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Review

Use of Biochar in Asphalts: Review

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Abstract: The growth of the world population has increased the production of wastes. These are generally incinerated or deposited in outdoor landfills, which impacts the environment and affects human health. A technique that allows to reuse of wastes and diminishes adverse effects on the environment is pyrolysis. Through this technique, a material known as Biochar (BC) is produced, which has proven to have interesting physical-chemical properties for it to be used as an asphalt modifier, and simultaneously, helps to mitigate negative impacts on the environment. The foregoing article presents a bibliographical review on the use of BC as a modifier for asphalt binders and asphalt mixes. This has the purpose of becoming a starting point for future research efforts. In the reviewed literature, there was no review found on this topic. In general terms, BC increases the performance of asphalt binders in high-temperature climates, and tends to reduce its performance in low-temperature ones. Few studies have evaluated the performance of BC on asphalt mixes and the long-term properties associated with durability. Based on the reviewed literature, at the end of the article, recommendations are provided for future study topics.

Keywords: Biochar; asphalt binder; asphalt mixture; modified asphalt; review

Citation: Rondón-Quintana, H.A.; Reyes-Lizcano, F.A.; Chaves-Pabón, S.B.; Bastidas-Martínez, J.G.; Zafra-Mejía, C.A. Use of Biochar in Asphalts: Review. *Sustainability* **2022**, *14*, 4745. https://doi.org/10.3390/su14084745

Academic Editor: Salvatore Cataldo

Received: 17 March 2022
Accepted: 8 April 2022
Published: 15 April 2022

1. Introduction

1.1. Biochar

Biochar (BC) is a material that is rich in carbon (C). It also contains nitrogen (N), hydrogen (H), inorganic elements, and small traces of heavy metals. It is obtained by pyrolysis (a process of thermal degradation in an inert atmosphere where oxygen is absent) biomass at temperatures that vary between 300 °C and 900 °C in the absence of oxygen [1]. It can also be obtained through gasification (mainly with biomass of a ligneous origin, it is a process involving heat, steam, and oxygen without combustion), torrefaction (the process of thermal degradation of biomass at temperatures between 200 and 300 °C, under atmospheric pressure and in the absence of biomass oxidizing agents) and hydrothermal carbonization (biomass is treated under hot compressed water). Biomass can be obtained from plants, animals, and industrial wastes [2,3]. In other words, industrial wasted, animal or human manure, organic wastes, municipal sludge, and food residue, among others, can be used as raw materials for producing BC [4–6]. The type of biomass bears an influence on the physical-chemical properties of BC: surface area, capacity of exchanging cations, water retention capacity as well as pore size and distribution [7]. Within the pyrolysis process, temperature inversely affects the performance of BC, however, increases the content of carbon [8] and porosity [9]. The H/C and O/C ratio bears an influence on the properties of BC, and both ratios decrease with the increase of pyrolysis temperature. Low O/C ratios are indicators of high stability and durability [10] and low polarity [11], whilst low H/C ratios are related to high aromaticity.

BC has a high specific surface area, porous structure with high carbon content, abundant functional groups on the surface, it is less expensive than activated carbon and generates fewer negative environmental impacts [12–14]. Presents low thermal conductivity, high chemical stability, and low flammability [7,15,16]. It is a renewable and environmentally friendly material and could inhibit VOC (volatile organic compound) emissions [17–19]. Additionally, it displays a high resistance to chemical and biological degradation [10].

1.2. Problem Statement and Uses

Environmental issues are currently one of the matters that most concern the world. The growth of industry and construction has increased CO_2 emissions [14]. Likewise, the growth of the world population has increased the number of residues and wastes (plastics, agricultural, animal, forest, domestic, municipal or organic, residual water sludges, among others) [6]. These wastes, on occasions, are incinerated or dumped in landfills, which negatively impact the environment and human health. Because of this reason, climate change, pollution, deforestation, energy consumption, and waste production, among others, are matters that bear a high level of priority at the moment of allocating efforts and resources in order to mitigate them.

