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A STUDY OF THE MECHANICAL, THERMAL, AND ENVIRONMENTAL PROPERTIES OF CEMENTITIOUS MATERIALS WITH ADDED BIOCHAR

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Abstract

Biochar a carbon-rich substance formed from the thermal breakdown of biomass, has received a lot of attention in recent years because of its potential as a sustainable additive in cement-based materials. This article provides a thorough analysis of the existing literature regarding the mechanical, thermal, and environmental characteristics of cementitious materials that contain biochar as an additive. Due to their potential to enhance the mechanical properties of concrete, biochar-infused cementitious materials have been the focus of recent research. It has been demonstrated that biochar, a carbon-rich substance created by roasting biological substances without oxygen, has a number of beneficial characteristics, including the capacity to enhancesoil fertility and sequester carbon. The addition of biochar to cementitious materials can enhance their thermal conductivity and lessen their thermal expansion coefficient in terms of their thermal characteristics. Since thermal insulation is needed in building and construction applications, they are better suited for utilisation in those environments. The environmental characteristics of cementitious materials that have biochar incorporated have also been researched. By trapping carbon dioxide during manufacture, biochar has been proven to dramatically lower the carbon footprint of cement-based compounds. The potential advantages of adding biochar to cement-based materials in terms of their mechanical, thermal, and environmental characteristics are highlighted in this review.

***Keywords**: Biochar, cementitious materials**,** mechanical and thermal properties, carbon sequestration, concrete, cement.*

1. Introduction

A type of charcoal produced through the pyrolysis of organic materials including wood chips, food waste, and other biomass under anoxic conditions is called biochar [1]. Pyrolysis is a thermochemical process where biomass is heated in a limited oxygen environment in the temperature range of 400 – 700 °C [2]. In recent years, biochar use as an ameliorant in agricultural lands and improving soil fertility has been mooted in various studies [3]. Biochar is a highly porous carbon-rich substance mainly characterized by having a high specific surface area, presence of various functional groups, and mineral matter content[3]. The pyrolysis conditions like temperature, heating rate, and residence duration, as well as the type of feedstock affect the properties of biochar [4]. These variables can be changed to produce biochar with physicochemical characteristics that can be adapted for a diversity of applications [5]. Biochar has a high adsorption capacity to adsorb wide range of organic and inorganic pollutants due to its porous structure, high specific surface area, and presence of functional groups [6]. Production of biochar using the biomass waste is a sustainable way to sequester carbon and manage waste. In this aspect, the use of biochar as an additive material for the partial replacement of cement in concrete has been in discussion and reported in various studies [7]. The application of biochar as a replacement material for cement in concrete reportedly not only increased the mechanical strength but also helped in the carbon sequestration process [8].

Addition of Biochar enhances the thermal properties and reactivity of the cement concrete. [9]. It also increases the Mechanical strength of concrete compared to nominal concrete mixes. However these properties may vary depending on the amount of Biochar added, the method of biochar preparation and climatic conditions in which it is used. As Biochar has the ability of capturing and storing atmospheric carbon dioxide, it is now considered as an construction material as around 40% of CO2 is being released from construction practices.[10]. The fineness of the biochar also decides the mechanical and thermal behaviour of the concrete mix. [11]. The source of biochar generally impacts the behaviour of mortar, food waste biochar is more preferable than ricehusk biochar when fine biochar is mixed in proper proportion to cement [12]. Environmental impact of Biochar mixed cement is considerably less when compared to nominal cement mixes as the CO2 absorption capacity of food waste biochar is more [14]. Incorporation of biochar into soils & cements shows impressive reduction in the emission of N_2O [15].

2.

3. Literature Review

“Some of the recent research works related biochar properties were reviewed in this section”

(i) Biochar and its properties

Juriga, M. and Šimanský, V., et al [16] have examined the alterations that biochar has on soil pH and sorption parameters alone, after reapplication, and when combined with fertiliser N. In 2018, soil samples were acquiredfrom plots that had diverse biochar application rates, specifically the initial application in 2014 (A) and the reapplication in 2018, at rates of 0 t. ha-1 (B0 control),20 t.ha-1 (B20) , and 10 t.ha-1 (B10), as well as dissimilar nitrogen fertilisation levels: N40 (40 kg.ha-1)andN0 (no nitrogen).The fertilised control treatment (B0N40) tested for all parameters was determined to have the worst results. However, the first application of biochar like the subsequent application of biochar with N led to a notable rise in the pH of the soil in H2O, KCl, SBC, CEC, and BS as well as a decline in hydrolytic acidity.

Fan, Y., et al [17] have created three different feedstock-derived biochars and used the colour spaces RGB, HSB, and CIE Lab* to extract the fundamental colour information from their scanned images. They then used a combination of various colour indicators to cluster biochar using NMDS (nonmetric multidimensional scaling analysis)andPCA (principal component analysis).The authors made the supposition that the NMDSand PCAclusters were as close as likely to the visual perception of biochar colour. They generated feedstock-independent colour indices [(R + G-B)/ (R + G + B), (R + B-G)/ (R + G + B), (G + B-R)/ (R + G + B), L, a, b] to describe the colour of biochar based on this supposition. These indices can offer a microscopic viewpoint to clarify colour differences in relation to feedstock type and pyrolysis temperature.

Oni, B.A., et al [18] have described how to make biochar for soil remediation by pyrolysis, gasification, and hydrothermal carbonization. In addition to enhancing agricultural productivity, lowering the bioavailability of environmental pollutants, reducing greenhouse gas emissions and global warming, reducing soil nutrient leaching losses, conserving atmospheric carbon into the soil, and all of the above, biochar has made significant advances in these areas. As a result, it has evolved into a value-added product that supports the bioeconomy.The research and utilisation of biological resources, which includes the application of biotechnology to produce novel bio-products with commercial value, is implied by the term "bio-economy." A marketable bio-product that has use in industry, agriculture, and the energy sector is biochar. Producing biochar can therefore improve soil qualities and open up prospects for additional income. The paper discussed the advantages of biochar for production, agriculture, and commerce.

