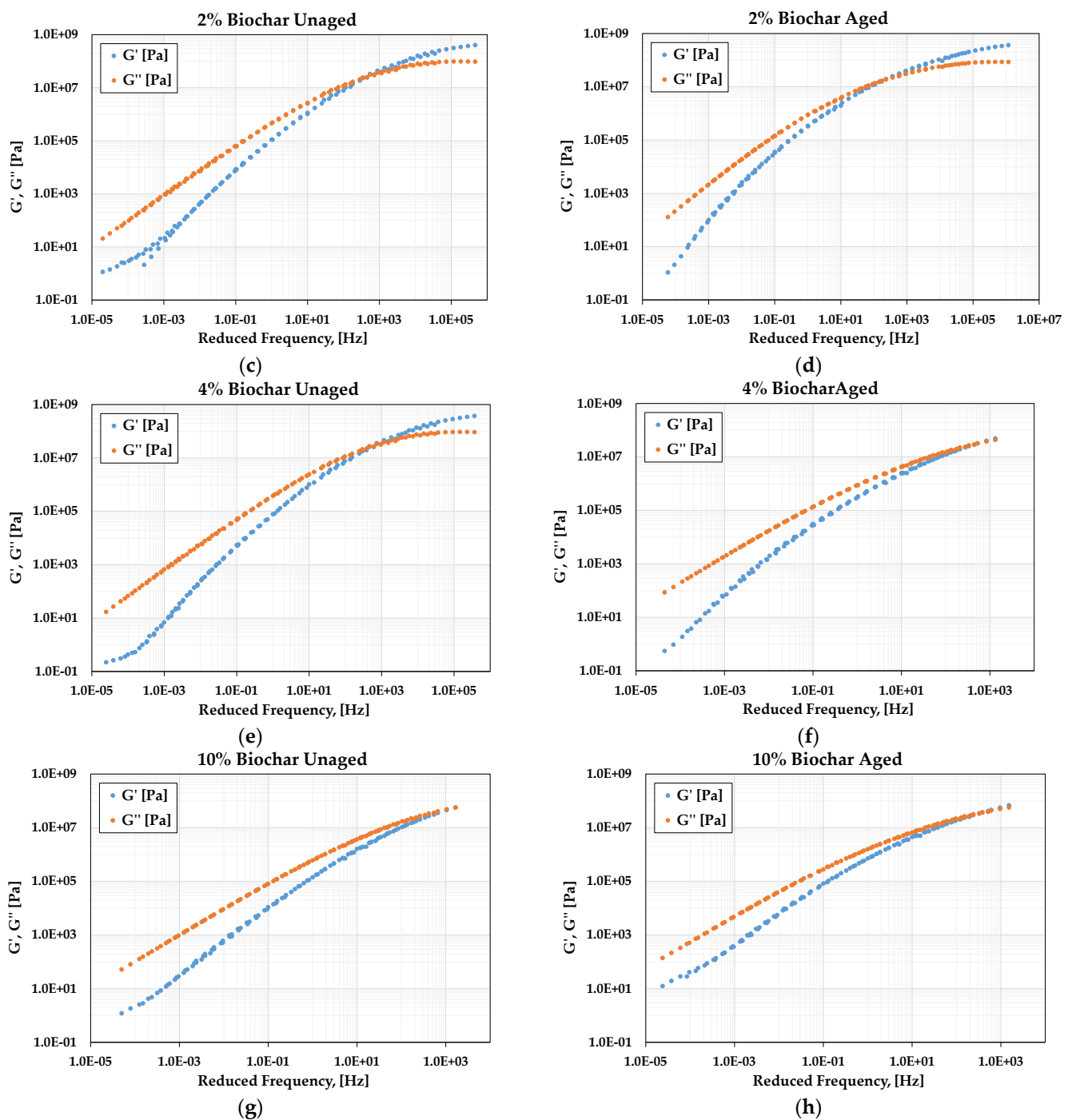


Figure 5. Cont.



**Figure 5.** Master curves of  $G'$  and  $G''$  for the unmodified and biochar-modified binders, for each biochar content and aging condition.

Furthermore, the crossover moduli and frequencies of biochar-modified binders were calculated, and the results are summarized in Table 3. As is known, the value of crossover modulus is the modulus corresponding to the intersection of the storage and loss moduli, i.e., invoking the viscoelastic behaviour for the binder when the elastic component is equal to the viscous one. The same goes for the crossover in terms of frequency; generally speaking, the material is in a gel-like condition at frequencies above the crossover, while the binder exhibits a fluid structure at lower frequencies [29,32]. From the results given in Table 3, it can be observed that the crossover modulus is strongly influenced by both the percentage of added biochar and the aging. Indeed, as the percentage of biochar added

increases, the modulus grows, while it decreases with aging. As expected, at the same concentration of added biochar to bitumen, the crossover modulus of the aged mixture is lower than that of the unaged mixture, probably due to an increase in the inhomogeneity of the mixture caused by aging [29,33].