Because of the above, several countries are driving the generation of energy and fuels through renewable organic materials instead of fossil fuels [20]. These have also opted for composting and anaerobically stabilizing wastes in order to produce biogas or other material with the purpose of fulfilling the objectives of a circular economy [21]. Another way of treating biomass waste is using pyrolysis. This technique reduces the emissions associated with the incineration process and avoids the use of landfills for the elimination of waste [22]. Through this mechanism, a valuable product is generated: BC. The conversion of biomass into BC could help the capture of carbon and reduce the possibility of greenhouse gas emissions [14]. BC has a huge potential for climate change mitigation [23–25]. According to Woolf et al. [23] and Robert et al. [26], this material is capable of reducing 870 kg of CO_2 equivalent to greenhouse effect gases (GEG) per ton of dry raw material. It is also capable of capturing CO_2 from the air and retaining it in its pores for decades. Furthermore, wastes found in outdoor landfills can be used as biomass, which helps to reduce environmental and social dilemmas that are inherent to this waste disposal system [11].

The most important current uses of BC are in the agricultural sector. In the sector of construction, these have been mainly studied for replacing cement in a mortar or in concrete. Few studies have been carried out for asphalt modification. The above, despite the broad knowledge that carbonaceous materials are highly compatible with asphalt binders and can be used as modifiers, given that they are made of carbon [27]. Perhaps some of the most studied ones are carbon fiber and carbon black. Vegetable carbons have also been used [28]. These materials have demonstrated a good performance (mainly in high-temperature service regions) as modifiers of asphalt mixes in different studies [29–31]. However, the main concern regarding these carbonaceous materials is still fatigue and cracking resistance at low temperatures [27].

Some of the uses of BC are: (i) it helps to improve soil properties, promotes the growth of vegetation (soil conditioning) [32], and water retention [33,34]. (ii) it can help to restore contaminated soils [35]; (iii) treatment of residual waters, water purification, and capture or direct extraction of carbon dioxide (CO_2) in the air thanks to its pore absorption [15,36–38]; (iv) as mineral filler, substitute for cement in cementitious materials, or as a replacement for light aggregates in construction materials [6,7,14,39–42]; (v) as a diet supplement in animal feeding [43]; (vi) replacement for activated carbon; (vii) as absorbent material to remove from wastewater, radioactive effluents in the nuclear industry [44–47]. Regarding the construction sector, the most important application of BC is as a substitute for cement in a mortar or in concrete. The addition of BC could help to reduce the capillary absorption in paste, accelerating cement hydrating and reducing cracking due to retraction [7]. Additionally, this sustainable replacement technique helps to mitigate CO2 emissions by reducing the production of cement and promoting the recycling of residual biomass [42]. In comparison to concrete, few studies have been carried out in the area of asphalt binders and asphalt mixes.

BC shows multiple advantages of use. Few disadvantages were found in the reference literature. The restrictions attributed to the use of BC are mainly due to the lack of studies, since this is a relatively new technique. Some studies highlight the need to: (i) deepen the physical-chemical interactions of BC such as particle size, pore size, pore volume [48]; (ii) make comprehensive techno-economic analysis correlating BC properties for certain applications with feedstock, production processes, BC upgrading, and modification strategies, economic impacts and recyclability [49–51]; (iii) assess and discuss the possible presence of some toxic chemicals compounds (dioxins, chlorinated hydrocarbons, and polycyclic aromatic hydrocarbons) [52,53]; (iv) investigate the reuse and disposal of spent BC [53,54]; make a life-cycle assessment of this technology [55].

1.3. Objective

No study was found that carried out a review on the use of BC in asphalts. This study had the main objective of conducting a bibliographical review on the use of BC in asphalt binders and/or asphalt mixes. This review will be taken by the authors as a starting point for conducting future studies using BC in asphalts. Additionally, these will be a source of consult and reference for undergraduate and postgraduate students, academics, and researchers within the area of civil engineering, pavements, roadways, geotechnics, materials, and related branches. Likewise, they can be consulted by entities that promote the development of environmentally sustainable techniques in roadway projects.