Zhu, L., et al [19] have investigated how surface modification affected the characteristics of porous biochar and artificially assessed various modification methods using main component analysis. The study discovered that porous biochar's surface and adsorption properties were considerably impacted by surface modification. The researchers addednHIO (nano-iron oxyhydroxide), nZVI (nano-zero valent iron), surface oxidation, and surface amination to potassium carbonate activated porous biochar.The amino and metal-O oxygen-containing functional groups in addition to the pore structure, especially the micropores, were significantly impacted by surface modification. Additionally, it altered how 2,4-Dichlorophenoxyacetic acid (2,4-D) diffused across the surface of the biochar. The adsorption capabilitywas not solely determined by the particular surface area. Surfaces with a lot of functional groups involving oxygen were more conducive to biochar's ability to bind 2,4-D. According to the study, -interaction, chemisorption, and hydrogen bonding all played a role in the biochars' ability to adhere to 2,4-D.

Wang, Z., et al [20] have investigated the biochar's adsorption of NH4+-N under acidic ageing circumstances by using four differentoxidation and acidtreatments to imitatebiochar aging situations.The outcomes shown that following an H2O2 alteration, the extreme NH4+-N adsorption abilityof PBC(peanut shell biochar) rose from 24.55 to 123.26 mgg1. The acid ageing procedures did not significantly change the biochar's chemical makeup, and the surface's chemical bonds and functional groups of the biochar were mostly unchanged.The improved NH4+-N sorption ability was mostly caused by changes in physical properties including surface areaandporosity. The N-containing functional groups on the surface of the aged biochar changed from pyrrolic nitrogen to pyridinic nitrogen throughout the NH4+ sorption process, indicating that the adsorption on its surface was primarily chemical in nature due to the hydrogen bonding effectand interaction of bonds in the sp2 hybrid orbital.

Usevičiūtė, L. and Baltrėnaitė-Gedienė, E., et al [21] have concentrated on figuring out the physical-chemical characteristics of biochar formed from five numerous lignocellulosic feedstocks at various pyrolysis temperatures (300-700 °C) and their relationship employing multiple regression analysis, the ability to hold water and wettability of the biochar. In accordance with the findings, average material pore size explained 54% of the range in biochar's wettability, and ash concentration explained 77% of the disparity in biochar's ability to hold water.The capacity of biochar to physically hold water between its particles by capillary forces and adsorb it onto its surface and internal pores, can be used to explain the connection between the biocharwettability and its regular pore size.

Mašek, O., et al [22] have examined to determine if, irrespective of the sizeand kindof the production unit, it was possible to get the parameters of biochar only based on the biomass feedstock's thermal evolution throughout slow pyrolysis. They analysed biochar produced from units at scales ranging from grammes to hundreds of kilogrammes, indicatingthe three main types of slow pyrolysis units (rotary kiln,screw reactor and fixed bed), using a larger range of biochar quality standards are represented by volatile matter content.The authors showed for the first time that these distinctive pyrolysis units could generate equivalent biochar with good consistency both within and between distinct production runs. Table 1 depicts the review of biochar properties.

Table 1. Review of Biochar properties

Author /Year	Techniques	Drawbacks	Future work
Juriga, M. and Šimanský, V. / 2019	Examined effects of biochar on sorption parameters and soil pH	The fertility control treatment (B0N40) produced the worst outcomes.	Additional research onbiochar application rates and degrees of nitrogen fertilisation
Fan, Y., et al/ 2021	Scanned photos of biochar were used to extract basic colour information using the colour spaces RGB, HSB, and CIE Lab*.	None mentioned	Utilising biochar colour indices to categorise and describe biochar
Oni, B.A., et al /2019	Discussed the processes of pyrolysis, gasification, and hydrothermal carbonization for producing biochar for soil remediation.		More research should be done on biochar as a product with value added for the industrial, agricultural, and energy sectors.
Zhu, L. et al / 2018	Surface modification methods, main component analysis	Limited study scope and artificial evaluation of modification approaches	Examination of additional modification techniques and their influence on the characteristics of biochar
Wang, Z. et al / 2020	Treatments with acids and oxidizers, NH4+-N adsorption capability.	Concentrating only on one kind of biochar	An examination of NH4+-N adsorption in various biochar types and soil conditions.
Usevičiūtė, L. and Baltrėnaitė-Gedienė, E. et al / 2021	Multiple regression analysis, physical-	Study scope is constrained and focuses on	Investigating how biochar's qualities affect other

	chemical characteristics	wettability and water-holding capacity	environmental uses like carbon sequestration or pollutant removal
Mašek, O. et al / 2018	Analysis of biochar produced by various slow pyrolysis equipment types	Limited attention on volatile matter content	Examining the influence of additional biochar characteristics on their prospective uses, such as soil improvement or energy production.

(ii) Use of Biochar in Cementitious Materials

Sirico, A., et al [23] have investigated the use of biochar as a sustainable component in cementitious materials, combining its abilities as a carbon sink with improved mechanical behaviour. Biochar, a solid carbonaceous by-product substance produced when residual biomass is pyrolyzed or gasified, is primarily being studied as an agricultural amendment. The sustainable performance of cementitious materials may be enhanced by using biochar, according to some research.

Praneeth, S., et al [24] have examined using biochar, a filler material madefrom the pyrolysis of corn stover biomass, in cement-fly ash blocks. To sequester carbon and increaseCO2 uptake in the blocks, mineral carbonation was applied for two hours after demolding the blocks by adding 2%, 4%, 6%, and 8% biochar to the total weight. After 28 days, the compressive strength of the uncarbonated blocks was assessed to ascertain the impact of the biochar filler on the specimens' strength.The ideal biochar dose was found to range from 4% to 6%, depending on the selected mix, and the results demonstrated an upsurge in CO2 uptake and compressive strength after three days. Additionally, the compressive strength of uncarbonated blocks after 28 days revealed arise in strength as biochar addition amplified up to a point, beyond which it declined as more biochar was added.