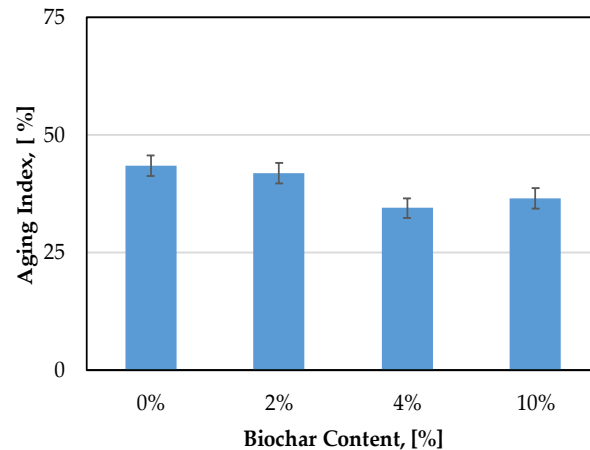


Figure 6. Aging Index (AI) of all investigated samples.

Table 3. Crossover frequency and crossover modulus of all samples investigated.

	Crossover Frequency [Hz] Unaged	Crossover Modulus [Pa] Unaged	Crossover Frequency [Hz] Aged	Crossover Modulus [Pa] Aged
0%Biochar	566	$2.32 \times 10^7$	246	$1.97 \times 10^7$
2% Biochar	348	$2.30 \times 10^7$	146	$1.53 \times 10^7$
4% Biochar	1525	$2.64 \times 10^7$	525	$2.28 \times 10^7$
10% Biochar	1044	$4.57 \times 10^7$	380	$3.75 \times 10^7$

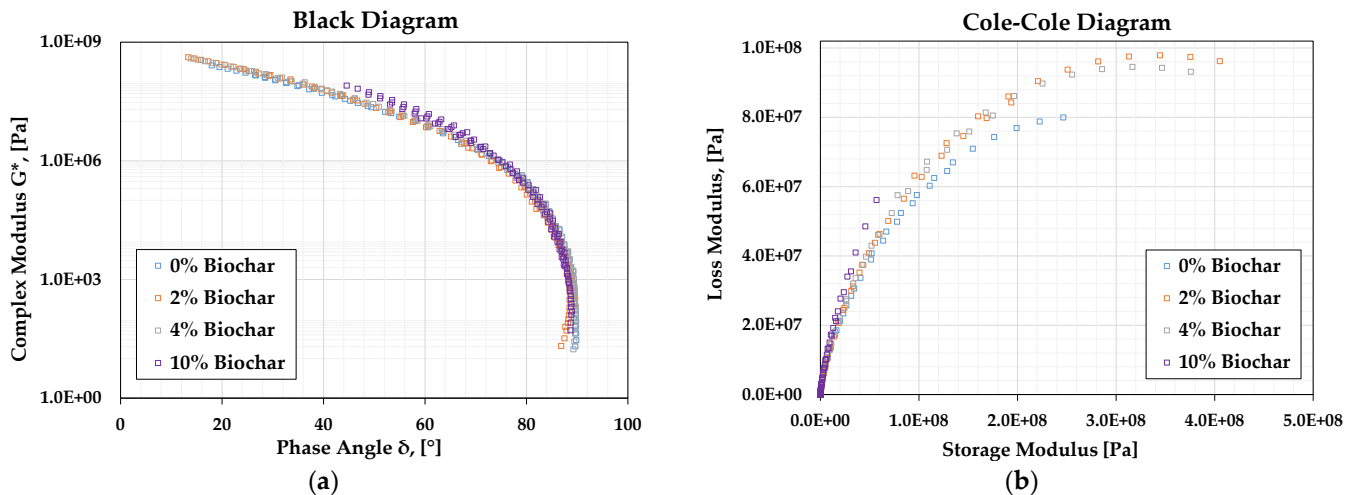
The complex modulus  $G^*$  versus phase angle  $\delta$  curve provides valuable information about the viscoelastic properties of asphalt, including its ability to resist deformation under repeated loading, its low-temperature behaviour, and its fatigue resistance. This curve is also known as a black diagram and offers the advantage of being based on the testing results (independently from the applied frequency or temperature); therefore, it is often used to compare the performance of different types of asphalt binders in a more straightforward way, if compared with the master curve.

