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2
3 **STRATEGIES FOR OPTIMIZING THE BIOCHAR CONTENT OF WOOD CHIPS,**
4 **PEANUT SHELLS, AND RICE HUSKS IN CEMENTITIOUS MATERIALS**
5

6 ***Abstract:***

7 The characteristic GHG emissions from cement production, primarily due to decarbonation and fossil fuel
8 consumption, are deeply concerning. Reducing the clinker content in cement is the fastest way to lower the carbon
9 footprint, particularly through the addition of biochar. This promising approach is the subject of several studies.
10 However, numerous factors come into play, ranging from the type of biomass used to the curing of the material.
11 This is, in fact, the source of the diversity in results and the resulting contradictions. The common thread among
12 these studies remains the negative impact of high biochar content. This review article aims to demonstrate the
13 importance of certain pyrolysis parameters on the properties of biochars, but above all to highlight the levers that
14 could enable an increase in biochar content in cementitious materials while preserving mechanical and durability
15 properties . In the literature, the beneficial effect of biochars on mechanical properties, dry shrinkage, crack
16 resistance, reduced water absorption, etc., is only significant when the biochar content is less than or equal to 1%.
17 The porous nature of biochar, which is both beneficial and detrimental, limits the amount of biochar that can be
18 added to or substituted for cement. However, alternatives such as pretreatment and accelerated carbonation
19 hardening allow for additions of up to 5% or even 10%. This review summarizes the individual factors (biochar
20 fineness, pretreatment, accelerated carbonation, etc.) that facilitate biochar incorporation. Unlike existing studies
21 that treat these factors separately, we recommend a standardized protocol that combines them to achieve a high
22 biochar content without compromising strength and durability.
23

24 ***Key words:***

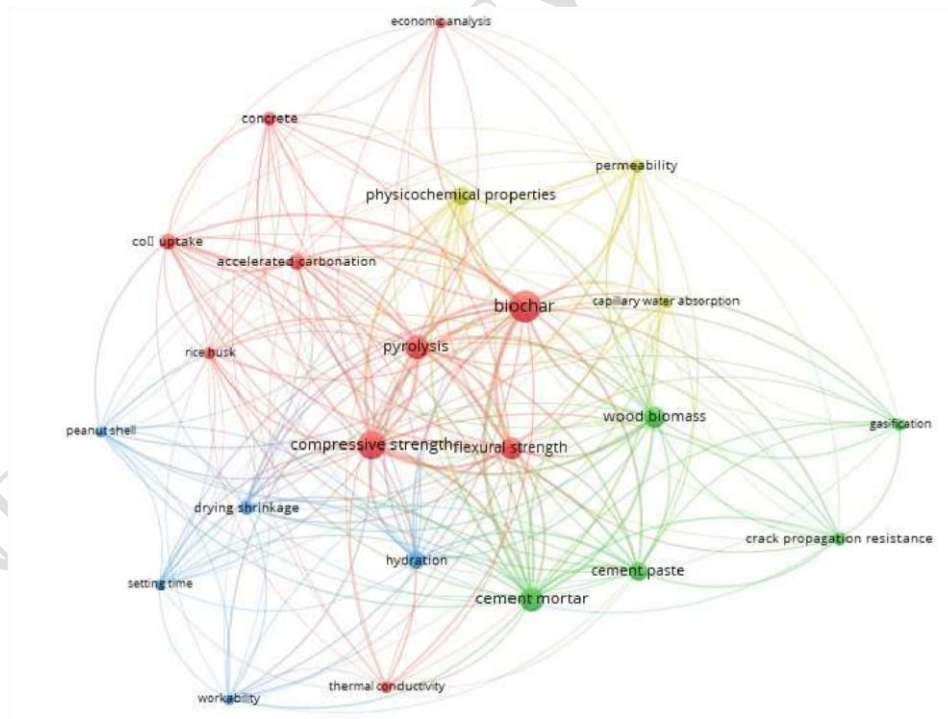
25 Biochar, Optimization, Cementitious materials, Mechanical properties, Durability
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27

28 **Introduction:-**

29 By far the most widely used construction material in the world for the past century[1] . The amount of concrete
30 poured annually worldwide is approximately 7.4 billion tons[2] . Although extremely durable, it has a very high
31 carbon footprint due to the materials it contains[1] . Among these, one stands out due to its considerable impact
32 compared to the others: cement, which accounts for 74–81% of concrete’s total CO₂ emissions[3] . The cement
33 industry is responsible for 5–7% of anthropogenicCO₂ emissions and ranks 4th in terms of CO₂ emissions into the
34 atmosphere, behind oil, coal, and natural gas[3] . In 2023, annual cement and clinker production is estimated at 4.1
35 and 3.8 billion tons, respectively [4] . Given increasing urbanization, rising demand remains evident, and has been
36 approximately 30% per decade since 2016[3] . Clinker production is considered highly “energy-intensive,” also
37 requiring a significant amount of nonrenewable natural resources, namely limestone and clay, which are dwindling
38 over the years. The production of 1 ton of ordinary Portland clinker requires approximately 1.22 tons of limestone
39 and 0.31 tons of clay[5] . The chemical reactions involved in the decarbonation of limestone generate 0.525 t of
40 CO₂;when combined with thermal energy emissions, this results in 0.82 t of CO₂per ton of clinker[6] . In cement
41 production, numerous artificial (slag, fly ash) or natural (limestone, pozzolans, etc.) materials with a low carbon
42 footprint are used as additives to clinker to address and improve the durability properties of the cements containing
43 them and reduce their carbon footprint. In this effort to maximize the replacement of clinker with low-carbon
44 cementitious materials, one of the administrative and regulatory barriers lies in standardization, particularly at the
45 European level. Indeed, the reference “product” standard EN 197-1[7] is based on the composition of common
46 cements and allows only a limited number of constituents in their composition[7] . Furthermore, the composition
47 ranges are strictly defined according to the type of material and with a tolerance of +/-2.5%, which limits their use.
48 These limitations hinder the optimization of cementitious materials and thus the reduction of cement’s carbon
49 footprint. This is why an approach based on demonstrating the performance of cements would help overcome these
50 obstacles. This is the focus of the RILEM TC-312 PHC technical committee[8] . Excessive concentrations of CO₂in
51 the atmosphere contribute to global warming. If no action is taken, the risk of catastrophic climate change will be
52 much higher and irreversible. As a result, strategies are being implemented by industry stakeholders, including
53 reducing the clinker content in cement by using other additives that are much less carbon-neutral[9] , or require less
54 energy to produce. To this end, several conventional materials have been used for decades, but they remain
55 insufficient given the urgent need to decarbonize the sector. Faced with this pressing need for a paradigm shift, a

56 particular material has been attracting attention for several decades and is the subject of numerous studies as a
 57 construction material: biochar. Its use in construction addresses a dual concern: biomass waste management in West
 58 Africa and the reduction of GHGs. Biomass waste management remains a major challenge we face. Beyond taking
 59 up space, it releases GHGs (CO₂ and CH₄) into the atmosphere when burned or left exposed to the open air[10].
 60 Numerous studies have been conducted on the use of raw biomass waste, particularly palm kernel shells[11], wood
 61 waste[12], rice straw stalks[13], rice husks[14], and couch grass straw[15] in construction. However, the
 62 incorporation of biomass into cementitious materials disrupts hydration reactions, leading to delayed setting and
 63 consequently a loss of material strength[16]. Converting biomass into biochar is an effective way to chemically
 64 stabilize the material and contribute to the strength and durability of cementitious materials. According to Gupta et
 65 al., biochar's three properties chemical stability, low thermal conductivity, and low flammability make it suitable for
 66 use as a construction material[17]. Thanks to its porous structure, biochar has water retention capacity; water is
 67 released over time, contributing to hydration and increased strength[18]. Daniel Suarez-Riera et al.[19] demonstrate
 68 a 13% and 30% increase, respectively, in compressive and flexural strength at 28 days for a 2% biochar addition
 69 compared to the control[19]. Most applications of biochar in cementitious materials use a low biochar content,
 70 rarely exceeding 5%. The overall objective of our study is to enable greater incorporation of rice husk, wood chip,
 71 and peanut shell biochars into cementitious materials. To this end, we will first review studies on biochars in
 72 general, and specifically on these three types of biochars. Next, we will identify the various strategies found in the
 73 literature that allow for optimizing the biochar content in cementitious materials without compromising their
 74 strength and durability. The purpose of my work is to demonstrate methods for increasing the typical biochar
 75 content incorporated into cementitious materials while maintaining the materials' properties intact. To visualize the
 76 structure of the research field on the incorporation of biochar from peanut shells, wood chips, and rice husks into
 77 cementitious materials, a bibliometric analysis based on keyword co-occurrence was performed using the
 78 VOSviewer software. Figure 1 shows the resulting map.

79



80

81 **Fig.1.** VOSviewer mapping of keyword co-occurrences

82 **1. Biochar**

83 Known for thousands of years[20] for its use as a soil amendment, charcoal is now referred to as biochar. Some of
84 these applications were primarily aimed at conserving or restoring degraded ecosystems, with the added benefit of
85 carbon sequestration[21] [22] . In fact, it is considered by the IPCC to be a carbon storage solution[10] . Biochar is a
86 porous, carbon-rich material containing oxygen-containing functional groups and aromatic surfaces[23] . It is
87 produced through the thermochemical conversion of biodegradable materials under specific conditions. Several
88 types of waste materials, such as algal and food waste, agricultural residues, biodegradable forestry and municipal
89 waste, animal waste, and urban activated sludge, are considered primary resources for this purpose[22][24] . Their
90 thermal conversion generally yields three byproducts: biochar, synthesis gas, and bio-oil in varying proportions.

91 **1.1 Biochar Production Methods**

92 Biochar production involves various methods, each with its own advantages and limitations[25] . The choice of
93 production method is primarily guided by several material-related factors, such as the type of biomass[26] , moisture
94 content, desired biochar properties, and available resources, which influence the choice of method[25] . Among
95 these methods, we will focus primarily on three (3).

96 **1.1.1 Pyrolysis**

97 Pyrolysis is the most commonly used process[27] [28] . It is the best method for producing biochar with significant
98 yields[29] . When lignocellulosic biomass is used, hemicelluloses decompose first at temperatures between 197 and
99 257°C, followed by cellulose between 237 and 347°C, and finally lignin, which is pyrolyzed between 277 and
100 497°C[30] . Pyrolysis parameters differ depending on whether or not one wishes to maximize biochar yields. In fact,
101 this is what has allowed pyrolysis to be classified into two main categories: slow pyrolysis and fast pyrolysis.
102 Pyrolysis can be considered slow or fast depending on temperature, heating rate, residence time, and pressure[31].

103 **1.1.1.1 Slow pyrolysis**

104 Slow pyrolysis has been used for thousands of years, primarily for the production of charcoal[20] . Characterized by
105 a low heating rate and a long residence time[32] , it promotes the production of biochar. During biomass pyrolysis,
106 the pyrolysis temperature range is typically 400–500°C, with a heating rate of 0.1 to 1°C/s over 5 to 30 minutes[32] .
107 The values of these parameters are not fixed; they may vary from one study to another. In the literature, biochars
108 obtained by slow pyrolysis have a cation exchange capacity (CEC) and ash content that are much higher than those
109 obtained by fast pyrolysis[33] . The increase in CEC and ash content are related because acidic functional groups are
110 reduced[34].