Tan, K., et al [25] have aimed to investigate the impacts of BC made from construction waste on the performance of evaporative cooling, water absorption, andstrength of pervious concrete. The results showed that the compressive/flexural strength of pervious concrete modified with BC was higher than unmodified pervious concreteconcrete when the BC content was between 1.0 and 3.0 weight percent (wt%), but the strength would be impaired if the concentration was higher than this. The amount of BC gradually increased the pervious concrete's ability to absorb water.Even though the existence of these dark carbonaceous particles would result in higher solar radiation absorption, the excess water absorbed might be cooled by evaporation to counteract the increase in solar absorption. Better cooling performance was achieved by pervious concrete that had been treated with BC, with anextreme temperature decrease of 10° C and a period of roughly 12 hours.

Gupta, S., et al [26] have employed carbon-sequestering cementitious mortar ingredient biochar. In their study, it was discovered that biochar produced at 300 °C had the capacity to sequester 1.67 mmol/g of CO2. They presented a cutting-edge strategy to use buildings as carbon sinks by including biochar—whether it was unsaturatedor saturatedwith CO_2—into mortar combination. The mortar's initial strength was markedly improved and the permeability was at the same time decreased by adding unsaturated biochar to the mixture.

Zeidabadi, Z.A., et al [27] have aimed to determine how the mechanical qualities of concrete samples containing varying proportions of tworice husk, bagasseand agricultural wastes, burned at 700°C without oxygen would be affected. The biochar was examined for use in concrete using scanning electron microscopy (SEM), BET, andX-ray diffraction. In total, biochar made from agricultural waste replaced 0%, 5%, and 10% of the cement (by mass).Splitting tensile and compressive strength were measured mechanically for various mixes and compared to control concrete (concrete without biochar). Based on theSEM, BET, and XRDmethodologies, the outcomes demonstrated that the synthesised materials might be employed as pozzolanic resources.

Sirico, A., et al [28] have focused on how the mechanical characteristics of cement mortars are alteredby biochar, a solid, porous, carbonaceous substance produced by biomass gasification of wood waste. To test whether biochar works well for structural purposes, they mixed it to cement at increasing percentages, up to 2.5% by weight.The experimental results demonstrated that adding the right amount of biochar led to compressive and flexural strengths that were analogous to control specimens, with a little upsurge in fracture energy.

Tan, K. et al [29] have examined water absorption, albedo, setting time,mechanical strength,fluidity and thermal conductivity of four dissimilar types of mortar samples that were combined with pulverised BC that had been pyrolyzed at various temperatures—400°C, 500°C, 600°C, and 700°C—to replace some of the cement. In terms of weight, the replacement ratios for BC and cement were set at 0%, 1%, 3%, 5%, and 10%, respectively. The findings indicated that a BC addition of 1-3% was the best choice (regardless of its pyrolysis temperature) to increase mortar strength without degrading the other mechanical parameters of BC-contained mortar composites.Under 400 C, adding 1.0% of BC reduced water absorption and fluidityby 9.0%and 3.0%, correspondingly.

Gupta, S. and Kashani, A., et al [30] have carried out an experiment and discovered that incorporating biochar produced in a minor loss in workability, which was reflected in arise in yield stress and a drop in flow. Depending on the mix composition, the biochar utilised in this study increased hydration by 13-23% and sped up final setting by 1-1.5 hours. The hydration kinetics and setting of cement pastes were affected by the occurrence of impurities like phosphorusand saltin the biochar.The enhanced cementitious matrix compactness brought about by the biochar's tiny particle size led to an increase in early age strength (up to 7 days) of fly ash and normalmortar by 18% and 22%, correspondingly. The findings indicated that adding biochar might hasten the strength growth of fly ash-cement, which was encouraging for the production of concrete with high early strengths and less cement. However, because unwashed peanut shells contain salts, mortar shrank more as biochar dosage rose.

Maljaee, H., et al [31] have conducted a study to examine the effects of replacing some of the cement in cement mortars with biochar of various chemical compositions. Rice husk, wood chips and olive stonefrom leftover forest biomass were among the biomass wastes from Portugal's agro-industrial and forestry industries that were chosen as feedstocks for the synthesis of biochar. At a temperature of 500 °C, biochar was produced through slow pyrolysis.

Between 0.5 and 4 weight percent of the cement's weight in biochar was added at varied replacement rates.Utilising XRD and TGA, the effect of biochar on the hydration products was assessed. The impact of biochar additiveon cement mortar's capillary water absorption, compressive and flexural strength was also examined in thiswork.

Cosentino, I., et al [32] focused on using standardised biochar in cement-based composites at various addition rates relative to cement weight, in line with earlier experimental research. The biochar employed in that earlier research was independently created by the pyrolysis of agro-food waste, as opposed to the biochar used in the current experimental activity, which was standardised in anticipation of potential manufacturing of biochar-based composites using cement. The strength, toughness, and ductility tests revealed a positive improvement.In fact, specimens with the additiveof biochar had better fracture energy and flexural strength values than specimens made of normal cement. Review table of cementitious materials uses in biochar is shown in table 2.