Figure 7a displays the black diagrams of complex modulus,  $G^*$ , versus phase angle,  $\delta$ , resulting from frequency sweep tests conducted at different temperatures on unaged binders. As seen in Figure 5a, in unaged conditions, the addition of biochar does not significantly alter the binder's rheological characteristics, in terms of overall complex modulus,  $G^*$ , where the shapes of the all the curves are very similar to each other, thus proving that the introduction of the biochar did not imply a real modification of the base bitumen.

Figure 7b illustrates another possible representation of the testing results, not based on the effect of loading frequency or testing temperature, which is useful for investigating the rheological properties of the material: the Cole–Cole diagram. This graph is commonly used in the field of rheology to depict how a viscoelastic substance responds to an external load [34]. It plots the relationship between the real part ( $G'$ ) and the imaginary part ( $G''$ ): the real part displays the substance's ability to resist elastic deformation, while the imaginary part indicates energy loss due to viscous deformation.

The full diagram presents a semicircle in the Cole–Cole space (with abscissa  $G'$  and ordinate  $G''$ ) that approaches the origin for increasing temperature and decreasing loading frequency (static modulus, equal to zero) and that tends to an asymptotic point on the real axis when the loading frequency tends to infinity and the temperature decreases below

the glass transition temperature (glassy modulus, in theory). In this curve, based on the experimental conditions applied, only the left open upward part of the curve is depicted: it represents the area in which the material exhibits dominant viscous behaviour. The right downward part (not depicted here by the experimental results) would represent the region where the material displays dominant elastic behaviour. As can be noticed, the curves of the biochar-modified binders are always higher than those of neat bitumen, confirming that the crossover modulus increases with the addition of biochar.



**Figure 7.** Viscoelastic properties of the binders studied at unaged conditions: (a) black diagram; (b) Cole–Cole diagram.

In particular, the curve for biochar-modified binders is always higher than that of the neat binder, with a visible effect of the introduction of the additive.

In any case, it is not possible to identify a clear trend with the dosage in biochar, with the results for all the percentages tested being very similar to each other and, in any case, within the usual testing variability.

### 3.2. Storage Stability Tests

Finally, for real-scale production purposes, the storage stability of the modified binders was evaluated to assess the risk of phase separation between the binder and the biochar. The purpose of this test is to determine if the modified binder can be safely stored in tanks at storage and distribution terminals prior to being transported to asphalt production plants. It also ensures that the process of handling and storage does not result in significant changes to the physical or chemical characteristics of the binder.

Tests were conducted on the outer, upper, and lower sections for several properties, including penetration, softening point, elastic recovery, and dynamic viscosity. According to [27] standards, the softening points should not differ by more than 3 °C, and the change in penetration value should be no more than 0.5 mm.

Although biochar and bitumen have similarities in their composition, being primarily composed of carbon atoms, the storage stability test did not yield the intended outcomes. According to Table 4, only the mixture containing 2% biochar met the standard requirements. The remaining blends were unable to be completed due to evident phase separation, as depicted in Figure 8.

### 3.3. UV Irradiation Aging

The photo-oxidation behaviour of neat and bitumen containing different amounts of biochar particles was investigated by subjecting the samples to UVB artificial aging and by monitoring the structural changes in time using surface spectroscopy analysis (ATR-FTIR). All the spectra obtained for neat and bitumen containing biochar, as a function of exposure time, are reported in Figures 9–12. Although the following degradation phenomena of

bitumen complex systems is a hard matter due to the presence of different constituents, also according to the literature [19], the aging behaviour of bitumen systems could be conveniently monitored by following the changes in carbonyl and hydroxyl accumulations. As known, the increases in carbonyl and hydroxyl accumulations are usually related to the development of oxygen-containing groups that are representative of the aging status of bitumen.

**Table 4.** Storage stability results for all sample products.

Requirements		Storage Stability		
Characteristic Standard Unit	Pen, 25°C [21] 0.1 dmm	$\Delta$ Pen EN [27] 0.1 dmm	T <sub>R&amp;B</sub> EN [22] °C	$\Delta$ T <sub>R&amp;B</sub> [27] °C
2% Biochar TOP	36		53	
2% Biochar BOTTOM	38	2	52.5	0.5
4% Biochar TOP	not applicable	not applicable	not applicable	not applicable
4% Biochar BOTTOM	not applicable	not applicable	not applicable	not applicable
10% Biochar TOP	not applicable	not applicable	not applicable	not applicable
10% Biochar BOTTOM	not applicable	not applicable	not applicable	not applicable