111 **1.1.1.2 Rapid pyrolysis**

112 Unlike slow pyrolysis, fast pyrolysis maximizes bio-oil production. Typically, fast pyrolysis processes yield 60–
113 65% bio-oil, 15–25% (10–30%[35]) charcoal, and 10–20% non-condensable gases, depending on the feedstock
114 used[20] . It is carried out at temperatures ranging from 600–1000°C, at a heating rate of 10–200°C/s[20] . The
115 increase in temperature can significantly increase the pore volume and specific surface area of biochars[36] . The
116 essential characteristics of fast pyrolysis for obtaining bio-oil are[37] : High heating and heat rates at the reaction
117 interface; Very short residence time < 2 s

118 **1.1.2 Gasification**

119 Gasification is one of the methods for converting biomass that prioritizes the production of synthesis gases (H₂, CO₂,
120 CH₄, CO, N₂) over biochar[24][38] . It is a complex process, limited by the choice of feedstock[39] . It involves the
121 following four steps: drying, pyrolysis, combustion/oxidation, and reduction[40] . The composition of synthesis
122 gases produced by biomass gasification depends primarily on the biomass, the type of reactor, and the gasification
123 agent[41] . Gasification occurs at high temperatures (>700°C) in the presence of gasification agents (air, oxygen-
124 enriched air, water vapor, carbon dioxide)[42] . When air is used as the gasification agent, N₂ is the primary product
125 (41.6–61.6%) (vol%), while steam and oxygen combined produce a large proportion of CO (approximately 42.5–
126 52%) (vol%)[43] . The biochar produced has a low yield of 5–10% with increased porosity, due to the release of
127 volatile matter influenced by the rise in temperature[39] . Daniel Suarez-Riera et al.[44] studied the effect of two

128 types of biochar on the mechanical properties of cement pastes and mortar. The results showed that gasified biochar
 129 has a higher water retention capacity than pyrolyzed biochar, due to its high internal porosity[44].

130 1.1.3 Hydrothermal carbonization (HTC)

131 HTC, also known as wet pyrolysis[29], is a process for converting wet biomass (sewage sludge, algae, kitchen
 132 waste, etc.) into a material called “hydrochar”[24]. In this process, biomass with a high water content is introduced
 133 into a closed reactor containing liquid, at a temperature range (180–250°C) and under a water vapor pressure
 134 determined by the temperature[45]. Depending on whether the processing temperature is < 250°C, [250–400°C], or
 135 > 400°C, the resulting products are, respectively, biochar (hydrothermal carbonization), bio-oil (hydrothermal
 136 liquefaction), and gaseous products (thermal gasification)[31]. HTC involves four steps: (i) hydrolysis of biomass
 137 into monomers, (ii) pH reduction, (iii) polymerization through dehydration of the monomers, and (iv)
 138 aromatization[39].

139 **Table 1** : Summary of the 3 biochar production processes

Criteria	Pyrolysis		Gazification	Carbonization hydrothermal
	slow	rapid		
Biomass	dry		dry	wet
Température (°C)	300-500	600-1000	>700	<250
Atmosphère	Inert		Air, O ₂ , vapor, CO ₂	Liquid
Main produit	biochar	oil	syngas	hydrochar
Application of biochar in cement	Common	Not recommended	rare	rare

140

141 1.2 Effect of pyrolysis source and parameters on biochar properties

142 1.2.1 Effect of raw material composition

143
 144 The waste materials used for biochar production are diverse but can generally be classified into two subgroups based
 145 on their composition. These are: lignocellulosic biomass and non-lignocellulosic biomass. In this section, we will
 146 specifically discuss the impact of the composition of lignocellulosic biomass on the properties of biochar.
 147 Lignocellulosic biomass consists primarily of three polymers (lignin, cellulose, and hemicellulose) in varying
 148 proportions depending on the biomass source. Cellulose and hemicellulose are responsible for volatile products,
 149 while lignin primarily produces biochar and a small amount of water during pyrolysis[46]. The proportion of
 150 hemicellulose, cellulose, and lignin in the biomass determines the amount of carbon stabilized in the biochar[23].
 151 Indeed, each component has a decomposition temperature that allows for the formation of stable aromatic carbon.
 152 However, the high lignin content of the raw materials is proportional to the formation of aromatic carbon, which is
 153 positively correlated with the stability of the biochar[39]. When lignocellulosic biomass is used for biochar
 154 production, a high carbon content is observed, unlike with non-lignocellulosic biomass[47]. The study by Xin Chen
 155 et al. shows a carbon content of 8.9% in biochar derived from municipal sludge pyrolyzed at 500°C for 1 hour[48].
 156 In contrast, a study conducted at the same pyrolysis temperature and residence time on lignocellulosic biomass
 157 shows a significantly higher carbon content, reaching 87.13%[49]. According to the study by Souradeep Gupta et
 158 al. (2020) on the incorporation of lignocellulosic and non-lignocellulosic biochars into cement mortar, the type of
 159 biomass also affects the mechanical strength of the added cementitious materials[50]. Wood biochar prepared at
 160 500 °C resulted in a slight 7% increase in 28-day strength compared to the control, while non-lignocellulosic algae
 161 biochar reduced the mortar’s strength by 15%[50]. For a comprehensive analysis of the effect of biomass
 162 composition on biochar, IR and NMR spectroscopy analyses are necessary and help highlight the thermal
 163 decomposition of cellulose and lignin, as well as the formation of aromatic structures[51].

164 1.2.2 Effect of pyrolysis parameters

165 **1.2.2.1 The temperature**

166
167 The pyrolysis temperature plays a key role in determining the properties of biochar. As the temperature rises,
168 volatile organic compounds are released, leaving voids in the material that form an open-pore network with a high
169 specific surface area. As the temperature continues to rise, the specific surface area also increases until it reaches an
170 optimum, after which it decreases. The surface area can improve water retention capacity and, to some extent, the
171 potential for biochar to interact with its environment[25] . The pores in biochar serve as water storage sites and, at
172 times, as nucleation sites for hydrated products. When the temperature is [500–700°C], volatile matter decreases
173 drastically[52] and the carbon skeleton becomes more robust.

174 The degree of decomposition of cellulose, hemicellulose, and lignin influences the extent to which the physical
175 structure of biomass changes during pyrolysis[17] . Cellulose, hemicellulose, and lignin decompose at different
176 temperatures[17] . This is why an ATG/DTG thermal analysis of raw materials is essential to determine the
177 appropriate pyrolysis temperature and associated mass losses. Leandro Rodriguez Ortiz et al. studied the influence
178 of temperature on the volatiles in walnut shells and kernels[53] . Respective reductions from 37.35±5.30% to
179 31.94±1.27% and from 59.19±0.96% to 50.03±1.22% for kernel and shell biochars are observed when the
180 temperature increases from 400 to 600°C[53] . The modification of biochar's structural properties under the
181 influence of temperature affects the fresh and hardened properties of the cementitious materials to which they are
182 added. While the nature of the biochar influences mechanical strength, temperature also plays a significant role. In
183 their study on the addition of rice straw biochar to cement paste, Xiaoyu Jiang et al. show that compressive strength
184 at 28 days increases with temperature and that a 32.5% increase in mechanical strength is achieved with a 1%
185 addition at 500°C[54] . Above 500°C, strength tends to decrease, although it remains higher than the control[54] .
186 Xin Chen et al. confirm in their study that temperature affects mechanical strength at 28 days and go further by
187 stating that increasing the temperature accelerates setting time and improves the degree of hydration[48] . These
188 results show a 5.8% increase in 28-day strength compared to the control when municipal sludge biochar is produced
189 at 500°C and then substituted for 2% of the cement[48] . Previous studies are insufficient to definitively determine
190 the impact of temperature on the properties of cementitious materials, but they unanimously show that a pyrolysis
191 temperature of 500°C yields the best results regardless of the biomass used.

192 **1.2.2.2 Heating rate**

193 The heating rate is a parameter that influences the nature and composition of the charcoal to some extent[32] .
194 Depending on whether the heating rate is low or high, the biochar yield changes. A low heating rate ensures that no
195 thermal cracking of the biomass occurs, and consequently the biochar yield is high[32] . Whereas a high heating rate
196 leads to the depolymerization of the biomass into volatile compounds[55] resulting in increased porosity. The work
197 of SevgiSensöz and DilekAngin on the pyrolysis of safflower seed cake shows biochar yields of 34.2%, 30%, and
198 29.7% when the heating rate is 10°C/min, 30°C/min, and 50°C/min, respectively[55] . There is no significant effect
199 of heating rate, despite the decrease in yield. However, a significant difference is observed when the temperature
200 increases from 400°C to 600°C, with yields ranging from 34.2% to 26.3% at a heating rate of 10%[55] . The authors
201 conclude that, in reality, the pyrolysis temperature is the primary factor influencing yield, and that the combination
202 of low temperature and a slow heating rate maximizes biochar yield.

203 **1.2.2.3 Residence time**

204 Increasing residence time promotes the repolymerization of biomass components by giving them sufficient time to
205 react[32] , thereby increasing the degree of carbonization of the biochar. Longer residence times reduce the vapors
206 produced during secondary reactions, resulting in a higher proportion of charcoal[17] . Mouhamed et al (2013) and
207 Tsai et al (2007) observed that residence time does not significantly affect biochar yield, but rather the composition
208 of bio-oil and gaseous products[56] [57] . Studies on the effect of residence time on yield generally show that
209 residence time alone is insignificant and that other associated parameters such as temperature and heating rate have a
210 much greater influence on biochar yield and certain biochar characteristics[58] .

211 **1.3 Use of biochars in materials**

212 **1.3.1 Biochar-cementitious composite**

213

214 The use of biochar in construction materials dates back decades. Several studies have been conducted, and the
215 results are promising in many cases. In the literature, biochar is incorporated into cement not only to reduce its
216 carbon footprint but also to improve the mechanical, thermal, and durability properties of cementitious materials.
217 While there are many studies, they remain limited in scope and rarely lead to practical implementation. In 2013, the
218 Ithaka Institute took action and decided to construct its first building using a biochar-based plaster composed of 50%
219 biochar, 30% clay, and 20% sand[59]. Biochar is also used in other building materials, notably lightweight biochar-
220 concrete panels, biochar-lime bricks, and insulating plasters for interiors (biochar-clay) and exteriors (biochar-
221 cement or lime)[60]. Their properties are enhanced and are undergoing extensive performance testing. While
222 biochar incorporated into cement reduces its carbon footprint, it also possesses essential properties that make it
223 unique. Preliminary results from the institute confirm this, demonstrating good insulation and excellent humidity
224 regulation in the building. A study by Gupta et al. (2017) reveals another aspect of biochar, as a coating for
225 polypropylene (PP) fibers reinforced in concrete[61]. The results were satisfactory, with a 28-day flexural strength
226 of 14 MPa for the biochar-coated polypropylene (PP) fiber-reinforced concrete, compared to 11 MPa for the
227 uncoated PP fiber-reinforced concrete[61].