Table 2. Review of Biochar in Cementitious Materials

Author /Year	Techniques	Drawbacks	Future work
Sirico, A., et al / 2022	Biochar is used in cementitious materials.	For some combinations, biochar dose optimisation is necessary.	More research is needed to determine how biochar affects the resilience and long-term behaviour of cementitious materials.
Praneeth, S., et al /2020	Use of biochar in cement-fly ash blocks; mineral carbonation	Compressive strength declines with increasing biochar concentrations	Future research projects may examine the long-term mechanical and durability characteristics of biochar-fly ash-cement composites in steam,water, and ACC under varied curing conditions.
Tan, K., et al / 2022	Evaporative cooling water absorption, and strengthtests on pervious concrete using biochar generated from construction waste.	Increased biochar concentrations result in a loss of strength.	The development of cement products with a higher percentage of BC as a cement substitute must be taken into account in future research.
Gupta, S. et al / 2018	Adding biochar to cementitious mortar as		Examine the stability and long-

	a carbon-sequestering ingredient		term usability of mortar that contains biochar.
Zeidabadi, Z.A. et al / 2018	Analysing the mechanical properties of concrete samples with various ratios of bagasseand rice husk biochar	The potential environmental advantages of utilising biochar in concrete were not looked into.	Examine the potential environmental advantages of using biochar into concrete.
Sirico, A. et al / 2020	Analysing the mechanical properties of biochar- and cement-based mortars	There was no research done on biochar's impact on carbon sequestration.	Future and prospective study development might be focussedto investigate the utilisation of silica-rich biochar as a cement replacement.
Tan, K. et al / 2020	Evaluating the water absorption, albedo, settingtime,mechanical strength,fluidity and thermal conductivity of four different types of mortar samples containing pulverised biochar	Did not look into how biochar might affect carbon sequestration	Examine the possibility of employing biochar to store carbon in concrete and mortar, as well as how it affects the composite material's thermal qualities.
Gupta, S. and Kashani, A. / 2021	Yield stress and flow measurements, XRD, TGA	Unwashed peanut shells with salts shrunk more when the amount of biochar was increased.	Examine the effects of various biochar impurities on cementitious characteristics as well as the possibility of using biochar to improve other aspects of cement-based materials.
Maljaee, H., et al / 2021	XRD, TGA, capillary water absorption, compressive and flexural strength measurements	The effects of adding biochar on hydration products and mechanical qualities varied	Future study must take into account the creation of concrete and cement mortar with a higher percentage of

		depending on the feedstock.	biochar as a cement substitute.
Cosentino, I., et al / 2019	Strength, toughness, and ductility tests	The results could be limited by the fact that the biochar utilised was standard rather than made from agro-food waste.	Explore the possibility of using biochar to enhance the other qualities of cement-based materials and the viability of producing biochar cement-based composites on an industrial scale.

(iii) Mechanical Properties of Cementitious Materials with Added Biochar

Lv, C., et al [33] have conducted research on how cement-solidified sludge's mechanical behaviour was affected by biochar and polypropylene fibre. On cement-solidified sludge that had been cured for 28 days with varying fibreand biocharcontents at two beginning water contents, they conducted unconfined compression tests performed repeatedly. They also provided microscopic visions into the interaction of fibreand biocharon sludge particle and on cement hydration products using SEM measurements.Additionally, the process by which polypropylene fibre and biocharalter the mechanical characteristics of cement-solidified sludge was examined using SEM.

Mo, L., et al [34] have utilised a laser displacement measurer, MIP, TG/DSC, SEM and a humidity sensor to examine the impact of biochar and its mixture with MgO expansive additive (MEA) on the autogenous shrinkage,compressive strength,internal relative humidity and microstructures of the cement pastes. The amalgamation of biochar enabled effective internal curing, sustaining a greater internal relative humidity and so reducing the autogenous shrinkage by 16.3% at the age of 180 h, according to the results, which were contrastedto the plain cement paste.

Gupta, S., et al [35] have examined the impact of biochar particles on the mechanical strength (split-tensile, flexural and compressive strength) and permeability properties of concrete under normal conditions (only wet-curing in this study) and after exposure to high temperature (300° C and 550°C). Biochar particles were created by pyrolyzing woody biomass at 500 C (BC 500). In concrete, biochar was injected at concentrations of 0.5%, 1%, and 2% by cement weight.28-day wet-cured concrete samples were exposed to thermal degradation by being placed in an electric kiln with a ramp rate of 5 C/min and a residence time of 1 h (at steady state). Concrete containing 10 wt% silica fume (SF 10%) and plain concrete were both exposed to the same environmental conditions, and the permeabilityand strengthperformance of the biochar-concrete composite were also evaluated.

Akhtar, A. and Sarmah, A.K., et al [36] have examined the impact of replacing up to 1% of the total volume of cement in concrete with a carbonaceous solid material made from three distinct waste supplies(rice husk, paper mill sludge, pulp and poultry litter). The investigation into the mechanical characteristics of the produced concrete used a variety of characterisation techniques. 168 samples in total were ready for mechanical testing. The results showed that adding 0.1% replacement of total volume of pulp and paper mill sludge biochar produced compressive strength values that were comparable to control specimens, while adding 0.1% replacement of rice husk biochar produced slightly improved splitting tensile strength values that were similar to those of thepaper mill sludge and pulpbiochar.

Yang, X., et al [37] have utilising a variety of experimental techniques, it was examined how biochar affected cementitious paste's high temperature resilience. When charcoal cementitious paste containing 2% and 5% biochar was exposed to temperatures of 300, 550, and 900 C, cracks,residual compressive strength,weight loss and UPV (ultrasonic pulse velocity) were all determined. Fourier transform infrared spectroscopy, XRD,SEM and thermogravimetric analysis were used to analyse the byproducts and microstructures of biochar cementitious paste exposed to high temperatures. The findings demonstrated that as biochar content increased, the fissures of specimens revealedto high temperatures shrank. The relative residual compressive strength at 550 °C and the residual compressive strength of the specimens subjected to 300 °C were both improved by the addition of 2% and 5% biochar.