2. Methods

The bibliographical review was carried out mainly in the Scopus, Web of Science, ScienceDirect, Taylor and Francis, SpringerLink, American Society of Civil Engineering, and MDPI Journals and scientific databases. Keywords such as "Biochar", "Biochar + asphalt", "Biochar + asphalt binder", "Biochar + asphalt modified", "Biochar + asphalt mix", "Biochar + asphalt mixture" were used to search. Most of the studies conducted using BC are in the area of agriculture. Few studies have been conducted using it as a construction material (mainly as a replacement for cement in mortar and concrete). Very few studies have been carried out using BC as an asphalt modifier. This is mainly due to the fact that BC is a relatively new material (in scientific databases, approximately 98.7% of the consultation documents on BC are from the last decade). Additionally, there are still certain legal, economic, and environmental aspects of its use that must be deepened [56–61]. The few studies about BC in asphalts were read, described and analyzed. No literature review was found in the literature consulted about BC in asphalts.

3. Biochar in Asphalts

Below is a summarized description of studies consulted in the referenced literature regarding the use of BC in asphalt binders and asphalt mixes.

Just as was previously mentioned, the microstructural, chemical and physical properties of BC significantly vary according to the pyrolysis method, processing temperature, pressure, and heating velocity, among others [62,63]. Because of this reason, Zhao et al. [63] evaluated the pyrolysis treatment method as variables of interest. According to them, the method of pyrolysis has a minor effect on the modification of asphalt binder, and its best performance was obtained using the finer particles (<75 μm) of BC produced at a lower heating rate (15 °C/min) and a lower maximum heating temperature (400 °C). The following were other conclusions drawn from this study: (i) the addition of BC increased viscosity and permanent deformation resistance of the asphalt binder at high service temperatures, whilst it showed little effect at low service temperatures; (ii) BC could improve aging resistance; (iii) BC demonstrated to be more effective than activated carbon as a modifier of asphalt binders. Zhao et al. [27] used the results presented in the previous study for modifying a PG (performance grade) 64–22 asphalt binder with a content of 5 and 10% of BC (produced through slow pyrolysis at 400 °C during 60 min, with a heating rate = 15 °C/min, Switchgrass as biomass and only particles smaller than 75 µm) were used in relation to the mass of asphalt binder. These percentages of addition were chosen based on a previous study conducted by the research group [63]. This modified asphalt was used in order to manufacture six types of hot-mix asphalts (HMA). BC increased permanent deformation resistance, especially with 10% de BC. According to the authors, BC increased moisture damage resistance. However, the results are unclear in this regard, given that indirect tensile strength values—ITS (dry and wet) and TSR (Tensile Strength Ratio) do not show significant variations regarding the control mix. Additionally, it is possible to observe a tendency to reduce moisture damage resistance when the content of BC is increased. They also report an increase in cracking resistance in the asphalt mix when BC is used as a modifier. However, in test results, it is unclear if the changes obtained are statistically significant. The following can be reported as limitations of these studies: (i) they only used two addition percentages in the binder; (ii) the process of mixing asphalt with BC is unclear (temperatures, time, and mixing rate); (iii) the process of manufacturing HMA with the modified asphalt is unclear in regards to the selection of mixing and manufacturing temperatures; (iv) resilient modulus was only obtained at 25 °C; (v) no fatigue resistance tests were conducted.

Walters et al. [64] used nanoclays (2 and 4% in weight) and BC (2, 5, and 10% in weight; produced through swine manure) in order to modify a PG 64-22 asphalt binder. According to them, BC could reduce thermal susceptibility and improving the dispersion of nanoclay in the asphalt binder and to improve aging resistance. One year later, Walters et al. [65] modified a PG 64-22 asphalt binder and a nano-modified asphalt binder with two percentages (3 and 6% in weight in relation to the asphalt binder) of BC sourced from swine manure. In this study, BC did not have effects on aging susceptibility of the asphalt binder. In both studies, the production process of BC is unclear. There is also a lack of clarity in the way BC was added to the binder (does not show temperatures, mixing time, mixing equipment, etc.). Furthermore, the effect of mixed nanoclay and BC is unclear. The effect of nano-particles and BC separately is not clear. Conclusions are based on rheology tests and chemical characterization of modified asphalt, however, properties in asphalt mixes were not evaluated.