228 The importance of biochar is recognized by the cement manufacturer Vicat, which has taken the initiative to
229 innovate by adding biochar to clinker to produce a new carbon-negative binder, named “Liant Carat” in July 2022.
230 The biochar from the company Soler used in this process is capable of sequestering 2.9 tons of CO₂ per ton of
231 biochar[62]. The Carat binder underwent several performance tests and was used for the first time in the
232 construction of the structural walls for a two-story office building project by the Corbioli company in Ambérieu-en-
233 Bugey (01)[62]. Large-scale testing of the binder’s performance was conducted as part of a project in which 850
234 m³ of Carat-based concrete was used to construct the building’s floors[63].

235 In the absence of established standards, the use of biochar as a cement additive continues, and progress is being
236 made. Its impact on cementitious materials varies depending on several parameters, which must be understood to
237 ensure its widespread use and, ultimately, standardization. The influence of biochar on cement, followed by an
238 analysis of the intrinsic properties of cement-biochar composites, is detailed in Part 3.

239 **1.3.2 Biochar-asphalt composite**

240 The incorporation of biochar into asphalt concrete stems from its chemical composition, which is equivalent to that
241 of carbon-based materials historically used as asphalt additives[64]. Indeed, these carbon-based materials, due to
242 their high tensile strength, can increase the crack resistance of asphalt pavements[64]. Carbon fiber and carbon
243 black are commonly used due to their availability[65]. Because of its high carbon content, biochar has the
244 advantage of being included in this range of carbon-based materials used in pavements, with the aim of improving
245 material performance. In their study, Zhao et al (2014), [65] reported that biochar showed significant results in terms
246 of the rheological properties and crack resistance of asphalt mixtures, unlike carbon fiber and carbon black[65]. An
247 addition of up to 10% biochar exhibited resistance similar to that of the control[65]. Chebil, S. et al (2000)[41] also
248 used biochar as a bitumen modifier for pavement applications. Among these results, we observe an increase in
249 bitumen viscosity with the addition of 15% biochar, and higher rutting resistance after adding 5% biochar under
250 multiple loading cycles (>100)[17] [41]. In summary, biochar is an excellent modifier for bituminous binders; not
251 only does it improve performance under certain conditions, but it also sequesters carbon in pavements.

252 **1.3.3 Biochar-polymer composite**

253 Carbon-based materials (carbon black, graphene, biochar, etc.) used as fillers in polymer composites, in addition to
254 having good interfacial adhesion[38], have the ability to improve the mechanical, electrical, and thermal properties
255 of these composites[66]. Consequently, numerous studies on the incorporation of biochar into resin composites,
256 rubber composites, and even plastic composites have been conducted[38].

257 Biochar is an eco-friendly and sustainable alternative to carbon black, the primary and standard reinforcing filler in
258 rubber composites. Synthesized from non-renewable resources at temperatures > 1600°C in an oxidizing
259 atmosphere, carbon black is known for its high carbon footprint[67]. It possesses a specific surface area, aggregate
260 structure, and surface chemistry that enhance its capabilities as a filler in elastomers[68]. Given its key
261 characteristics, biochar is attracting attention due to its carbon content and low carbon footprint. In the literature,
262 biochar can be found in various rubber composites: natural rubber composites, nitrile rubber composites, styrene-

263 butadiene rubber composites, and mixtures of natural rubber and butadiene[67] . To improve its effectiveness in
264 rubber composites, treatments are sometimes necessary to modify its surface chemistry[69] . Steven C. Peterson and
265 A. J. Thomas (2022) modified biochar to make it a viable co-filler; treatments suitable for the current rubber
266 industry are being carried out[69] . A respective increase of 19% and 40% in tensile strength and toughness is
267 observed with biochar first treated with CO₂ and then coated with lauric acid[69] .

268 The study by Mauro Giorcelli et al. (2019) demonstrates that the electrical performance of epoxy biochar composites
269 increases with the conductivity of Miscanthus biochar[66] . Nevertheless, the type of biochar and pyrolysis
270 conditions can influence the electrical properties of the final composite[66] . However, it is necessary to pre-select
271 the biochars used in order to achieve the desired results[66] .

272 **2. Incorporation of rice husk, peanut shell, and wood chip biochars into cementitious** 273 **materials**

274 The addition of biochar to cementitious materials was driven by its ability to sequester carbon over its lifespan.
275 Biochar in a structure was previously considered a carbon sink. Over the years, various studies began to explore in
276 depth the role, limitations, and both positive and negative effects of biochar in cementitious materials. This revealed
277 its remarkable properties, which we will explore in this section, and attracted the attention of researchers in the field.

278 **2.1 Impact of Adding Biochar on the Fresh Properties of Cementitious Materials**

279 **2.1.1 Workability**

280
281 The incorporation of biochar into cementitious materials negatively affects workability. Indeed, part of the mixing
282 water is absorbed by the pores of the biochar, thereby reducing the workability of the material. This limitation is a
283 major reason for the restriction on the biochar incorporation rate, which rarely exceeds 5%[70] . The pore
284 distribution of biochar is critical, as it significantly influences the mixture's water absorption capacity. It has been
285 reported that biochar pores in the range of 5 to 30 μm are most effective at absorbing and retaining water[71] .
286 Furthermore, fine, angular biochar particles also contribute to reduced workability. The angular shape of biochar
287 tends to restrict the movement of the cement paste and particles[72] . Gupta et al. (2018) confirm these observations
288 in their study, noting that angular wood sawdust biochar, which has a high water absorption capacity, exhibits the
289 greatest reduction in flow compared to other biochars[47] . To overcome this undesirable effect and allow for a
290 higher incorporation rate of biochar, a high-water-reducing superplasticizer is added in a dosage proportional to the
291 biochar content. In the literature, the W/C ratio remains constant for all mixtures, and the dosage of the
292 superplasticizer is varied until the desired workability is achieved. However, the use of the superplasticizer no
293 longer has the desired effect at certain biochar dosages, and furthermore, it could delay the hydration of the material,
294 thereby reducing early-age strength[73] . In some studies, biochar is pre-saturated before mixing, which ensures
295 moisture transfer into the cementitious matrix while maintaining workability at a reduced W/C ratio. The study by
296 Gupta et al. (2018) is a specific example of this, except that the workability of samples incorporating biochar pre-
297 soaked for 6 hours prior to mixing is reduced, despite the addition of superplasticizers[74] .

298 **2.1.2 Hydration kinetics**

299 Hydration is an essential process that leads to the formation of hydrates, which are responsible for the strength of
300 cementitious materials. It is accompanied by the release of varying amounts of heat and is generally described in
301 four stages: the initial stage, the induction stage, the acceleration stage, and the deceleration stage. Biochar, like any
302 other additive, can accelerate or delay hydration, based on previous research. In a study by Gupta et al. (2021), the
303 thermal evolution rate of cement pastes containing 1% and 2% mixed wood waste biochar (MWBC) showed a
304 shortening of the induction period by approximately 30 minutes, followed by a slight acceleration of hydration[75] .
305 Contradictory results were reported by Carolina et al.[76] , who observed a prolongation of the induction period by
306 73.1%, 48.9%, and 77.9%, respectively, for additions of 1%, 2%, and 3% biochar compared to the control[76] .
307 Cement pastes containing 1% fine and coarse wood sawdust biochar show, respectively, an increase in the amplitude
308 of the first peak[77] , corresponding to the hydration of tricalcium silicates (C₃S), followed by dicalcium silicates
309 (C₂S)[78] . In some cases, the addition of biochar not only accelerates hydration but also amplifies the hydration
310 peak. It has an accelerating effect. Biochar has the ability to provide additional nucleation sites where the formed
311 hydrates precipitate. Indeed, the addition of biochar fills the voids between fine aggregates and cement particles, and

312 their negative surface charges (due to the presence of OH⁻ groups)[75] attract the positively charged hydrated
313 cement particles around them[12] . This attraction has enabled the formation of nucleation sites, promoting an
314 enhanced hydration reaction through the attraction of neighboring particles, leading to the precipitation of hydrates
315 on their surfaces[12] . Consequently, biochar acts as a filler and contributes to the densification of the cementitious
316 material[52] , more so than its pozzolanic effect in some cases[79] .

317 Several factors can contribute to improved hydration, such as the specific surface area of the biochar[50] , its
318 chemical composition, pre-soaking the biochar during air-drying[74] , etc. The pyrolysis temperature plays an
319 important role in hydration. Indeed, a low pyrolysis temperature results in incomplete decomposition of cellulose
320 and hemicellulose, which are sources of sucrose and glucose formation[80] , responsible for delaying hydration. A
321 study by K. Kochova et al. found that the higher the sugar concentration, the greater the delay in the peak heat flow
322 of primary hydration[81] . If the sugars tested were ranked by their impact on cement hydration from strongest to
323 weakest, the order would be: sucrose, then glucose, and finally fructose[81] . The delay in cement setting is
324 explained by two main mechanisms: the adsorption of sugars by cement grains and the chelation of Ca²⁺-ions. Sugar
325 adsorbed by hydrated cement grains eventually forms a semipermeable layer, leading to delayed hydration[82] . In
326 an acidic environment, certain functional groups of the dissolved sugar are capable of capturing Ca²⁺-ions present in
327 the interstitial solution, which are intended for the formation of portlandite and C-S-H[81] . In addition to the
328 presence of saccharides, the ash content of biochars and impurities can also hinder the hydration of cementitious
329 materials[50] .

330 **2.1.3 Setting time**

331 Setting time is the interval between the start and end of setting; it is the period during which the material hardens.
332 The start of setting is often correlated with the start of the acceleration phase of the hydration kinetics. Both the start
333 and end of setting can be shortened or prolonged following the incorporation of biochar, and there are numerous
334 reasons for this. The incorporation of peanut shell biochar (500°C) at 3% by weight shortened the initial and final
335 setting times by 40 and 88 minutes, respectively, compared to the control, unlike lower dosages, which showed no
336 significant influence[83] . A similar effect was observed by Gupta et al (2018) using CO₂-saturated and unsaturated
337 sawdust biochars (300°C) [84] . Municipal sludge biochars pyrolyzed at 500°C and 600°C accelerated setting time,
338 whereas those pyrolyzed at 300°C delayed it, for the same dosage of 2% by weight[48] . The setting time of cement
339 pastes proved less sensitive to the presence of sugarcane and orange bagasse biochar; the results in Figures 5a and
340 5b showed that the end of setting occurs before the acceleration peak[76] . The reduction in setting time achieved by
341 biochars could be an asset in terms of the speed of construction and project delivery.

342 **2.2 Impact of adding biochars on the hardened properties of cementitious materials**

343 The dosage that yields the best mechanical performance can vary from one study to another. In most cases, a low
344 biochar dosage results in improved mechanical strength. In two different studies, the best compressive strength was
345 achieved with a 1% dosage of olive pit biochar[85] and peanut shell biochar, although in one of them, a 3% dosage
346 showed superior performance compared to the control[83] . In their study, Gupta et al. (2019) recorded the highest
347 compressive and flexural strength at the same dosage of mixed wood sawdust biochar, resulting in improvements of
348 8.38% and 8%, respectively, compared to the control[77] . The 10% increase in strength following the addition of
349 olive pit biochar is attributed to the high potassium content in the biochar, which is capable of reacting with cement
350 particles during hydration[85] . The authors cite several reasons to explain this improvement in strength at low
351 biochar dosages, including the fineness of the biochar[83] , the biochar production conditions[86] , and even the
352 morphology of the biochar, which enhances the interlocking between the aggregate and the cement matrix[85] . The
353 study by Restuccia et al. showed that dosages of 0.5% and 0.8% of hazelnut shell biochar and coffee grounds were
354 more than sufficient to achieve the best mechanical strength[87] .