Khan, K., et al [38] have investigated the use of biochar, produced using a local agricultural waste byproduct (date palm fronds) as an addition to create strong and long-lasting concrete.The authors measured the mechanical characteristics, like flexuraland compressivestrength, for the control and all other biochar-containing mixes at 7, 14, and 28 days. Additionally, they used tests for electric resistivity and ultrasonic pulse velocity to look at the durability characteristics of the concrete samples for the mixtures.Finally, they performed a SWOT analysis (strengths, weaknesses, opportunities, and threats) to help them decide how to employ biochar in concrete. The outcomes showed that adding 0.75 to 1.5 weight percent of biochar raised the concrete's compressive strength to 28 to 29%.

Ling, Y., et al [39] have analysed how biochar doses and fineness levels affected thedurability and mechanical characteristics of biochar concrete. Variable biochar dosages (0%, 1%, 3%, 5%, 10%) and fineness dimensions (44.70, 73.28, 750, 1020 m), with the 0% dosage providingas the control group (CK), were used to assess the materials' flexuraland compressivestrength, carbonation resistance, and resistance to chloride ion penetration.The findings demonstrated that the chloride diffusion coefficient and fast carbonation depth of concrete may be successfully decreased by adding 1-3 wt% of biochar. With an increase in biochar content, the flexural andcompressive strength of biochar concrete primarilyimproved and then dropped, with biochar with a fineness of 73.28 m having the greatest impact on the mechanical strength of concrete. Biochar was discovered to improve the development of cement hydration products when added to cement at a dosage of 3 weight percent.

Li, Z., et al [40] have examined the effects of biochar generated from waste caryacathayensis peel, a particular biomass in Zhejiang province, China, on the fundamental mechanical properties of concrete. In three different ways, the researchers added biochar to concrete mixtures: (1) as an additional filler at a ratio of 1%, 2%, 3%, 4%, and 5% by cement weight; (2) as a partial replacement for cement at 1%, 2%, 3%, 4%, and 5% by cement weight; and (3) as a partial replacement for sand at 5%, 10%, 15%, 20%, and 25% by sand volume. Experimental research was done on the biochar concrete's strength, porosity, and microstructures, and it was associated to regular concrete.The compressive and splitting strength of concrete with a 5% biochar sand replacement volume addition showed the greatest strength gain, increasing by 16.6% and 27.5%, correspondingly. In comparison to the ITZ between sand and cementitious matrix, those between biochar cementitious matrix and particleswere glossierandtighter. The mechanical properties of biochar are illustrated in table 3.

Table 3. Review of Mechanical Properties of Biochar

Author /Year	Techniques	Drawbacks	Future work
Lv, C., et al / 2022	Unconfined compression tests, SEM measurements	Only two initial water contents were tested, and only a small amount of biochar and fibre.	Look at the impact of increased biochar and fibre concentrations on the sludge's mechanical characteristics after being solidified in cement.
Mo, L., et al / 2019	Humidity sensor, laser displacement measurer, MIP, TG/DSC, SEM	Combining biochar with only one kind of expanding additive	Explore how the characteristics of cement pastes are affected when biochar is coupled with other forms of expansive additives.
Gupta, S., et al / 2020	Compressive, split-tensile, and flexuralstrength tests, permeability testing, exposure to high temperature	Only wet-curing was employed, and only a small amount of biochar was evaluated.	The significance of biochar porosity in preventing internal impairment in biochar-concrete at high temperatures may be further explored by modelling the vapour pressure surrounding capillary and biochar pores.
Akhtar, A. and Sarmah, A.K., / 2018	Mechanical testing of concrete samples	The carbonaceous solid substance was madefrom just three different kinds of waste sources.	Further study will get us closer to environmentally friendly concrete solutions, where waste-derived materials can be seen as the best means of reducing CO2

			emissions during the manufacture of concrete and as a means of carbon storage.
Yang, X. et al / 2021	Cracks,residual compressive strength,weight loss and UPV, X-ray diffraction, Fourier transform infrared spectroscopy, thermogravimetric analysis, SEM	Lack of testing for long-term durability	Evaluate the cementitious paste made with biochar's long-term durability.
Khan, K. et al / 2022	Compressive and flexural strength, electric resistivity, ultrasonic pulse velocity, SWOT analysis	Lack of environmental testing in hot and severe circumstances	Explore the resilience of biochar-concrete under conditions of extreme heat and abrasiveness.
Ling, Y. et al / 2023	Compressive and flexural strength, carbonation resistance, resistance to chloride ion penetration	Lack of research into how biochar affects different qualities of concrete	Assess the impact of biochar on the elasticity, shrinkage, and other features of concrete.
Li, Z. et al / 2023	Compressive and splitting strength, porosity, microstructures	Lack of research on how biochar affects other mechanical characteristics of concrete	Determine how biochar affects other concrete mechanical qualities like tensile strength, rupture modulus, and impact resistance.

(iv) Thermal Properties of Cementitious Materials with Added Biochar

Muthukrishnan, S., et al [41] have investigated the thermally processing iRHA, enhanced physical and chemical ash may be produced, which can be used to lower the weight of cement in mortar by 20%. Additionally, the durabilityandmechanicalfeatures of iRHA-RHB mortar were improved by combining rice husk biochar (RHB) and iRHA, where RHB was utilised to replace 10% and 40% by weight of iRHA, respectively. Performance was compared between the mortar manufactured under controlled laboratory settings (LabRHA) and the control (without RHA).In comparison to mortar with iRHA, experimental outcomesdemonstratedthat adding TRHA reinforced the mortar by 21% and 33%, respectively, at the early stage (after 7 days) and mature age (after 120 days). The TRHA-mortar displayed lower water permeabilityand autogenous shrinkage, representing increased durability as a building material, even though strength development was comparable to the control. RHB was added in place of iRHA to provide a 40% replacement that increased long-term (120-day) water tightnessand compressive strength by 22% and 17%, correspondingly.