Çeloğlu et al. [66] used two types of BC (derived from walnut crust and apricot seed shell) in order to modify (5%, 10%, and 15% per weight) an asphalt binder (penetration of 190 mm/10). The modification of the asphalt binder was carried out at 180 °C. The conclusion was that BC increases the stiffness of the asphalt binder and its performance grade at high temperatures. This study only conducted the typical characterization and rheology tests performed on binders. There was no study carried out on mixes. Modification temperature of the binder with BC was high, and it is unclear if the asphalt's stiffening is due to this temperature or to the used BC [67,68]. There were also no tests carried out in order to evaluate response at intermediate and low service temperatures.

Kumar et al. [69] used BC obtained through pyrolysis (at 450 °C with a heating rate of 40 °C/min and nitrogen flow rate of 100 mL/min) of a Mesua ferrea seed cover as a modifier of two asphalt binders (51.6 and 47.3 mm/10 penetration grade, sourced from different refineries). Further details on the pyrolysis process can be found in [70]. BC was added in 5, 10, 15, and 20% with relation to the weight of asphalt binders and was mixed for 30 min at 160 °C using a high shear mechanical blender. Only physical and rheological characterization tests were carried out on modified asphalt binders. There was no study carried out on mixes. BC increased viscosity, improved permanent deformation resistance, and reduced aging susceptibility of asphalt binders.

Zhang et al. [71] modified a PG 58-28 asphalt binder with BC (2%, 4%, and 8% in asphalt binder weight) produced from pyrolysis (500–650 °C and heating rate of 104–105 °C/s) of a waste wood resource. Particle sizes of BC ranging from 75–150 µm and less than 75 µm were chosen. BC was mixed with the asphalt binder at 120 °C for one hour using a high-speed shearing mixer. They carried out tests with Scanning Electron Microscopy and rheological characterization on the modified asphalt binder. The conclusion was that BC (particle size less than 75 µm and content less than 4%) could increase resistance to permanent deformation and aging of the asphalt binder, keeping a good low-temperature crack resistance. A similar study was conducted by Zhang et al. [72] using the same type of asphalt binder and modifier. They concluded that the adding of BC increased permanent deformation resistance at high temperatures whilst maintaining a good fatigue resistance. Additionally, they advised a content between 2 and 4% of BC as an asphalt binder modifier and BC particle sizes smaller than 75 µm. Not having carried out tests on asphalt mixes is the main limitation in both studies.

Dong et al. [73] modified an asphalt cement (penetration = 63 mm/10) using a BC named DS-510F. BC was mixed with the asphalt binder at 145 °C for 45 min using a high-speed shearing mixer. Five BC contents were used in relation to the asphalt binder mass (5, 7.5, 10, 12.5 and 15%). Based on rheology tests carried out on the modified binder, the conclusion was that BC improved aging resistance. However, low temperature performance of biochar-modified asphalt binder tends to drop, but its impact was not significant. There was no study carried out on mixes. Additionally, there is no knowledge regarding the BC biomass, nor a description of the pyrolysis process.

Zhou and Adhikari [74] and Zhou et al. [17] modified a bio-asphalt (produced by mixing at 120 °C for 30 min at 2000 rpm, a PG 58-28 or 60-80 penetration asphalt binder with 10% of bio-oil), with BC derived from cypress waste wood (sawdust). Pyrolysis temperature was 500 °C (at 2.0 g/s) and BC particle size was smaller than 75 µm. 2, 4, 6 and 8% of BC was mixed with bio-asphalt at 135 °C forg one hour at 2000 rpm. Based on rheological and chemical characterization tests, they concluded that BC improves flow-induced crystallization ability, performance at high service temperatures and aging resistance of bio-asphalt. Furthermore, BC produces SiO_2 particles in a bio-asphalt system and does not affect the low temperature hardening of its chemical components. The main limitation in both studies was not conducting tests on asphalt mixes.