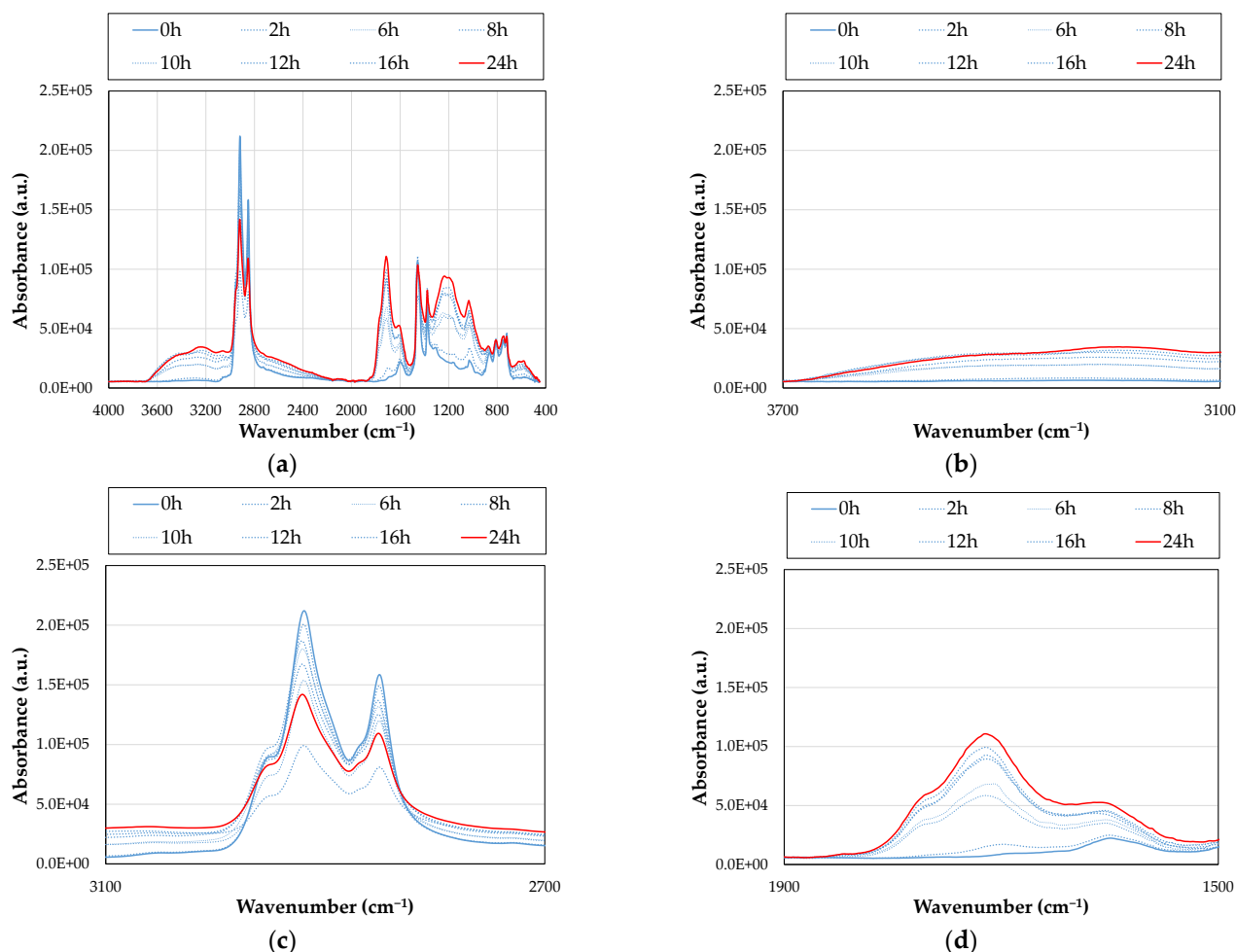


**Figure 8.** Storage Stability—4% biochar TOP portion.

Overall, based on the results discussed above, the presence of biochar particles slightly increases bitumen stiffness, without compromising its processability at its processing temperature. In addition, although slightly pronounced, the biochar has a beneficial effect on bitumen aging during RTFOT aging, which simulates the processing conditions. This good result suggests that the biochars containing bitumen are subjected to less preliminary degradation during processing. Therefore, the chemical nature of biochar is very similar to that of the matrix, and obviously, this suggests very good compatibility between bitumen and these particles. According to the literature, the biochar particles coming from biomasses are mainly composed of C, H, N, and O atoms, and obviously, this results in a good compatibility with organic-based complex bitumen systems. Additionally, according to the literature, the biochar surface could contain some oxygen-containing groups, such as carboxyl and hydroxyl groups, and this could be considered responsible for their good dispersion and protection ability.