355 A common finding across all studies is a reduction in mechanical performance when biochar is applied at high rates.
356 This is not the case, however, when the biochar has pozzolanic properties, as adding up to 4% rice husk biochar
357 slightly increased compressive strength compared to the control[85] . These results contrast with those of Xu Yang
358 et al., who, despite adding only 2% rice husk biochar, observed reductions of 10.76% and 4.9% at 7 days and 28
359 days, respectively[88] . The reduction in compressive strength at later ages is less evident[88] . The addition of 2%
360 wood chip biochar reduced the flexural strength of the mortar by 2%[89] . High biochar dosages should be avoided
361 because the particles can agglomerate and create areas of weakness, increase porosity, and cause the water needed

362 for hydration to be absorbed by the pores, resulting in incomplete hydration and a decrease in hydrated products[44]
 363 . Regarding flexural strength, it is more sensitive to pores in the tensile plane because these defects tend to open
 364 under tension[77] . Analysis of experimental data using machine learning identified initial saturation, the oxygen-to-
 365 carbon ratio, and soluble silicon content as the biochar characteristics that control mortar strength[90] .

366 **Table2** : Variation in mechanical properties at 7 and 28 days for several studies incorporating biochar into
 367 cementitious materials

Biomass	T (°C)	Biochar content %	Appl.	Biochar as	Optimal content (%)	Change in mechanical properties at 28 and 7 days (%) / Control		Réf
						Rm	Rf	
Ricehusks	450 - 550	2 ; 5 ; 10	Mortar	Sbstcement	2	↘ 4,9	-	[88]
Wood shavings	500	0,5 ; 1 ; 2 ; 4	Mortar	Sbstcement	1	↗ 5,76	↗ 3,07	[85]
Pine cones	500	3 ; 6	Mortar	Sbstcement	3	↗ 22,94	↘ 10	[91]
Drieddistillery grains	500	1 ; 2 ; 3	Concrete	Sbstsand	3	↗ 24,56	-	[92]
				Sbstaggregate	3	↗ 28,07	-	
Sawdust	300	1 ; 2 ; 5	Mortar	Additive	1	↗ 18,97	↗ 4,66	[47]
Wood waste	-	1 ; 2 ; 5	Mortar	Additive	1	↘ 1,63	↗ 7,69	[44]
			Cementpaste		2	↗ 13,11	↗ 23,52	
Mixed wood shavings	500	0,25 ; 0,5 ; 1 ; 2	Mortar	Additive	1	↗ 8,38	↗ 8	[77]
Ricehusks	500	0,1 ; 0,25 ; 0,5 ; 0,75	Concrete	Sbstcement	0,1	↘ 7,79	-	[79]
Peanutshells	500	1 ; 3	Mortar	Sbstcement	1	↗ 20,51	-	[83]
Wood shavings	700	2	Mortar	Sbstcement	2	-	↘ 2	[89]
				Additive			↘ 2	
			Cementpaste	Sbstcement			↘ 30	
				Additive			↗ 15	

368 MS : Mechanical strength; FS : Flexural strength; Sbst : Substitute

369 **2.3 Study of the durability of biochar-cement composites**

370 Cementitious materials mixed with biochar are subjected to durability tests to assess their long-term resistance while
371 maintaining their integrity. In this section, we will review the tests conducted and discuss the impact of biochar. The
372 dry shrinkage of a material is the phenomenon by which it undergoes a reduction in volume due to the loss of
373 moisture to the outside through evaporation. A low biochar content resulted in a significant reduction in dry
374 shrinkage (36.2%), a reduction that was much more pronounced with the incorporation of sludge ash, bringing the
375 reduction rate to 55.17% compared to the control[91] . The addition of biochar to a cement paste incorporating the
376 expansive additive MgO— known for its ability to mitigate autogenous shrinkage—significantly influenced this
377 shrinkage to the point of achieving an expansion of 80 microstrains at 180 hours[93] . In their study, Gupta et al.
378 succeeded in reducing dry and autogenous shrinkage through the use of biochar and rice husk ash; according to the
379 authors, this reduction is due to the release of alkaline cations by the inorganic components of the biochar, which
380 affects the structure and quantity of hydrated products[39] .

381 A reduction in the water absorption of mortars is observed following the incorporation of a small amount of biochar;
382 the opposite effect occurs as the biochar content increases[94] . Even when combined with silica fume, the results
383 remain the same. Wood biochar combined with 2% and 4% silica fume shows a 74% and 75% reduction in water
384 absorption compared to the control; whereas at a 6% addition, a 50% increase is observed[95] . As the amount of
385 biochar increases, the composite's pore network expands, which can lead to high water absorption through the
386 biochar's pores. Resistance to erosion is also determined, even though it is not at all common. We distinguish
387 between resistance to acid attack and erosion by sulfate, chloride, and other ions. Resistance to erosion by sulfate
388 ions after 120 days of exposure is much higher for silica-poor biochars (MWBC) than for silica-rich biochars
389 (RHB)[75] . The latter are less resistant due to the dissolution of amorphous silica by sulfate ions, which weakens
390 the particles to the point of cracking[75] . Studies demonstrate the importance of biochar on its own but also when
391 combined with other amendments. The synergistic effect of biochar with other amendments improves certain
392 properties and must be taken into account to maximize their potential.

393 **3. Strategies for Optimizing the Biochar Content in Cementitious Materials**

394 The diversity of biochars produced and their specific properties, combined with the various protocols used in the
395 production of cement paste, mortar, and even concrete, make comparison and even reproducibility quite difficult.
396 The results are comparable, and each procedure is unique. However, certain key factors that allow for an increase in
397 the biochar content defy standard protocols and stand out. It is these factors, identified in the literature, that we will
398 discuss in this section. The improvement of cementitious material properties through additives occurs in two ways:
399 either physically or chemically. In terms of clinker substitution—clinker being the main active component of
400 cement—the ideal approach would be to use an additive with cementitious properties, i.e., one containing oxides
401 that can chemically react with the hydrates present during hydration. These additives, better known as pozzolanic
402 materials, have high silica and alumina contents. Unlike ash, which is commonly used for its pozzolanic properties,
403 biochar is generally chemically inert due to its production method and the type of biomass used. However,
404 alternatives are employed, notably the pretreatment of biomass with acid or water. Pre-treatment of rice husk and
405 sugarcane bagasse biomass with hydrochloric acid (0.1N) at 23°C modified the chemical and physical structure and
406 improved the reactivity of the corresponding biochars[96] . The pretreated rice husk and sugarcane bagasse biochars,
407 when substituted at a 5% replacement rate, showed a 36% and 54.8% increase in compressive strength at 28 days,
408 respectively[96] . In fact, the amorphous silica contained in these biochars reacted with portlandite (CH) to form
409 other hydrated calcium silicates responsible for mechanical strength[97] . Of all the biochars studied, rice husk
410 biochar is the most likely to exhibit pozzolanic properties, due to the high silica content in its biomass.

411 The order in which the components are introduced may seem unimportant, but it contributes to whether or not the
412 resulting mechanical properties of the composites are improved. Daniel Sueraz et al. (2020) demonstrate in their
413 study a significant variation in the flexural strength of cement pastes incorporating 2% biochar as an additive[89] .
414 Depending on whether the biochar is first mixed with water and the superplasticizer (pre-wetting) or with the cement
415 (dry pre-mixing), the results differ; pre-wetting shows a 15% increase in strength compared to the control, whereas
416 the latter shows an 8% reduction[89] . In another study by Daniel Sueraz et al. (2023), only pre-wetting was
417 performed, and a significant improvement in the compressive and flexural strength of cement pastes containing 2%
418 NB biochar was observed[44] . While the order of ingredient addition is important, the production method and

419 particle size of the biochar are also critical, as among the two types of biochar used, the pyrolyzed (NB) biochar
420 with a finer particle size (F) demonstrated the best performance[44] .

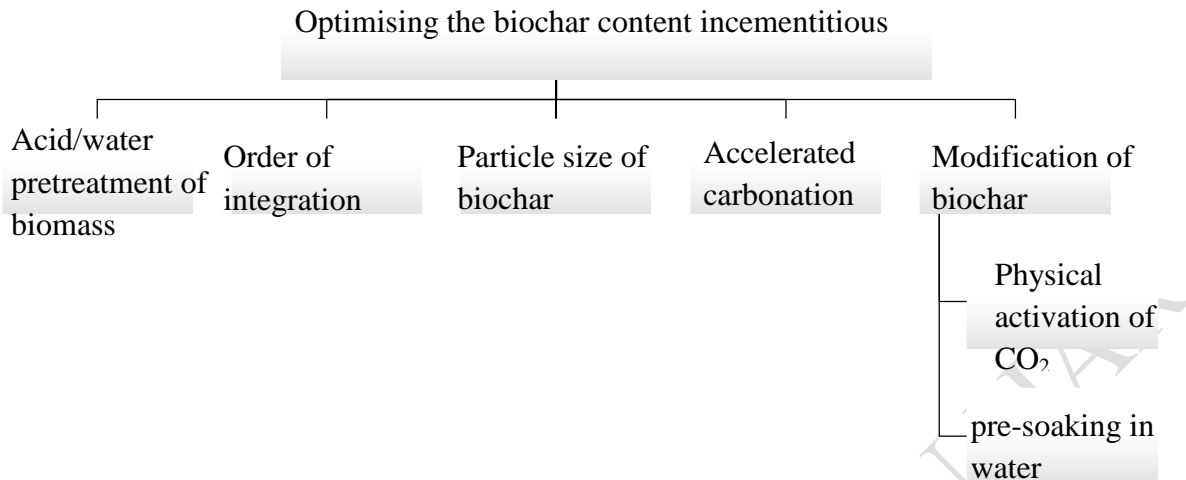
421 The particle size distribution of biochar in the mixture is critical because it affects the intrinsic properties of the
422 cementitious material. Fine particles tend to densify the matrix by filling existing voids or cavities. The substitution
423 of cement with biochar in ultra-high-performance concrete is studied by Anjaneya et al. (2019), and according to
424 them, the effect of biochar on the compressive strength of concrete depends on the size and quantity used to replace
425 the cement[98] . Among the three particle sizes used, the fine particle size (<125 μm) added at 5% generally
426 exhibited better strength, comparable to the control; the fine particles accelerated the hydration kinetics of the
427 cement-biochar paste mixture[98] . It should be noted that the biochars were pre-soaked before mixing, which could
428 explain this increase in the degree of hydration, highlighting another important aspect, namely the condition of the
429 biochars prior to incorporation into the mixture. Fine biochar particles [0.10–2 μm] offer greater early-age strength
430 and water impermeability than coarse particles [2–100 μm][77] .