Saadeh et al. [75] mixed a PG 64-10 asphalt binder with crumb rubber (combining 18% rubber and 82% binder) with BC (addition percentages in relation to binder mass of 5%). The biomass used was swine manure. The particle size of BC is unclear. They conducted tests on asphalt mixes, mainly Semi-Circular Bending (SCB) test and Hamburg Wheel Test (HWT). The results showed that BC decreased the fracture resistance of the mixture but helped maintain it after aging. According to the authors, BC could improve the performance and durability of HMA with time, especially because it increases aging resistance. However, tests conducted were limited in order to be able to support this statement. This study did not carry out a phase of physical-rheological and chemical characterization of the modified asphalt.

Wu et al. [76] used BC from rice straw as filler in an asphalt mastic. However, it could seem that BC was not obtained through pyrolysis. They describe its sourcing from ash that is produced in the incineration process of rice straw in an oven at 500 °C for one hour. Mass ratio of 58.5:41.5 of mineral filler to asphalt binder (asphalt cement—AC 60/70 penetration grade) was used to prepare asphalt mastic. Natural mineral filler was replaced by BC with a volume fraction of 40, 80, and 100%. Mineral filler and binder were blended at 150 °C for 3 min. According to them, BC can increase stiffness in the asphalt mastic. Low temperature performance, moisture damage, cracking, and aging resistance were not measured. The mechanical resistance of asphalt mixtures was not evaluated either.

Gan and Zhang [77] used BC sourced from crop straw in order to modify an AC with penetration = 75.2 mm/10. This crop straw was subjected to 450 °C for two hours in a muffle furnace, maintaining an oxygen-deficit environment. BC particle size used was <0.075 mm. BC (2%, 4%, 6%, 8%, 10%, and 12%, percentage by mass of asphalt binder) was mixed with AC at 150 °C for 30 min. The addition of BC significantly improved asphalt performance at high temperatures, but reduced its performance at low temperatures. Six percent was the optimal BC quantity in the asphalt binder. No tests were carried out on asphalt mixes. Additionally, the experimental phase was limited and did not conduct rheology tests.

Zhou et al. [78] studied the effects of pyrolysis parameters (mainly temperature: 450, 500 and 550 °C) the on physical-chemical properties of two types of BC obtained from swine manure and wood waste, when used as bio-asphalt modifiers. Chemical and physical-rheological characterization tests were carried out. The emphasis of the study was the chemical analysis of the modified bio-asphalt. In this study, BC notoriously changed the parameters of the asphalt binder, such as, penetration, softening point, ductility, viscosity, and the complex modulus. The general trend is to stiffen the binder. No tests were carried out on asphalt mixes.

Liu et al. [79] studied the application of BC in the performance of runoff purification of a porous asphalt mixture (PA). Three fillers made with different kinds of BC were used (derived from rice straw, nut shell, and coconut shell) in order to manufacture the mix. The mix used a styrenebutadiene-styrene (SBS) modified asphalt as binder (PG 76-22). BC replaced the mineral filler of PA. The sourcing process of BC was not described. Additionally, the influence of BC on mechanical properties of PA was not evaluated. According to them, BC presents nitrogen and phosphorus pollutants which can be lixiviated. However, in this study, lixiviation of these components was reduced when BC was used as a filler in PA. They advise to take prior measures of cleaning BC in order to minimize possible contamination due to lixiviation.

Ma et al. [80] modified an asphalt cement (penetration 60–80 mm/10) with BC (5, 7.5, 10, 12.5 and 15% in asphalt binder weight) obtained through thermal cracking of commercially available straw stalk. BC and binder were blended using a high-speed shearing machine (150–160 °C for one hour at 5000 rpm). BC was obtained under an N2 atmosphere at 450 °C with a residence time of 30 s and a feed rate of 5 kg/h (particle size of BC = 150 mesh; carbon content = 76%). Chemical and physical-rheological characterization tests were carried out. No tests were carried out on asphalt mixes. Moisture damage and aging resistance were not evaluated. BC improved permanent deformation resistance and properties of the asphalt binder at high temperatures. However, it reduced its resistance at low temperatures. They advise applying BC as an asphalt modifier in subtropical and tropical regions.