Cuthbertson, D., et al [42] have investigated the potential of using Dry distillers grains used as a filler in biochar made from leftover biomass from the bio-ethanol industryin standard concrete to simultaneously achieve carbon sequestration and enhancedperformanceand propertiesof the concrete.Concrete density decreased linearly with the addition of biochar, reaching 1454 kg/m3 at 15 weight percent biochar. Because it generated pore networks inside the concrete, the adding of biochar also significantly boosted the sound absorption coefficient of concrete across the frequency range of 200-2000 Hz.With 2 wt% of biochar, the thermal conductivity of the concrete reduced the most, falling to 0.192 W/(mK). Bio-enhanced concretes are categorised as low-strength concrete since the inclusion of biochar decreased the concrete's compressive strength.

Yang, X., et al [43] have evaluated how well eight different types of biomasses would work as raw materials to make biochar. In order to evaluate volatile solids,changes in ash content,higher heating value (HHV), fixed carbon and yield, the materials were pyrolyzed at either 350 °C or 500 °C. For pyrolysis at 350 °C, there were significant correlations (p 0.01) among the ash and fixed carbon content of the biochars and their HHVs.According to their higher HHVs, higher energy densities, more fixed carbon, and lower ash fillings, the biochar made from Chinese fir, masson pine, and bamboo sawdust that was pyrolyzed at 350°C was determined to be appropriate for direct use in fuel applications.

Lee, H., et al [44] have determined whether biochar can be used in structures, a unique biocomposite was created utilising biochar and NIC(natural inorganic clay).After making biochar fromcoconut shell,bamboo, and rice husk, the researchers combined it with NIC in four different ratios to create a board, then they evaluated the board's morphological, thermal, and moisture performance. After morphological study with field-emission SEM proved its microstructure, each biochar's shape was discernible in the bio-composite mixed with biochar.According to a TCi analysis, biochar reduced thermal conductivity at its fastest rate at 67.21%. Due to the poor thermal conductivity of biochar, dynamic heat transfer studies proved that the biocomposite was less delicate to thermal change. The CUP test revealed that adding biochar raised the water vapour resistance factor by up to 22.58%, demonstrating that the biochar can lower water vapour permeability.

Liu, Z., et al [45] have carried out a study to identify the mechanisms underlying the impacts of applying biochar to a clay-textured red soil's thermal characteristics. The findings showed that applying biochar at rates up to 2.5% w/w did not mainly alter soil thermal characteristics through altering the arrangement of soil solids. After a 2-year application of biochar, soil thermal characteristics under field conditions drastically decreased.The impacts of biochar on the thermal characteristics of the soil were explained by two basic underlying mechanisms. One was the decrease in soil heat capacity and conductivity caused by biochar application, which was mostly related to the rise in macro- and meso-porosity. Another was the way applying biochar boosted soil's ability to retain water, which increased the soil's water content and enhanced soil's thermal qualities.

Yang, S., et al [46] have devised environmentally friendly red clay and biochar materials were employed to create eco-friendly building materials, and the mechanical and thermal performance of various biochar additives.The authors carried out tests on thermal conductivity, compressive strength, imaging with SEM, and infrared heat transfer. The findings specified that the biochar combination had a tendency to reduce heat conductivity. Samples mixed with rice husk had a lower compressive strength, whereas those containing coconut shell and bamboo had a tendency to have a higher compressive strength.The infrared heat transfer test revealed that the mixed rice husk specimens had significantly worse thermal performance than the ones mixed with bambooandcoconut shell. A thorough analysis of the development in strength and thermal performance revealed that a bamboo blend of 10% was the most successful.

Boumaaza, M., et al [47] have aimed to aid in the conservation of the environment by incompletely replacing cement with biochar made from Washingtoniafilifera pyrolysis waste for the production of biomaterials. They discovered that adding biochar made from waste Washingtoniafilifera rachis to bio-mortar mixes in place of 1 and 2 wt% cement enhanced the compressive strength. When using biochar as a cement substitute instead of additions of 3, 4, and 5 wt%, the compressive strength, which has been attributed to low porosity by the inclusion of 1 and 2 wt% of WFWB, was decreased at increasing rates above 2%. Additionally, compared to WFWB400 and WFWB300, WFWB500 biochar exhibited higher strength when used in place of cement in the created bio-mortars. However, specimens with increased biochar content exhibited improvements in capillary water absorption and porosityof bio-mortars, and a considerable development in thermal conductivity was detected, which supported their use as insulating supplies.

Kim, Y.U., et al [48] have enhanced the thermal performance of artificial stone utilized as finishing materials for buildings by integrating PCM with biochar. Depending on the kind, biochar was combined with cement in proportions of 2%, 4%, or 6%, and a PCM was infused into the pores of lightweight aggregates. Depending on the PCM employed, the manufactured specimens showed distinct latent heat values and peak temperatures. The compressive strength of the specimens with biochar up to 4% was comparable to or higher than that of the specimens without biochar, and the usage of 6% biochar was linked to a reduction in strength.Additionally, as additional biochar was blended, the specimen's thermal conductivity reduced, and it was discovered that RH, ST, and MS biochar all had lower thermal conductivities than other types. The biochar's pore properties were found to be the cause of this. The heat storage capabilities of the specimens and the temperature delay effect (of about 2.7 h) were confirmed through the heat transfer test. Table 4 shows review of the thermal properties of biochar.