431 The natural state of biochar after pyrolysis is modified to achieve a specific goal. For example, saturating the
432 biochar with CO_2 (or physically activating the biochar) before incorporating it into the mixture not only reduces CO_2
433 emissions but also improves mechanical strength through the mineralization of calcium carbonate. In a study by
434 Gupta (2021), the construction of a 0.03 m^3 roof slab incorporating 2.5% saturated biochar sequestered 1.47 kg CO_2 -
435 eq[99] . Furthermore, the 2.5% biochar-saturated paste mixture can improve early compressive strength (7 days) by
436 25–30% and by 12–15% compared to the non-carbonated control and the mixture with 8% silica fume—at 28 days,
437 this same mixture offers similar strength to the previous mixtures[99] .

438 Biochar that has been pre-soaked in water until saturated and then incorporated into the mixture acts as an internal
439 hardening agent. This is because the water contained in the biochar's pores desorbs, improving internal hydration.
440 The internal hardening provided by the saturated biochar particles improved mechanical strength by 40% and 30%
441 compared to the control mortar and the mortar incorporating dry biochar, respectively—specifically, flexural
442 strength and splitting tensile strength—and reduced porosity by 20% compared to the control[49] .

443 Just like internal curing, external curing plays a role and significantly influences the final result. Given the current
444 context and existing curing methods, carbonation curing could meet our expectations in two ways. Accelerated
445 carbonation curing (ACC), which is less costly, is one of the carbon capture and storage processes and the most
446 widely used method for storing carbon in cementitious materials[100] . Unlike natural carbonation, it is carried out
447 under strict conditions, taking into account a high CO_2 concentration and a controlled environment (temperature and
448 relative humidity). Furthermore, the carbonation reaction rate of cement paste reaches its maximum when relative
449 humidity is [50 – 80%][101] . Cementitious materials incorporating biochar are subjected to several curing tests:
450 wet[47][49] [74] , sealed[99] [102] , air[74][103] , underwater[80][103] , and even carbon dioxide[80][99] [102]
451 [104] . The finding is that the development of mechanical strength in the presence of biochar is more pronounced
452 during air curing than in water; nevertheless, underwater curing still yields the material's maximum performance,
453 especially in the long term[103] . Compared to sealed and underwater curing, carbonation curing generally exhibits
454 better mechanical strength at the 7-day mark; beyond that, specifically at 28 days, CO_2 curing no longer affects
455 strength and even tends to decrease compared to the curing methods mentioned above[99] [102] [105] . CO_2 curing
456 made it possible to increase the biochar content of rice husks and wood flour substituted for cement up to 10%, and
457 to improve mechanical strength at 28 days by 24.2%, even though porosity and water absorption increased[106] .
458 Furthermore, the CO_2 equivalent emissions of the mortar were reduced by 7.7% compared to the control[106] .

459 Admittedly, CO_2 curing delivers compelling results in both mechanical and environmental terms—which sets it
460 apart from other curing methods—but it has its own requirements and limitations. The duration of carbonation, the
461 type of preconditioning used before carbonation, etc., make all the difference. A new technique is used to address
462 the decrease in strength caused by hardening before curing: spraying water after carbonation until all the water is
463 absorbed[107] . All the factors mentioned above are summarized in Figure 2 below.



464

465

466 **Fig.2.** : Some strategies for optimizing the biochar content in cementitious materials

467 **4. Benefits of adding biochar to cementitious materials**

468 **4.1 Reduced carbon footprint**

469

470 The value of biochar in cementitious materials is not limited to improving mechanical properties and durability. The
 471 environmental aspect is significantly influenced by the reduction of the carbon footprint at various levels. First, in its
 472 current production method known as pyrolysis, which releases part of the carbon from the biomass in the form of
 473 CO and CO₂ and stores the remainder as a solid structure within the biochar[84] . The partial substitution of fossil
 474 fuels with renewable energy sources such as synthetic oil and gas derived from pyrolysis would be a major
 475 advantage and would further reduce GHG emissions[108] . The life cycle assessment (LCA) of the pyrolysis-
 476 biochar system reveals a reduction in net greenhouse gas emissions of -864 and -885 kg CO₂ eq per ton of dry matter
 477 from corn stalks and green waste, respectively, of which 62 to 66% stems from biomass carbon sequestration[109] .

478 Next, its substitution for clinker, which aims to reduce emissions from decarbonation. An assessment of biochar's
 479 performance in reducing the global warming potential (GWP) of blended CEM II/A shows a reduction in net carbon
 480 emissions of 8%, 17%, and 26% for additions of 2%, 4%, and 6% biochar, respectively[70] .

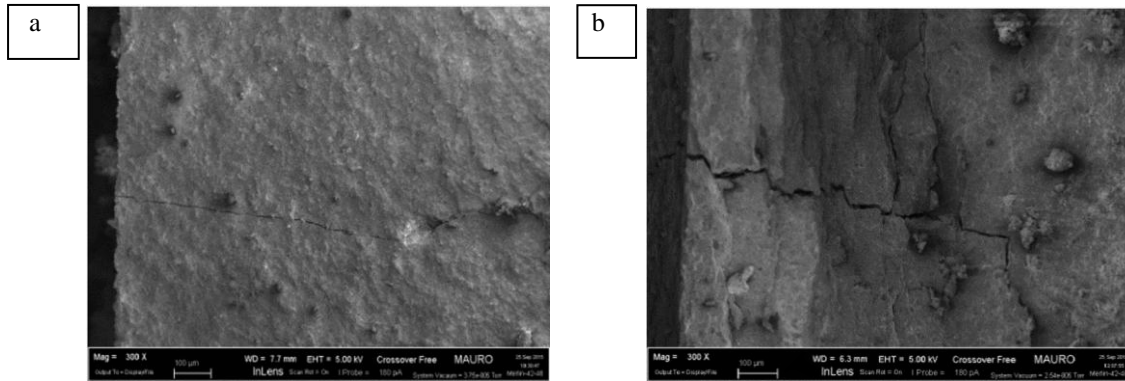
481 Finally, its ability to adsorb atmospheric CO₂ in structures and buildings could contribute to an additional 25%
 482 reduction in GHG emissions[17] . However, this ability to adsorb CO₂ is only possible due to the presence of basic
 483 functional groups[110] , a specific surface area[111] , and microporosity, which are responsible for the adsorption of
 484 gases and solvents[112] . CO₂ curing is performed on biochars prior to their incorporation into cementitious
 485 materials, as well as in mortars and concretes containing biochar. According to Maljaee et al. (2021), the saturation
 486 of biochars with CO₂ via adsorption does not affect their chemical or physical properties[73] .

487 **4.2 Improved crack propagation resistance**

488 Toughness is a material's ability to absorb energy without breaking once a crack has formed. Numerous studies have
 489 shown that biochar can improve this toughness. The impact of biochar on toughness is much more pronounced in
 490 cement pastes than in mortars; for additions of 2% and 5%, an improvement of 175% and 240% is achieved for
 491 pastes, compared to an improvement of 17% and 30% and a reduction of 11% and 10% for mortars incorporating
 492 pyrolyzed and gasified biochar, respectively[44] . The rate of increase in fracture toughness is higher for smaller
 493 epoxy resin particles[113] ; drawing an analogy with the biochar used, one could infer that the submicrometer size
 494 of pyrolyzed biochar is responsible for the increase in toughness[44] . According to Restuccia et al (2017), the high
 495 carbon content of biochars alters the crack path by increasing its tortuosity; indeed, the carbon content confers
 496 increased strength and stiffness, inducing reinforcement mechanisms[114] . SEM analysis of cement pastes

497 containing 0% and 0.8% hazelnut shell biochar shows a linear crack path for the control sample, whereas in the
498 presence of biochar, the crack becomes much more tortuous, thus confirming the analyses by Restuccia et al[87] .
499 Bamboo biochar incorporated at 1% by weight into the mortar increased both crack initiation and crack propagation
500 resistance, although it reduced the stable crack propagation length[115] . The reasons cited are the filling and
501 bridging effects of bamboo biochar in the cementitious matrix[115]

502



503

504 **Fig.3.** : Crack path on the surface of the cement paste: a) without biochar; b) with 0.8% hazelnut shell biochar
505 [87]

506 4.3 Improved thermal insulation

507 Thermal conductivity is a material's ability to conduct heat due to a temperature gradient[116] . The low thermal
508 conductivity of concrete[52] is further reduced by the incorporation of biochar, according to certain studies. A heat
509 transfer analysis of biochar shows low thermal reactivity[117] . The work by Tan et al. identifies the porosity of
510 biochar as the main reason for the reduction in thermal conductivity of mortar mixed with biochar derived from
511 wood waste pyrolyzed at 400°C[118] .A decrease of 16%, 22%, 30%, and 39% compared to the control is observed
512 for respective additions of 1%, 3%, 5%, and 10% biochar[118] . Rodieret al.[116] also observed a 45% and 30%
513 reduction in the thermal conductivity of cement pastes to which 6% sugarcane bagasse biochar was added, at 28
514 days and 90 days, respectively[116] . Rice husk biochar mixed with clay exhibits the lowest thermal conductivity,
515 ranging from 0.123 W/mK to 0.184 W/mK depending on the dosage[119] . Researchers agree that the porous nature
516 of biochar largely due to the raw material used and the pyrolysis temperature[120] is the cause of this phenomenon.
517 The porosity of biochars helps break thermal bridges in building materials and consequently improves thermal
518 insulation in buildings, which will reduce energy consumption for heating or cooling buildings[17] .

519 4.4 Absorption and shielding of electromagnetic waves

520 According to electromagnetic theories, the primary shielding mechanism involves reflecting radiation at the
521 material's interface and dissipating the wave's energy within the material[121] . The combined effect of graphene
522 and carbon nanotubes improves shielding performance against electromagnetic interference[121] . However, their
523 high cost and poor distribution in cement under certain conditions limit their use, paving the way for research into
524 other materials such as biochar[122] .

525 Coals derived from woody biomass, particularly cellulose, lignin, and wood monoliths, exhibit good electrical
526 conductivity, low weight, increased porosity, and a stable structure[123] . This makes them and their composites
527 powerful contenders in the fields of electromagnetic wave absorption (EMWA)[124] and electromagnetic
528 interference (EMI)[125] . A study conducted by Filipe et al (2020) presents a gypsum-biochar composite with
529 increasing shielding efficiency, proportional to the biochar content, primarily in the microwave range[126] . The
530 work of Khushnood et al (2016), incorporating 0.5% by weight of hazelnut and peanut shell biochar into cement, also
531 demonstrates an improvement in total shielding effectiveness[122] . Compared to the control, the peanut biochar-

532 cement composite yielded the best results, with an additional increase in total shielding efficiency of 353%, 223%,
533 126%, and 83% at frequencies of 0.94 GHz, 1.56 GHz, 2.46 GHz, and 10.0 GHz, respectively[122] .