A summary of the studies consulted is shown in Tables 1–3.

Table 1. Summary of BC content and particle size, and biomass type.

Ref.	BC Content *	Biomass	BC Particle Size
[27]	5, 10%	Switchgrass	<75 µm
[62]	5, 10, 15, 20% for MR BC and 10% for TF BC		150 > diameter > 75 µm for MR BC; < 75 µm for TF-BC at 400 °C and 150 > diameter > 75 µm at 500 °C
[63]	5, 10%		Passing No. 4 sieve
[64]	2, 5, 10%	Waste of a thermochemical process to convert swine manure into bio-oil	It is not clearly described
[65]	3, 6%		It is not clearly described
[66]	5, 10, 15%	Walnut crust and apricot seed shell	Passing No. 200 sieve
[69]	5, 10, 15, 20%	Mesua ferrea seed cover	Passing 150-µm sieve
[71]	2, 4, 8%	Waste wood resource	75 µm–150 µm and less than 75 µm
[72]			

Table 1. *Cont.*

Ref.	BC Content *	Biomass	BC Particle Size
[73]	5, 7.5, 10, 12.5, 15%	It is not clearly described (DS-510F)	150 mesh
[17]	2, 4, 6, 8%	Cypress waste wood (sawdust)	<75 µm
[74]			
[75]	5%	Swine manure	It is not clearly described
[76]	Does not apply (BC was used as filler in an asphalt mastic)—Mass ratio of 58.5:41.5 of mineral filler to asphalt binder	Rice straw	It is not clearly described. However, it could be assumed that the filler was made up of particles <75 µm
[77]	2, 4, 6, 8, 10, 12%	Crop straw	<0.075 mm
[78]	2% BC was added into AC 60 mm/10 (BC-modified asphalt); 2% BC + 8% bio-oil modified asphalt (BC and bio-oil modified asphalt)	Swine manure and wood waste	<2 mm
[79]	Does not apply (BC replaced the mineral filler of porous asphalt mixture—PA)	Rice straw, nut shell, and coconut shell	<0.075 mm (filler), 1−2 mm and 3−5 mm (filter layer under the pavement surface)
[80]	5, 7.5, 10, 12.5, 15%	Straw stalk	150 mesh

* by weight of asphalt binder; MR: Microwave reactor; TF: Tube furnace.

Table 2. Summary of modified asphalt binder and BC pyrolysis process.

Ref.	Asphalt Binder	BC Pyrolysis Process
[27]	PG 64-22	TF pyrolysis method (slow pyrolysis); Starting temperature = 25 °C, PT = 400 and 500 °C, HR = 15 °C/min, PD = 60 min
[62]		MR BC (HR = 400–500 °C/min); TF BC (HR = 15 °C/min; 400–500 °C)
[63]		MR pyrolysis method
[64]	PG 64-22 and Bio-binder	It is not clearly described
[65]		
[66]	AC 190 mm/10 penetration	BC pyrolysis process in compliance with ASTM E 897-83 standard
[69]	AC 51.6 and 47.3 mm/10 penetration	450 °C with heating rate 40 °C/min and a nitrogen flow rate of 100 mL/min. More details in [70]
[71]	PG 58-28	500–650 °C and a heating rate of 104–105 °C/s
[72]		
[73]	AC 63 mm/10 penetration	It is not clearly described
[17]	Bio-asphalt (PG 58-28 or 60-80 penetration with 10% of bio-oil)	500 °C with N2 (at 2.0 g/s)
[74]		
[75]	18% crumb rubber + 82% PG 64-10	Hydrothermal liquefaction process (HTL)
[76]	AC 60/70 penetration	Not pyrolysis. Incineration process of rice straw in an oven at 500 °C for one hour
[77]	AC 75.2 mm/10 penetration	450 °C for 2 h in a muffle furnace, maintaining an oxygen-deficit environment
[78]	Bio-oil	Fast pyrolysis temperatures: 450, 500, and 550 °C. Heating speeds: 25–150, 150–300, and 300–450/500/550 °C at 3, 5, and 10 °C/min, respectively; N2 flow velocities: 10, 20, and 30 L/min, respectively.
[79]	SBS modified asphalt (PG 76-22)	It is not described
[80]	AC 60–80 mm/10 penetration	Thermal cracking; N2 atmosphere at 450 °C with a residence time of 30 s and a feed rate of 5 kg/h

PT: Pyrolysis temperature; HR: Heating rate; PD: Pyrolysis duration; SBS: Styrenebutadiene-styrene.