Therefore, calculations of carbonyl and hydroxyl accumulations were performed for all the investigated samples, as a function of exposure time, considering the equations reported in the Experimental section, and the obtained trends are shown in Figure 13a,b. It can be noticed that the bitumen with biochar has a slightly pronounced beneficial effect

on oxidation behaviour before UVB aging (0 h), as also mentioned above. The carbonyl and hydroxyl accumulations of all the investigated samples increase with increasing the exposure UVB time, as expected. It is worth noting that the trends of carbonyl and hydroxyl accumulations of neat bitumen are less pronounced in comparison to those of bitumen containing different biochar amounts. This result highlights the protection ability of biochar, although limited, against photo-oxidation exposure of bitumen.

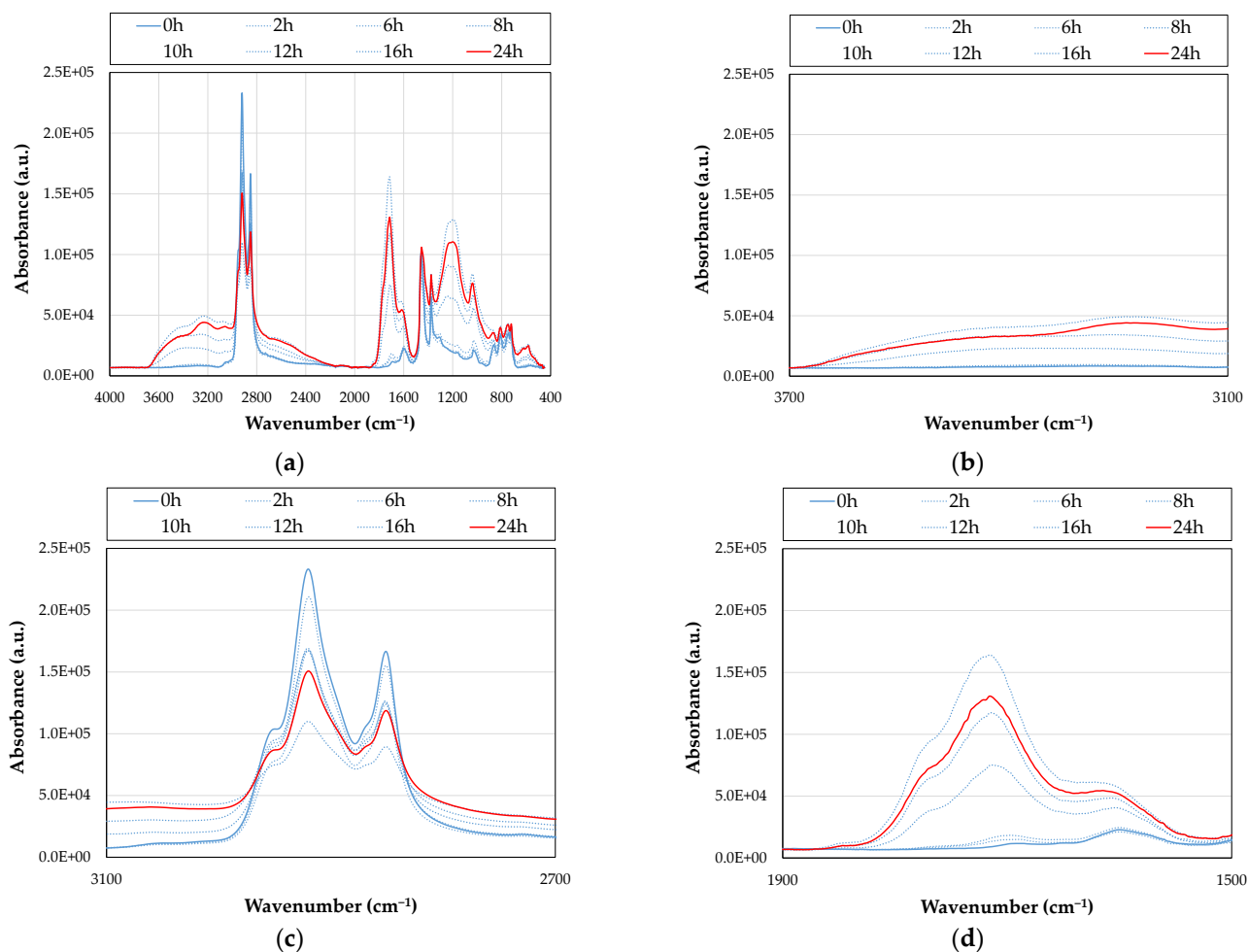


**Figure 9.** ATR-FTIR spectra of 0% BCH aged at several UV irradiation times: (a) whole spectra, (b) hydroxyl range, (c) CH stretching range, and (d) carbonyl range.