Table 4. Review of Thermal Properties of Biochar

Author /Year	Techniques	Drawbacks	Future work
Muthukrishnan, S., et al / 2019	Thermal treatment of iRHA, combining RHB and iRHA	Compressive strength loss with RHB	More research on the usage of RHB as an alternative to iRHA in various types of concrete

Cuthbertson, D., et al /2019	Normal concrete with the additiveof biochar made from dry distillers grains	Reduced compressive strength of concrete	Enhancing the biochar content to attain better characteristics and performance without noticeably weakening
Yang, X., et al / 2017	Pyrolysis of eight types of biomass to create biochar	Rice straw was not a suitable substrate for biochar production	Additional research on the various applications of biochar generated from Chinese fir, masson pine, and bamboo sawdust is needed.
Lee, H., et al / 2019	Creation of biocomposite using biochar and NIC.		Additional analysis of the biocomposite characteristics and effectiveness in other applications
Liu, Z., et al / 2018	Analysisto determine the mechanisms underlying the effects of adding biochar to the soil's thermal properties	Tested at low application rates (up to 2.5% w/w)	To identify the best application rates and long-term outcomes, additional research is required.
Yang, S., et al / 2019	Tests on the thermal conductivity and compressive strength of biochar-infused eco-friendly building components	Samples with rice husk had lower compressive strength	Additional research is required to identify the best biochar mixes for strength and thermal performance.
Boumaaza, M., et al / 2023	Partially replacing cement with biochar made from pyrolysis waste for production of biomaterials	At increasing biochar content, compressive strength is reported to be lower.	The experimental programme will produce further mixes with various cement-to-sand ratios and water-to-binder ratio ranges.
Kim, Y.U., et al / 2021	Integration of PCM with biochar to enhance thermal	Reduction in strength observed at higher biochar content	To find the ideal biochar-to-cement ratio for thermal

	performance of artificial stone		performance, more research is required.

(v) Applications of Biochar

Dixit, A., et al [49] have studied the combined impact of marine clay and biochar on hydration improvement and shrinkage control in UHPC and examined a unique technique of dual waste valorisation in UHPC. Samples were made by substituting 30% by weight of QP with marine clay that had been calcined at 700 °C and combiningbiochar at 2% and 5% by weight of cement. The samples' long-term shrinkage, hydration, and strengthwere then examined. By the end of the seventh day, samples containing biochar had up to 10% more heat evolution than the reference samples.At 28 days, the degree of hydration (DOH) expandedfrom 51% in the reference samples to 60% in the biochar-treated samples. In samples containing biochar, shrinkage reduction of up to 20% was seen after 100 days. The 28th day compressive strength was 10% lower after QP was replaced with marine clay, but adding more biochar had no statistically significant impact on the strength.

Haque, M.I., et al [50] have suggested a new method for making biochar-based cementitious composites with multifunctional properties. Using chemo-mechanical modification, SHCP(super-hydrophobic carbonaceous powder) was created from biochar. Then, in paste and mortar samples, this SHCP was employed as a partial substitutefor Ordinary Portland Cement (OPC) up to 15% by weight. It was shown that using SHCP in this way reduced the rate of water absorption of the mortar samples by up to 70%.About 82% of the biochar under study's weight was made up of carbon. The electrical conductivity of the mortar samples was consequently improved by employing SHCP by up to 27%. As a result, the piezoresistive (self-sensing) properties of the mortar samples containing SHCP were evident, as shown by the linear correlation among theapplied stressesand FCR (fractional change in resistivity). The usage of SHCP also led to a smaller carbon footprint for the cement and mortar samples in contrast to the control batch because of the decreased OPC content and the absorption of the carbon found in the biochar.

Wang, L., et al [51] have aimed to investigate the viability of biochar made from wood waste as a green additive and evaluate the impact of various physico-chemical characteristics of dredged sediment on the durability of items made from cement-based sediment. The formation and evolution of pore structures in sediments was establishedby the particle size distribution of the sediments, according to X-ray diffraction and porosimetryresearch.Thermal and calorimetric tests showed that while the insertion of biochar marginally improved the cement hydration reaction, its relatively big and brittle particles caused microcracks and reduced the strength of sediment products. However, the inclusion of biochar increased the immobilisation of potentially harmful substances and organic pollutants, making the sediment products more environmentally friendly. Therefore, this study's novel methodology might recycle dredging silt and waste wood charcoal to create environmentally friendly building materials like fill material and paving blocks.

Gupta, S., et al [52] have examined the effects of biochar on the strength, hydration, shrinkage, and permeability of cement mortar when it was introduced as a partial replacement for cement and silica fume. Wood waste and coconut shell were utilised to make biochar, which was used to replace 33% and 5 wt% of the silica fume in cement, respectively. At a 91-day age, it was found that the mortar with silica fume (10 wt% of cement) and biochar (5 wt% of cement) combined could minimise drying shrinkage andautogenous shrinkage by 23%and61%, respectively.It was discovered that higher permeability and lower pore tortuosity biochar resulted in a greater reduction in autogenous shrinkage. In comparison to the control, mortar with a 5-weight percent addition of biochar made from coconut shells and woodshowed improved water permeability, strength and hydration. When contrastedto a control mortar, the mortar with silica fume and biochar demonstrated better 28-day strength and gave comparable strength and water permeability.

Quan, G., et al [53] have studied the changes in organo-mineral complexes in soils that had been remedied with biochar for around 8 years and 3 years, correspondingly, in saline-alkali and acidic paddy soil. According to the findings, applying 40 t ha-1 biochar to the saline-alkali and acidic paddy soilresulted in increases in loosely combined humus of 30.1% and 25.1%, respectively. The rise in the complexes content, meantime, was caused by a rise in cement (Fe-oxides). With the treatment of 40 t ha-1 biochar, complex iron in the saline-alkali soil was 30% greater than in the acidic paddy soil.Oxygen-containing functional groups were seen on the surface of the biochar that had been removed from the repaired field using Fourier Transform Infrared Spectroscopy. Both sedimentation and complexationwere involved in the immobilisation of heavy metals, according to an X-ray diffraction examination.

Chen, L., et al [54] have revised cement-bonded particleboards with a significant amount of pre-soaked 50–70% biochar to make the final goods carbon-negative. The functions of biochar in the MOSC(magnesium oxysulfate cement) system were examined, and the excellent mechanical and practical qualities of particleboards made with biochar cement were shown. The thermogravimetric analyses (TGA) and XRD provedthat the levels of hydration products were enriched in the cement systems when biochar was included.In addition, compared to particleboards made of regular concrete, the high proportion of biochar dramatically decreased the heat conductivity of the material.