534 In the literature, the improved performance of carbon-based materials derived from lignin, cellulose, and wood
535 monoliths in terms of electromagnetic wave adsorption and shielding is attributed to the water dispersibility of the
536 precursors (lignin and cellulose) and their porous structure[123] . Indeed, these properties promote the uniform
537 loading of functional groups, the dissipation of electromagnetic waves, and the enhancement of multiple reflections
538 of EMWs in the case of wood monoliths[123] . The highly porous structure of biochars plays a decisive role in
539 improving microwave absorption capabilities[127].

540 **Conclusion**

541 This review article discusses the use of biochar a bio-based material and carbon sink as an additive in cementitious
542 materials to reduce the carbon footprint of cement. Consequently, the article addresses biochar production methods,
543 its impact on the fresh and hardened properties of materials, durability, optimization of biochar content, and the
544 benefits of its use. Slow pyrolysis of lignocellulosic biomass is more commonly reported in the literature, as it
545 yields a high biochar yield and results in a relatively high carbon content; consequently, this leads to a reduction in
546 CO₂ emissions and improved mechanical strength and crack propagation resistance. Due primarily to the porous
547 nature of biochar, the workability, mechanical strength, and even the durability of cementitious materials tend to
548 decrease, hence the need to limit the biochar content to reduce porosity and prevent potential particle agglomeration.
549 To overcome this barrier posed by the incorporated biochar content and improve mechanical and durability
550 properties, acid/water pretreatment of biomass, pre-soaking of biochar, physical activation with CO₂ of biochar, the
551 use of fine biochar particles, and accelerated carbonation of the composites have been reported in the literature.
552 Biochars have the ability to reduce the carbon footprint, improve the thermal conductivity of composites, and absorb
553 electromagnetic waves. The discrepancies noted in the studies are partly due to the variability in biochar properties,
554 caused by the biomass used and the pyrolysis parameters. Thus, for the same biomass, two given studies may
555 present different optimal rates. Among the studies reviewed, none considered the cement-biochar mixture as a new
556 binder requiring comprehensive characterization according to standards applicable to hydraulic binders. To date,
557 they have been limited to the addition of biochar and its effect on the mechanical properties and durability of
558 cementitious materials. Beyond the lack of standardized tests, there is a near-total absence of full-scale applications.
559 Regarding durability, erosion resistance has been little studied. Since this material is not currently recognized or
560 authorized under the European cement standard EN 197-1, adopting a performance-based approach to cement would
561 facilitate the development of manufacturing, standardization, and applications for this type of innovative cement
562 composition. Another alternative would be to consider biochar not merely as an additive to cement, but rather as a
563 component of a new type of binder, and thus develop a specific “product” standard for it, similar to alumina cements
564 (EN 14647)[128] or supersulfated cements (EN 15743+A1)[129] . Such an approach will allow for a comparison of
565 the performance of cement-biochar binders with that of conventional binders. This should also include the
566 establishment of a standardized protocol for the cement-biochar mixture.

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570 **References**

- 571 [1] M. Alexander, A. Bentur, and S. Mindess, *Durability of Concrete: Design and Construction*, Taylor and
572 RoyaumeUni, 2017. doi: 0.1201/9781315118413-6.
- 573 [2] L. Izoret, “Matériaux de construction durables,” Cotonou, 2025.
- 574 [3] A. Nazari and J. G. Sanjayan, *Handbook of low carbon concrete*. 2017.
- 575 [4] A. Hatfield, “Mineral Commodity Summaries 2024 - Cement,” 2024.

- 576 [5] L. Coppola, D. Coffetti, E. Crotti, G. Gazzaniga, and T. Pastore, “An Empathetic Added Sustainability
577 Index (EASI) for cementitious based construction materials,” *J. Clean. Prod.*, vol. 220, pp. 475–482, 2019, doi:
578 10.1016/j.jclepro.2019.02.160.
- 579 [6] France Stratégie, “Les coûts d’abattement - Partie 6 -Ciment.,” 2023.
- 580 [7] Comité Européenne de Normalisation, “EN 197-1: 2012 Cement – Partie 1 : Composition, spécifications et
581 critères de conformité des ciments courants.”
- 582 [8] L. Izoret ; K. S. and F. B. , “RILEM/TC-PHC ‘Performance-based approach on Hydraulic Cement’ and the
583 future of the European Standardization of cement A plea for a paradigm shift in EU standardization. Key-note
584 lecture RILEM Week Toulouse August 2024,” no. August, 2024.
- 585 [9] “Feuille de route de décarbonation de la filière Ciment Mai 2023,” pp. 1–25, 2023.
- 586 [10] G. Follin-arbelet, M. Aulanier, A. Tazi, and V. Choïnard, “Y a-t-il des bénéfices carbone à intégrer du
587 biochar dans les matériaux de construction ?,” vol. 2022, pp. 1–7, 2025.
- 588 [11] K. Joël, “Valorisation des coques de noix de palmiste dans la construction des routes à faible trafic,” Thèse
589 de Doctorat en cotutelle, Université d’Abomey Calavi, Université de Limoges (France), 2022.
- 590 [12] A. Danish, M. Ali, M. Usama, N. Ahmad, F. Ahmad, and A. Ahmad, “Reusing biochar as a filler or cement
591 replacement material in cementitious composites : A review,” *Constr. Build. Mater.*, vol. 300, no. July, p. 124295,
592 2021, doi: 10.1016/j.conbuildmat.2021.124295.
- 593 [13] M. T. Adagbe, “Utilisation de la terre renforcée par des tiges de paille de riz comme matériau des
594 éléments porteurs des bâtiments armés avec le rônier,” Thèse de Doctorat en cotutelle, Université d’Abomey Calavi
595 (Bénin), Université de Toulouse (France), 2021.
- 596 [14] G. S. G. MILOHIN, “Valorisation de rebuts de bouteilles en verre et des cendres de bois dans la fabrication
597 de briques en argile cuite,” Thèse de Doctorat en cotutelle, Université d’Abomey Calavi (Bénin), Université de Lorraine
598 (France), 2019.
- 599 [15] G. J. D. KIKI, “Amélioration de l’efficacité énergétique des bâtiments publics du Sud du Bénin par
600 utilisation des matériaux biosourcés locaux,” Thèse de Doctorat en cotutelle, Université d’Abomey Calavi (Bénin),
601 Université de Liège (Belgique), 2023.
- 602 [16] J. Wen et al., “Resources , Conservation & Recycling New insights into the green cement composites with
603 low carbon footprint : The role of biochar as cement additive / alternative,” *Resour. Conserv. Recycl.*, vol. 197, no.
604 June, p. 107081, 2023, doi: 10.1016/j.resconrec.2023.107081.
- 605 [17] S. Gupta and H. Kua, “Factors Determining the Potential of Biochar As a Carbon Capturing and
606 Sequestering Construction Material : Critical Review Factors Determining the Potential of Biochar As a Carbon
607 Capturing and Sequestering Construction Material : Critical Review,” *J. Mater. Civ. Eng.*, no. April, 2017, doi:
608 10.1061/(ASCE)MT.1943-5533.0001924.
- 609 [18] L. Chen et al., “A review on the roles of biochar incorporated into cementitious materials : Mechanisms ,
610 application and perspectives,” *Constr. Build. Mater.*, vol. 409, no. November, p. 134204, 2023, doi:
611 10.1016/j.conbuildmat.2023.134204.

- 612 [19] D. Suarez-riera, L. Lavagna, J. F. Carvajal, J. Tulliani, D. Falliano, and L. Restuccia, "Enhancing Cement
613 Paste Properties with Biochar : Mechanical and Rheological Insights," *Appl. Sci.*, vol. 14, pp. 1–17, 2024, doi: .
614 <https://doi.org/10.3390/app14062616>.
- 615 [20] M. K. Bahng, C. Mukarakate, D. J. Robichaud, and M. R. Nimlos, "Current technologies for analysis of
616 biomass thermochemical processing: A review," *Anal. Chim. Acta*, vol. 651, no. 2, pp. 117–138, 2009, doi:
617 10.1016/j.aca.2009.08.016.
- 618 [21] R. Gillett, "IBI Biochar Newsletter - Faitssailants du mois," p. 8, 2019.
- 619 [22] M. Ayaz, S. T. Muntaha, E. Baltrėnaitė-Gedienė, and Z. Kriauciūnienė, "Biochar and carbon-negative
620 technologies: exploring opportunities for climate change mitigation," *Biochar*, vol. 7, no. 1, pp. 1–26, 2025, doi:
621 10.1007/s42773-024-00421-3.
- 622 [23] W. A. W. A. K. Ghani et al., "Biochar production from waste rubber-wood-sawdust and its potential use in
623 C sequestration: Chemical and physical characterization," *Ind. Crops Prod.*, vol. 44, pp. 18–24, 2013, doi:
624 10.1016/j.indcrop.2012.10.017.
- 625 [24] V. Rajput et al., "Biochar production methods and their transformative potential for environmental
626 remediation," *Discov. Appl. Sci.*, vol. 6, no. 8, 2024, doi: 10.1007/s42452-024-06125-4.
- 627 [25] S. Barbhuiya, B. Bhusan, and F. Kanavaris, "Case Studies in Construction Materials Biochar-concrete : A
628 comprehensive review of properties , production and sustainability," *Case Stud. Constr. Mater.*, vol. 20, no.
629 November 2023, p. e02859, 2024, doi: 10.1016/j.cscm.2024.e02859.
- 630 [26] G. Ravindiran et al., "Production and modifications of biochar to engineered materials and its application
631 for environmental sustainability: a review," *Biochar*, vol. 6, no. 1, pp. 1–27, 2024, doi: 10.1007/s42773-024-00350-
632 1.
- 633 [27] P. K. G, K. F. Tee, J. Gimbut, and S. C. Chin, "Biochar in cementitious material — A review on physical ,
634 chemical , mechanical , and durability properties," *AIMS Mater. Sci.*, vol. 10, no. December 2022, pp. 405–425,
635 2023, doi: 10.3934/matser.2023022.
- 636 [28] G. Maschio, C. Koufopoulos, and A. Lucchesi, "Pyrolysis , a Promising Route for Biomass Utilization,"
637 *Bioresour. Technol.*, vol. 42, pp. 219–231, 1992.
- 638 [29] J. A. Libra et al., "Hydrothermal carbonization of biomass residuals: a comparative review of the
639 chemistry, processes and applications of wet and dry pyrolysis," *Biofuels*, vol. 2, no. 1, pp. 89–124, 2011, [Online].
640 Available: <https://doi.org/10.4155/bfs.10.81>
- 641 [30] A. Demirbas and G. Arin, "An Overview of Biomass Pyrolysis," *Energy Sources*, vol. 24, no. 5, pp. 471–
642 482, May 2002, doi: 10.1080/00908310252889979.
- 643 [31] P. R. Yaashikaa, P. S. Kumar, S. Varjani, and A. Saravanan, "A critical review on the biochar production
644 techniques, characterization, stability and applications for circular bioeconomy," *Biotechnol. Reports*, vol. 28, p.
645 e00570, 2020, doi: 10.1016/j.btre.2020.e00570.
- 646 [32] M. Tripathi, J. N. Sahu, and P. Ganesan, "Effect of process parameters on production of biochar from
647 biomass waste through pyrolysis: A review," *Renew. Sustain. Energy Rev.*, vol. 55, pp. 467–481, 2016, doi:
648 10.1016/j.rser.2015.10.122.