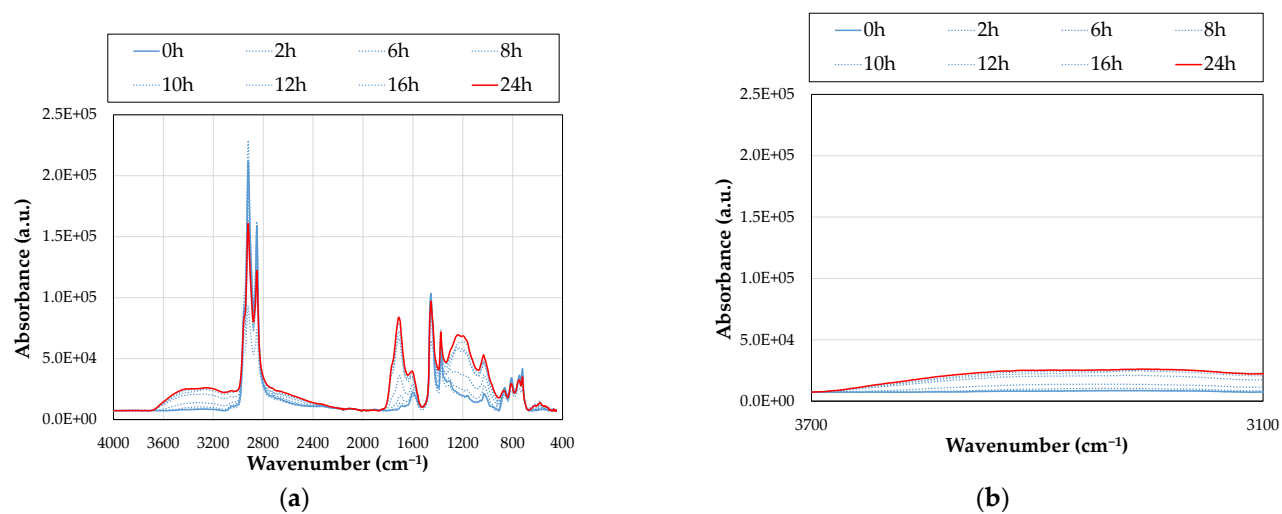
Therefore, the protection ability of biochar particles could be understood considering their mainly carbon-based nature, and this could account for their protection ability against UVB light, similarly to that shown by other carbon-based particles, such as carbon black particles and multi-walled carbon nanotubes [33,35,36]. According to the literature, carbonaceous particles can adsorb UV light, due to their dark colour, and this effect slows down the accumulation of oxygen-containing groups in the host matrix. The protection ability of biochar for the bitumen system is clearly observed, despite the heterogeneous nature of the host matrix.

It is worth noting that the protection ability of biochar particles cannot be exactly related to their amount, and, as is noticeable, the sample containing 4% wt of biochar shows faster oxygen-containing group accumulations rather the bitumen containing 2% wt. This could likely be understood considering the very high inhomogeneity of the bitumen system that plays a determinant role, especially at high exposure times.

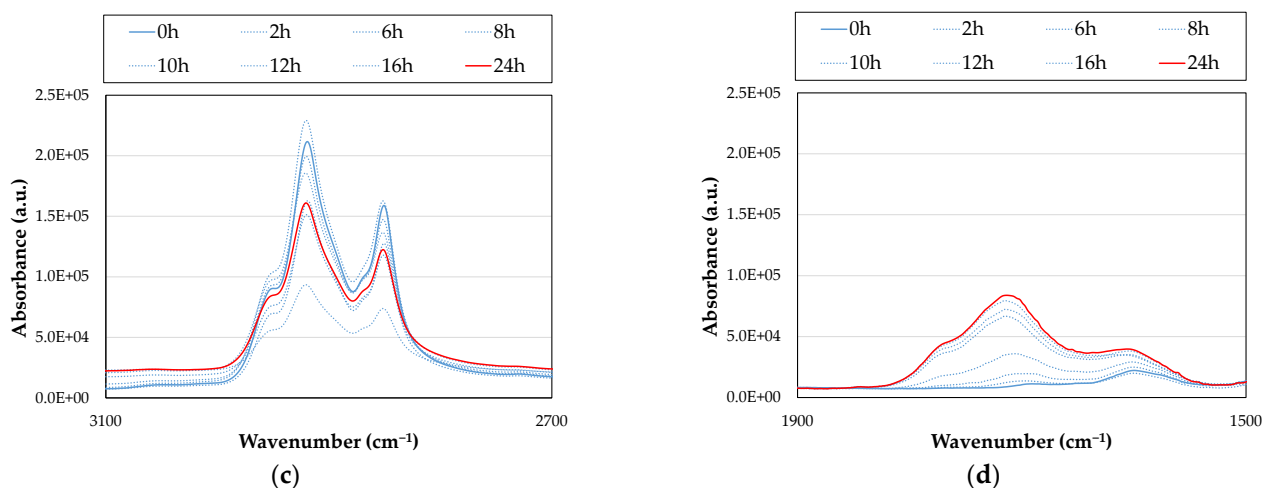
As expected, at high-exposure aging times, the protection ability of biochar particles contrasts with the system inhomogeneity, and an exact quantification from spectroscopic methods is not always possible.