Table 3. Summary of most important tests or parameters measured and significant findings.

Ref.	Most Important Tests or Parameters	Most Significant Findings
[27]	DSR; Resilient Modulus; APA (Rutting); TSR; Superpave IDT; SCB	Pyrolysis method has a minor effect on the modification of asphalt binder; Best performance is obtained using the finer particles (<75 µm) of BC; BC increased viscosity and rutting resistance; Best performance is obtained using a BC produced at 15 °C/min and heating temperature of 400 °C; BC showed little effect at low service temperatures; BC demonstrated to be more effective than activated carbon as a modifier of asphalt binders; BC increased moisture damage resistance; BC increased cracking resistance in the asphalt mix
[62]	DSR; SEM	
[63]	Superpave Rutting and Fatigue Index (DSR); G* at low temperature; APA Rutting; TSR; Superpave IDT	
[64]	RV; XRD; Temperature and Shear Susceptibility	BC could reduce thermal susceptibility and improving the dispersion of nanoclay in the asphalt binder; BC improves aging resistance
[65]	DSR; Viscosity, Shear and Aging Temperature Susceptibility; Sorption Procedure for Chromium Removal	BC did not have effects on the aging susceptibility of the asphalt; BC improved dispersion of the nano-clay in the asphalt binder; BC has the ability to remove about 75% of Cr (VI) from the Cr(VI) contaminated surface runoff
[66]	Rheological properties using DSR	BC increases the stiffness of the asphalt binder and its performance grade at high temperatures
[69]	Rheological properties using DSR	BC increased viscosity, improved permanent deformation resistance, and reduced aging susceptibility of asphalt binders
[71]	RV; Rheological properties using DSR; BBR; Microscopic Morphology	BC (particle size < 75 µm and content < 4%) could increase resistance to permanent deformation and aging of the asphalt binder, keeping a good low-temperature crack resistance; BC-modified asphalt with 2–4% mixing amount and particle size < 75 µm was recommended
[72]		
[73]	Rheological properties using DSR; BBR; FTIR	BC improved aging resistance; BC tends to reduce low temperature performance of biochar modified asphalt binder
[17]	Rheological properties using DSR; X-ray scattering; Molecular dynamic simulation; FTIR; Microscope experiments; TLC–FID	BC improves flow-induced crystallization ability, performance at high service temperatures, and aging resistance of bio-asphalt; BC produces SiO_2 particles in a bio-asphalt system and does not affect the low temperature hardening of its chemical components
[74]		
[75]	SCB; HWT	BC decreased the fracture resistance of the mixture but helped maintain it after aging. BC could improve the performance and durability of asphalt mixtures because it increases aging resistance
[76]	SEM; Rheological properties using DSR	BC can increase stiffness in the asphalt mastic, which would contribute to the rutting performance of asphalt pavement
[77]	SEM; Laser particle size analysis; penetration, softening point, ductility	BC improved asphalt performance at high temperatures, but reduced its performance at low temperatures. Six percent was the optimal BC content. BC has properties similar to commercial coal
[78]	XRF; HPLC; XRD; MLRS; FTIR; DSR	BC and bio-oil can be co-used for asphalt modification and replacement. BC tends to stiffen the binder
[79]	Leachate contamination; Pavement infiltration; Water quality	Lixiviation of nitrogen and phosphorus pollutants was reduced when BC was used as a filler in PA
[80]	Rheological properties using DSR; BBR; FTIR	BC improved permanent deformation resistance. BC reduced resistance at low temperatures. They advise applying BC as an asphalt modifier in subtropical and tropical regions