- 649 [33] J. A. Ippolito et al., “Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a
650 comprehensive meta-data analysis review,” *Biochar*, vol. 2, no. 4, pp. 421–438, 2020, doi: 10.1007/s42773-020-
651 00067-x.
- 652 [34] I. Lima et al., “Characterization of Designer Biochar Produced at Different Temperatures and Their Effects
653 on a Loamy Sand,” *Ann. Environ. Sci.*, vol. 3, no. January, pp. 195–206, 2009, [Online]. Available:
654 www.aes.northeastern.edu,
- 655 [35] C. E. Brewer, Y.-Y. Hu, K. Schmidt-Rohr, T. E. Loynachan, D. A. Laird, and R. C. Brown, “Extent of
656 Pyrolysis Impacts on Fast Pyrolysis Biochar Properties,” *J. Environ. Qual.*, vol. 41, no. 4, pp. 1115–1122, 2012, doi:
657 10.2134/jeq2011.0118.
- 658 [36] F. Lian and B. Xing, “Black Carbon (Biochar) in Water/Soil Environments: Molecular Structure, Sorption,
659 Stability, and Potential Risk,” *Environ. Sci. Technol.*, vol. 51, no. 23, pp. 13517–13532, 2017, doi:
660 10.1021/acs.est.7b02528.
- 661 [37] A. V. Bridgwater, “Renewable fuels and chemicals by thermal processing of biomass,” *Chem. Eng. J.*, vol.
662 91, no. 2–3, pp. 87–102, 2003, doi: 10.1016/S1385-8947(02)00142-0.
- 663 [38] Y. Zhang et al., “Biochar as construction materials for achieving carbon neutrality,” *Biochar*, vol. 4, no. 1,
664 2022, doi: 10.1007/s42773-022-00182-x.
- 665 [39] P. Ye et al., “The state-of-the-art review on biochar as green additives in cementitious composites:
666 performance, applications, machine learning predictions, and environmental and economic implications,” *Biochar*,
667 vol. 7, no. 1, pp. 1–30, 2025, doi: 10.1007/s42773-024-00423-1.
- 668 [40] S. You, Y. S. Ok, D. C. W. Tsang, E. E. Kwon, and C. H. Wang, “Towards practical application of
669 gasification: a critical review from syngas and biochar perspectives,” *Crit. Rev. Environ. Sci. Technol.*, vol. 48, no.
670 22–24, pp. 1165–1213, 2018, doi: 10.1080/10643389.2018.1518860.
- 671 [41] S. Chebil, A. Chaala, and C. Roy, “Use of softwood bark charcoal as a modifier for road bitumen,” *Fuel*,
672 vol. 79, pp. 671–683, 2000.
- 673 [42] E. Shayan, V. Zare, and I. Mirzaee, “Hydrogen production from biomass gasification; a theoretical
674 comparison of using different gasification agents,” *Energy Convers. Manag.*, vol. 159, no. August 2017, pp. 30–41,
675 2018.
- 676 [43] J. Gil, J. Corella, M. P. Aznar, and M. A. Caballero, “Biomass gasification in atmospheric and bubbling
677 fluidized bed: Effect of the type of gasifying agent on the product distribution,” *Biomass and Bioenergy*, vol. 17, no.
678 5, pp. 389–403, 1999, doi: 10.1016/S0961-9534(99)00055-0.
- 679 [44] D. Suarez-riera et al., “The Effect of Different Biochar on the Mechanical Properties of Cement-Pastes and
680 Mortars,” *Buildings*, vol. 13, pp. 1–14, 2023, doi: <https://doi.org/10.3390/buildings1312290>.
- 681 [45] J. Mumme, L. Eckervogt, J. Pielert, M. Diakit , F. Rupp, and J. Kern, “Hydrothermal carbonization of
682 anaerobically digested maize silage,” *Bioresour. Technol.*, vol. 102, no. 19, pp. 9255–9260, 2011, doi:
683 10.1016/j.biortech.2011.06.099.
- 684 [46] H. Yang et al., “In-Depth Investigation of Biomass Pyrolysis Based on Three Major Components :
685 Hemicellulose , Cellulose and Lignin,” *Energy and fuels*, vol. 20, no. 1, pp. 388–393, 2006.

- 686 [47] S. Gupta, H. W. Kua, and H. J. Koh, "Application of biochar from food and wood waste as green admixture
687 for cement mortar," *Sci. Total Environ.*, vol. 619–620, pp. 419–435, 2018, doi: 10.1016/j.scitotenv.2017.11.044.
- 688 [48] X. Chen, J. Li, Q. Xue, X. Huang, L. Liu, and C. Sun, "Sludge biochar as a green additive in cement-based
689 composites : Mechanical properties and hydration kinetics," *Constr. Build. Mater.*, vol. 262, p. 120723, 2020, doi:
690 10.1016/j.conbuildmat.2020.120723.
- 691 [49] S. Gupta, K. Harn, and P. Sze, "Effect of biochar on mechanical and permeability properties of concrete
692 exposed to elevated temperature," *Constr. Build. Mater.*, vol. 234, p. 117338, 2020, doi:
693 10.1016/j.conbuildmat.2019.117338.
- 694 [50] S. Gupta, K. Niroshika, P. Dulanja, Y. Sik, and H. Wei, "Carbonaceous inserts from lignocellulosic and
695 non-lignocellulosic sources in cement mortar : Preparation conditions and its effect on hydration kinetics and
696 physical properties," *Constr. Build. Mater.*, vol. 264, p. 120214, 2020, doi: 10.1016/j.conbuildmat.2020.120214.
- 697 [51] A. Budai, L. Calucci, and D. P. et al Rasse, "Effects of pyrolysis conditions on Miscanthus and corncob
698 chars: Characterization by IR, solid state NMR and BPCA analysis," *J. Anal. Appl. Pyrolysis*, pp. 335–345, 2017.
- 699 [52] R. A. Mensah et al., "Biochar-Added Cementitious Materials — A Review on Mechanical , Thermal , and
700 Environmental Properties," *Sustainability*, vol. 13, pp. 1–27, 2021, doi: <https://doi.org/10.3390/su13169336>.
- 701 [53] L. Rodriguez, E. Torres, D. Zalazar, and H. Zhang, "Influence of pyrolysis temperature and bio-waste
702 composition on biochar characteristics," *Renew. Energy*, vol. 155, pp. 837–847, 2020, doi:
703 <https://doi.org/10.1016/j.renene.2020.03.181>.
- 704 [54] X. Jiang, B. Li, J. Li, and J. Guo, "Study on the properties of different biochar to cement paste," in *IOP
705 Conf. Series: Earth and Environmental Science*, 2020. doi: 10.1088/1755-1315/526/1/012085.
- 706 [55] S. Sensöz and D. Angin, "Pyrolysis of safflower (*Charthamustinctorius L .*) seed press cake : Part 1 . The
707 effects of pyrolysis parameters on the product yields," *Bioresour. Technol.*, vol. 99, pp. 5492–5497, 2008, doi:
708 10.1016/j.biortech.2007.10.046.
- 709 [56] A. R. Mohamed, Z. Hamzah, M. Zulkali, and M. Daud, "The Effects of Holding Time and The Sweeping
710 Nitrogen Gas Flowrates On The Pyrolysis Of EFB Using A Fixed Bed Reactor," *Procedia Eng.*, vol. 53, pp. 185–
711 191, 2013, doi: 10.1016/j.proeng.2013.02.024.
- 712 [57] W. T. Tsai, M. K. Lee, and Y. M. Chang, "Fast pyrolysis of rice husk : Product yields and compositions,"
713 *Bioresour. Technol.*, vol. 98, pp. 22–28, 2007, doi: 10.1016/j.biortech.2005.12.005.
- 714 [58] W. Ferdinand, L. Van De Steene, S. Toure, G. Volle, and P. Girard, "Pyrolysis of Pinuspinaster in a two-
715 stage gasifier : Influence of processing parameters and thermal cracking of tar," *Fuel Process. Technol.*, vol. 90, no.
716 1, pp. 75–90, 2008, doi: 10.1016/j.fuproc.2008.07.016.
- 717 [59] S. HP, "Biochar as Building Material for Optimal Indoor Climate," pp. 450–454, [Online]. Available:
718 www.ithaka-journal.net/en/ct/145
- 719 [60] S. HP, "The use of biochar as building material - cities as carbon sinks," *Ithaka-Journal 2013 Arbaz*, pp.
720 450–454, 2013, [Online]. Available: Www.ithaka-journal.net/en/ct/149
- 721 [61] S. Gupta, H. W. Kua, and S. Y. Tan Cynthia, "Use of biochar-coated polypropylene fibers for carbon
722 sequestration and physical improvement of mortar," *Cem. Concr. Compos.*, vol. 83, pp. 171–187, Oct. 2017, doi:
723 10.1016/j.cemconcomp.2017.07.012.

- 724 [62] G. Sidos, "VicatdévoileCarat : son liant « puits de carbone » En quoi estuneréponse à la RE2020 ? Zoom
725 sur le biochar," 2022.
- 726 [63] Vicat and L. Grosse, "Avec le nouveau liantCarat ,Vicat et Léon Grosse décarbonent le secteur du BTP,"
727 2023.
- 728 [64] S. M. Abtahi, M. Sheikhzadeh, and S. M. Hejazi, "Fiber-reinforced asphalt-concrete – A review," *Constr.*
729 *Build. Mater.*, vol. 24, no. 6, pp. 871–877, Jun. 2010, doi: 10.1016/j.conbuildmat.2009.11.009.
- 730 [65] S. Zhao, B. Huang, X. Shu, and P. Ye, "Laboratory Investigation of Biochar-Modified Asphalt Mixture," *J.*
731 *Transp. Res. Board*, vol. 2445, no. 1, pp. 56–63, Jan. 2014, doi: 10.3141/2445-07.
- 732 [66] M. Giorcelli, P. Savi, A. Khan, and A. Tagliaferro, "Analysis of biochar with different pyrolysis
733 temperatures used as filler in epoxy resin composites," *Biomass and Bioenergy*, vol. 122, no. December 2018, pp.
734 466–471, 2019, doi: 10.1016/j.biombioe.2019.01.007.
- 735 [67] L. Karunanayake, T. Etampawala, D. J. de Silva, J. Bandara, A. U. Rajapaksha, and M. Vithanage, "Role
736 and potential of biochar as a sustainable alternative reinforcing filler to carbon black in rubber composites," *Biochar*,
737 vol. 7, no. 1, 2025, doi: 10.1007/s42773-025-00429-3.
- 738 [68] C. G. Robertson and N. J. Hardman, "Nature of carbon black reinforcement of rubber: Perspective on the
739 original polymer nanocomposite," *Polymers (Basel)*, vol. 13, no. 4, pp. 1–28, 2021, doi: 10.3390/polym13040538.
- 740 [69] S. C. Peterson and A. J. Thomas, "Lauric Acid Treatments to Oxidized and Control Biochars and Their
741 Effects on Rubber Composite Tensile Properties," *C-Journal Carbon Res.*, vol. 8, no. 4, 2022, doi:
742 10.3390/c8040058.
- 743 [70] S. Keane et al., "Assessing the use of Biochar as a Cementitious Replacement in Structural Concrete By,"
744 *Mémoire de Master, University of Limerick*, 2023.
- 745 [71] S. T. Shafie, M. A. Mohd, L. L. Hang, W. Azlina, W. Abdul, and K. Ghani, "Effect of pyrolysis
746 temperature on the biochar nutrient and water retention capacity," *J. Purity*, vol. 1, no. 6, pp. 323–337, 2012.
- 747 [72] M. Sidney, *Developments in the formulation and reinforcement of concrete*, Elsevier. Cambridge:
748 Woodhead Publishing in materials, 2014.
- 749 [73] H. Maljaee, R. Madadi, H. Paiva, L. Tarelho, and V. M. Ferreira, "Incorporation of biochar in cementitious
750 materials: A roadmap of biochar selection," *Constr. Build. Mater.*, vol. 283, p. 122757, 2021, doi:
751 10.1016/j.conbuildmat.2021.122757.
- 752 [74] S. Gupta and H. W. Kua, "Effect of water entrainment by pre-soaked biochar particles on strength and
753 permeability of cement mortar," *Constr. Build. Mater.*, vol. 159, pp. 107–125, 2018, doi:
754 10.1016/j.conbuildmat.2017.10.095.
- 755 [75] S. Gupta, S. Muthukrishnan, and H. Wei, "Comparing influence of inert biochar and silica rich biochar on
756 cement mortar – Hydration kinetics and durability under chloride and sulfate environment," *Constr. Build. Mater.*,
757 vol. 268, p. 121142, 2021, doi: 10.1016/j.conbuildmat.2020.121142.
- 758 [76] A. Carolina et al., "Evaluation of biochar in cementitious pastes properties," *J. Build. Eng.*, vol. 121, no.
759 December 2025, pp. 1–22, 2026, doi: 10.1016/j.jobbe.2026.115712.