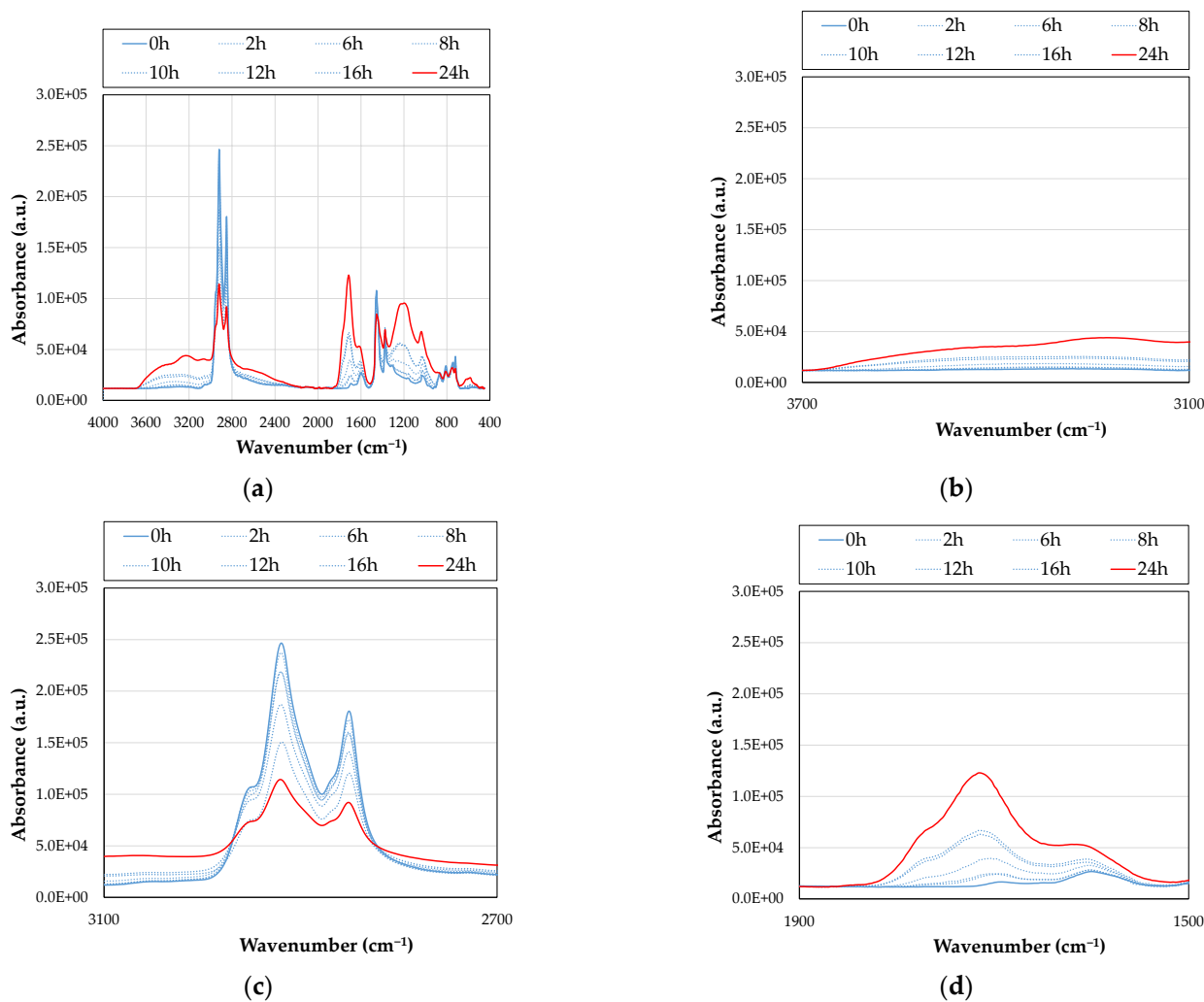
**Figure 10.** ATR-FTIR spectra of 2% BCH aged at several UV irradiation times: (a) whole spectra, (b) hydroxyl range, (c) CH stretching range, and (d) carbonyl range.