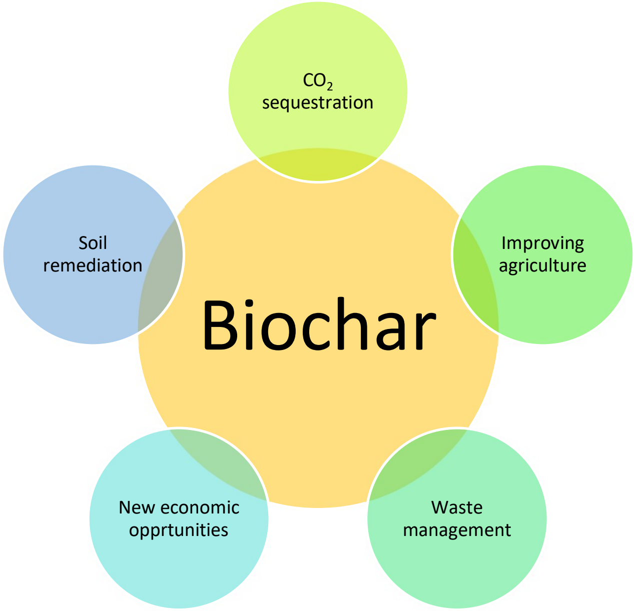
Sirico, A., et al [55] have assessedthe potential for employing biochar as a filler in structural concrete. They obtained the biochar for their study from a business that turned woodchips into energy by pyrogasification. Chemical and morphological characteristics of the biochar were determined before it was used as a filler in concrete at various ratios, up to 10% by weight of cement. The implications of its infusion on the physical and mechanical properties of the newly hardened concrete in addition to on the internal matrix microstructure were evaluated in comparison to a reference concrete. To assess the impact of biochar on concrete in terms of long-term behaviourand internal curing action, several curing conditions (dryandwet) and curing timeframes (up to 365 days) were treated. The review of applications of biochar is explained in the table 5.

Table 5. Review of Applications of Biochar

Author /Year	Techniques	Drawbacks	Future work
Dixit, A., et al / 2021	Substitution of QP with marine clay calcined at 700 °C; addition of biochar at	10% less compressive strength after marine clay was substituted for QP;	Future research is required to support these materials' additional properties,

	2% and 5% by weight of cement	additional biochar had no statistically significant effect on strength.	such as their effect on durability and charcoal feedstock, among others.
Haque, M.I., et al / 2021	Using biochar to make super-hydrophobic carbonaceous powder (SHCP), which can replace OPC up to 15% by weight.		Look at how employing SHCP affects the workability, toughness, and other characteristics of cementitious materials.
Wang, L., et al / 2019	An assessment of the impact of different physico-chemical characteristics of dredged sediment on the mechanical properties of cement-based sediment products; assessment of the practicality of biochar generated from wood waste as a green additive.	Microcracks created by the comparatively large and brittle biochar particles; decreased strength of sediment products as a result of the usage of biochar.	Examine the utilisation of various biochars with improved physico-chemical properties.
Gupta, S. et al / 2020	Partial replacement of silica fume and cementwith biochar in cement mortar	Reduced shrinkage caused by autogenesis and drying by 61% and 23%, correspondingly. improved water permeability, strength, and hydration.	Look at how biochar affects the resilience and fire resistance of cement-based materials, as well as other qualities.
Quan, G. et al / 2020	Application of biochar in acidic paddy soil and saline-alkali soil	An increase of 30.1% and 25.1%, correspondingly, in loosely combined humus. complexation and sedimentation have a role in the	The outcome has major implications for future environmental sustainability and soil remediation.

		immobilisation of heavy metals.	
Chen, L. et al / 2022	Use of pre-soaked biochar in cement-bonded particleboards	Enrichment of hydration products in cement systems when biochar was included. Dramatic decrease in heat conductivity of the material.	Analyse the viability of using biochar into other building materials.
Sirico, A. et al / 2021	Use of biochar as a filler in structural concrete	Evaluation of the effects on the physicaland mechanicalproperties of newly-poured and hardened concrete. The effectiveness of internal healing and long-term behaviours were assessed.	Examine how biochar affects the durability and fire resistance of concrete, as well as other aspects.



Applications of biochar

4. Conclusion

Biochar, which is made from biomass, exhibits promising thermal and mechanical qualities, making it a desirable cement component. Additionally, using biochar helps to sequester carbon and lowers greenhouse gas emissions, addressing environmental issues.The potential advantages and difficulties of using biochar into cementitious materials are highlighted in this review paper.Despite the fact that biochar-added concrete was not produced on a big scale, it did not show a significant reduction in production costs. But it's expected that widespread manufacturecould result in financial gains. The amount of biochar used depends on variables including the type of feedstock and particle size, demanding additional study and optimisation for better performance. It is advised to use coarse-sized particles with a lower proportion since they effectively fill spaces in the concrete mixture and increase strength.The concrete industry must be effectively informed of the benefits of incorporating biochar into concrete in order to break down market entrance obstacles. This will refute the idea that biochar is only appropriate for soil-based uses and promote biochar's widespread use.But there's also a chance that adding biochar to concrete will have unforeseen results. The high surface area of biochar makes it possible to absorb and retain water, which may affect the material's behaviour. Additionally, the efficiency of chemical admixtures in a biochar/concrete combination may change due to the potential of adsorption within the pores of the biochar. Future research should therefore examine how biochar affects the effectiveness of chemical admixtures.To optimise biochar incorporation, address potential issues, and prove its viability as a workable solution for lowering greenhouse gas emissions and improving the general performance of cementitious materials, more research and development is required.

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