DSR: Dynamic Shear Rheometer; APA: Asphalt Pavement Analyzer; IDT: Indirect Tensile Test; SCB: Semicircular Bending Notched Fracture; SEM: Scanning Electron Microscope; G*: complex modulus; RV: Rotational Viscosity; XRD: X-Ray Diffraction; BBR: Bending Beam Rheometer; FTIR: Fourier-transform infrared spectroscopy; TLC–FID: Thin-layer chromatography-flame ion detector; HWT: Hamburg Wheel Test; XRF: X-ray fluorescence; HPLC: High-pressure liquid chromatography; MLRS: micro-confocal laser Raman spectrometer.

4. Conclusions

Based on the bibliographical review, the following is concluded:

1. BC is a material that offers use advantages from an environmental standpoint.

2. The greater part of studies conducted on BC is related to the agricultural sector. In the construction sector, the greater part of studies has evaluated the use of BC as a cement substitute in mortar or concrete.
3. Most studies carried out on BC as an asphalt modifier belong to this last decade.
4. As an asphalt modifier, BC tends to increase the viscosity and stiffness of asphalt binders, increasing their resistance to permanent deformation (rutting). It also tends to increase aging resistance. However, more studies are needed in order to validate this last statement.
5. The majority of studies agree that it reduces binder performance in low temperature climates. Because of this, several studies recommend the use of BC in tropical climates.
6. No study evaluated the performance of BC-modified binders at intermediate service temperatures.
7. Generally, the use of particles with less size is advised (smaller than 0.075 mm). Its use has been studied as an asphalt binder modifier via the wet process and as a substitute of mineral filler in asphalt mixes.
8. BC content ranged from 2 to 20% (percentage by mass of asphalt binder). Optimal BC contents were found below 10%.
9. During the last years, the interest of using BC as a modifier of bio-asphalts has increased.
10. It is unclear if the increase in binder viscosity is because of the BC or the modification process (e.g., high mixing temperatures with the binder). Likewise, greater viscosity is equivalent to higher mixing temperatures, hindering the process of manufacturing and construction, and impacting negatively the environment. This last aspect has not been analyzed.
11. BC's long-term performance is unclear in terms of durability. Very few studies have conducted tests on asphalt mixes and no study was carried out using Full-Scale Accelerated Pavement Testing (FS/APT). Few studies evaluated long-term aging resistance, moisture damage resistance, and fatigue resistance. Also, there are no studies conducted on environmental and economic impact.
12. Future studies must focus on evaluating: (i) the effect of using different types of biomass for producing BC; (ii) the influence of the pyrolysis process; (iii) the influence of asphalt type and content; (iv) the influence of the binder-BC-aggregate interaction and asphalt mix gradation; (v) long-term performance of binders and mixes (aging, moisture damage resistance, etc.); (vi) performance grade at intermediate temperatures of service; (vii) in situ and/or FS/APT tests; (viii) environmental and socio-economic impacts; (ix) physical-chemical and micro-structural performance.

Author Contributions: Conceptualization, H.A.R.-Q., F.A.R.-L., S.B.C.-P., J.G.B.-M. and C.A.Z.-M.; methodology, H.A.R.-Q.; validation and formal analysis, H.A.R.-Q., F.A.R.-L., S.B.C.-P., J.G.B.-M. and C.A.Z.-M.; resources, H.A.R.-Q., F.A.R.-L., S.B.C.-P., J.G.B.-M. and C.A.Z.-M.; writing—original draft preparation, H.A.R.-Q.; writing—review and editing, S.B.C.-P., J.G.B.-M. and C.A.Z.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We thank the participating institutions (Universidad Distrital Francisco José de Caldas, Pontificia Universidad Javeriana, Universidad Militar Nueva Granada, and Universidad Piloto de Colombia) for the support granted to researchers. In the case of the author Saieth Baudilio Chaves-Pabón it is mentioned that it is a product of his academic work as a professor at the Universidad Militar Nueva Granada.

Conflicts of Interest: The authors declare no conflict of interest.

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