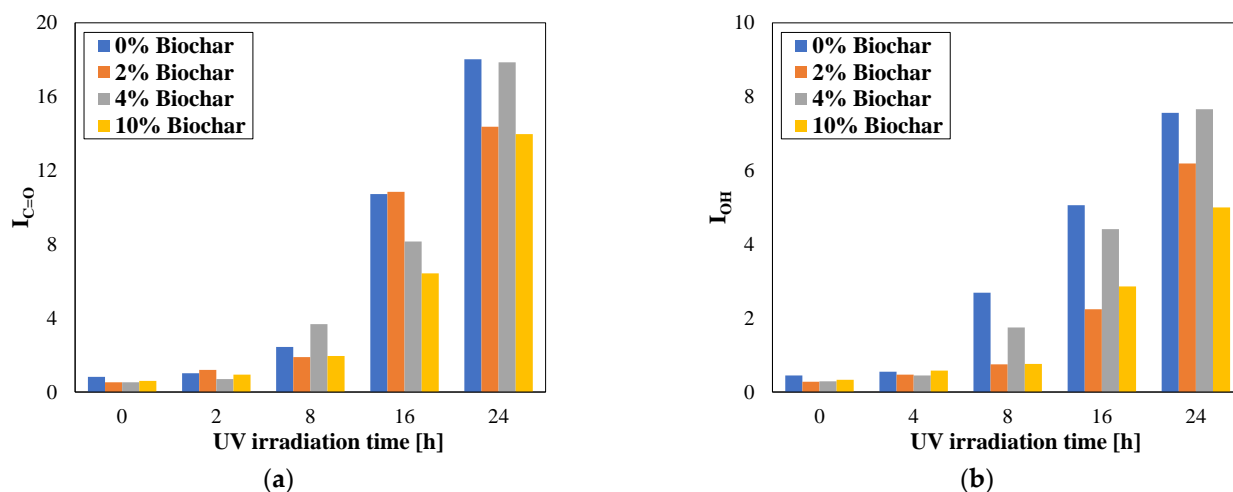
**Figure 11.** Cont.



**Figure 11.** ATR-FTIR spectra of 4% BCH aged at several UV irradiation times: (a) whole spectra, (b) hydroxyl range, (c) CH stretching range, and (d) carbonyl range.



**Figure 12.** ATR-FTIR spectra of 10% BCH aged at several UV irradiation times: (a) whole spectra, (b) hydroxyl range, (c) CH stretching range, and (d) carbonyl range.



**Figure 13.** Carbonyl (a) and hydroxyl (b) trends of neat and bitumen containing biochar particles as a function of UVB aging time.

#### 4. Conclusions

The potential of using biochar as a modifier in bitumen for road applications was investigated in this work. Different percentages of biochar were added to neat bitumen (50–70 penetration grade, widely used in Italy), and the properties of the modified mixtures produced, before and after short-term aging, were evaluated in terms of conventional and rheological characteristics. All the results obtained with the experimental program carried out suggest that the presence of biochar particles slightly increases the bitumen stiffness, mainly at high temperature, without damaging its workability and processability. This evidence is clear when comparing the results of the dynamic mechanical analysis carried out for the modified binders produced with those of the neat bitumen after short-term aging.

The influence of biochar presence on short-term and UV aging behavior (using UVB lamps) was investigated; the changes in the structure of bitumen were observed at different exposure times. The trends of carbonyl and hydroxyl group accumulations suggest that the biochar particles have a protective effect against the photo-oxidation exposure of bitumen. Therefore, the presence of biochar in bitumen has a good influence on the oxidative resistance of bitumen and produces bitumen that is more stable with UV irradiation. This is particularly of interest for bituminous mixtures that are more exposed to UV irradiation during service life, such as porous asphalt in surface courses, due to their high content of air voids and related air-void distribution and connectivity, once in place. This result is also important for urban flexible pavement, where the surface is exposed to UV radiation in thermal conditions that are exacerbated by the heat island effect. The results reported recommend the development of future studies to identify the biochar optimal dosage as well as to avoid possible overdosages. In conclusion, all obtained results suggest that there is potential for the use of this bio-additive for bitumen modification and, in particular, for slowing the aging processes of asphalt mixture and, thus, improving pavement durability and service life in a sustainable manner.

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