- 760 [77] S. Gupta and H. W. Kua, "Carbonaceous micro- filler for cement : Effect of particle size and dosage of
761 biochar on fresh and hardened properties of cement mortar," *Sci. Total Environ.*, vol. 662, pp. 952–962, 2019, doi:
762 10.1016/j.scitotenv.2019.01.269.
- 763 [78] S. Gupta, P. Krishnan, A. Kashani, and H. Wei, "Application of biochar from coconut and wood waste to
764 reduce shrinkage and improve physical properties of silica fume-cement mortar," *Constr. Build. Mater.*, vol. 262, p.
765 120688, 2020, doi: 10.1016/j.conbuildmat.2020.120688.
- 766 [79] A. Akhtar and A. K. Sarmah, "Novel biochar-concrete composites : Manufacturing , characterization and
767 evaluation of the mechanical properties," *Sci. Total Environ.*, vol. 616–617, pp. 408–416, 2018, doi:
768 10.1016/j.scitotenv.2017.10.319.
- 769 [80] S. Gupta, A. Kashani, A. H. Mahmood, and T. Han, "Carbon sequestration in cementitious composites
770 using biochar and fly ash – Effect on mechanical and durability properties," *Constr. Build. Mater.*, vol. 291, p.
771 123363, 2021, doi: 10.1016/j.conbuildmat.2021.123363.
- 772 [81] K. Kochova, K. Schollbach, F. Gauvin, and H. J. H. Brouwers, "Effect of saccharides on the hydration of
773 ordinary Portland cement," *Constr. Build. Mater.*, vol. 150, no. 2017, pp. 268–275, 2025, doi:
774 10.1016/j.conbuildmat.2017.05.149.
- 775 [82] M. C. Garcíjuenger and H. M. Jennings, "New insights into the effects of sugar on the hydration and
776 microstructure of cement pastes," *Cem. Concr. Res.*, vol. 32, no. 3, pp. 393–399, Mar. 2002, doi: 10.1016/S0008-
777 8846(01)00689-5.
- 778 [83] S. Gupta and A. Kashani, "Utilization of biochar from unwashed peanut shell in cementitious building
779 materials – Effect on early age properties and environmental benefits," *Fuel Process. Technol.*, vol. 218, no. April,
780 p. 106841, 2021, doi: 10.1016/j.fuproc.2021.106841.
- 781 [84] S. Gupta, H. W. Kua, and C. Y. Low, "Use of biochar as carbon sequestering additive in cement mortar,"
782 *Cem. Concr. Compos.*, vol. 87, pp. 110–129, 2018, doi: 10.1016/j.cemconcomp.2017.12.009.
- 783 [85] H. Maljaee, H. Paiva, R. Madadi, L. A. C. Tarelho, M. Morais, and V. M. Ferreira, "Effect of cement
784 partial substitution by waste-based biochar in mortars properties," *Constr. Build. Mater.*, vol. 301, p. 124074, 2021,
785 doi: 10.1016/j.conbuildmat.2021.124074.
- 786 [86] A. Sirico et al., "Mechanical characterization of cement-based materials containing biochar from
787 gasification," *Constr. Build. Mater.*, vol. 246, p. 118490, 2020, doi: 10.1016/j.conbuildmat.2020.118490.
- 788 [87] L. Restuccia and G. A. Ferro, "Promising low cost carbon-based materials to improve strength and
789 toughness in cement composites," *Constr. Build. Mater.*, vol. 126, no. November, pp. 1034–1043, 2016, doi:
790 10.1016/j.conbuildmat.2016.09.101.
- 791 [88] X. Yang and X. Wang, "Hydration-strength-durability-workability of biochar-cement binary blends," *J.*
792 *Build. Eng.*, vol. 42, no. July, p. 103064, 2021, doi: 10.1016/j.job.2021.103064.
- 793 [89] D. Suarez-riera, L. Restuccia, and G. A. Ferro, "The use of Biochar to reduce the carbon footprint of
794 cement-based materials," *Procedia Struct. Integr.*, vol. 26, no. 2019, pp. 199–210, 2020, doi:
795 10.1016/j.prostr.2020.06.023.
- 796 [90] J. Hylton, A. Huguen, S. M. Rowland, M. Griffin, and L. E. Tunstall, "Relevant biochar characteristics
797 influencing compressive strength of biochar-cement mortars," *Biochar*, vol. 6, no. 1, 2024, doi: 10.1007/s42773-
798 024-00375-6.

- 799 [91] M. A. Mosaberpanah, S. B. Olabimtan, and A. P. Balkis, "Effect of Biochar and Sewage Sludge Ash as
800 Partial Replacement for Cement in Cementitious Composites: Mechanical , and Durability Properties,"
801 Sustainability, vol. 16, pp. 1–29, 2024.
- 802 [92] D. Cuthbertson, U. Berardi, C. Briens, and F. Berruti, "Biochar from residual biomass as a concrete filler
803 for improved thermal and acoustic properties," Biomass and Bioenergy, vol. 120, no. October 2018, pp. 77–83,
804 2019, doi: <https://doi.org/10.1016/j.biombioe.2018.11.007>.
- 805 [93] L. Mo, J. Fang, B. Huang, A. Wang, and M. Deng, "Combined effects of biochar and MgO expansive
806 additive on the autogenous shrinkage , internal relative humidity and compressive strength of cement pastes,"
807 Constr. Build. Mater., vol. 229, p. 116877, 2019, doi: [10.1016/j.conbuildmat.2019.116877](https://doi.org/10.1016/j.conbuildmat.2019.116877).
- 808 [94] M. Haris, M. Ali, W. Ahmad, M. Tariq, R. Alrowais, and M. Bilal, "Effect of various biochars on physical ,
809 mechanical , and microstructural characteristics of cement pastes and mortars," J. Build. Eng., vol. 57, no. April, p.
810 104850, 2022, doi: [10.1016/j.jobe.2022.104850](https://doi.org/10.1016/j.jobe.2022.104850).
- 811 [95] S. Gupta, "Combination of Biochar and Silica Fume as Partial Cement Replacement in Mortar:
812 Performance Evaluation Under Normal and Elevated Temperature," Waste and Biomass Valorization, 1877, doi:
813 [10.1007/s12649-018-00573-x](https://doi.org/10.1007/s12649-018-00573-x).
- 814 [96] Z. A. Zeidabadi, S. Bakhtiari, H. Abbaslou, and A. R. Ghanizadeh, "Synthesis , characterization and
815 evaluation of biochar from agricultural waste biomass for use in building materials," Constr. Build. Mater., vol. 181,
816 pp. 301–308, 2018, doi: [10.1016/j.conbuildmat.2018.05.271](https://doi.org/10.1016/j.conbuildmat.2018.05.271).
- 817 [97] K. Tan, T. Wang, Z. Zhou, Y. Qin, and M. Asce, "Biochar as a Partial Cement Replacement Material for
818 Developing Sustainable Concrete : An Overview," J. Mater. Civ. Eng., vol. 33, no. 12, 2021, doi:
819 [10.1061/\(ASCE\)MT.1943-5533.0003987](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003987).
- 820 [98] A. Dixit, S. Gupta, S. D. Pang, and H. W. Kua, "Waste valorisation using biochar for cement replacement
821 and internal curing in ultra-high performance concrete," J. Clean. Prod., vol. 238, 2019, doi:
822 [10.1016/j.jclepro.2019.117876](https://doi.org/10.1016/j.jclepro.2019.117876).
- 823 [99] S. Gupta, "Carbon sequestration in cementitious matrix containing pyrogenic carbon from waste biomass :
824 A comparison of external and internal carbonation approach," J. Build. Eng., vol. 43, no. June, p. 102910, 2021, doi:
825 [10.1016/j.jobe.2021.102910](https://doi.org/10.1016/j.jobe.2021.102910).
- 826 [100] W. Ashraf, "Carbonation of cement-based materials : Challenges and opportunities," Constr. Build. Mater.,
827 vol. 120, pp. 558–570, 2016, doi: <http://dx.doi.org/10.1016/j.conbuildmat.2016.05.080>.
- 828 [101] Y. F. Houst, "Carbonation shrinkage of hydrated cement paste," in 4th CANMET/ACI International
829 Conference on Durability of Concrete, 1997.
- 830 [102] X. Yang and X. Wang, "Strength and durability improvements of biochar-blended mortar or paste using
831 accelerated carbonation curing," J. CO2 Util., vol. 54, no. June, p. 101766, 2021, doi: [10.1016/j.jcou.2021.101766](https://doi.org/10.1016/j.jcou.2021.101766).
- 832 [103] S. Alice, "Biochar from wood waste as additive for structural concrete," Constr. Build. Mater., vol. 303, no.
833 January, pp. 124500.1-124500.14, 2025, doi: [10.1016/j.conbuildmat.2021.124500](https://doi.org/10.1016/j.conbuildmat.2021.124500).
- 834 [104] L. Wang et al., "Biochar as green additives in cement-based composites with carbon dioxide curing," J.
835 Clean. Prod., vol. 258, 2020, doi: [10.1016/j.jclepro.2020.120678](https://doi.org/10.1016/j.jclepro.2020.120678).

- 836 [105] P. Fong, E. Gunn, C. Chuen, K. Hung, and H. Voon, "Enhancing carbon sequestration in cement mortar
837 using high volume local rice husk biochar coupled with carbonation curing," *Case Stud. Constr. Mater.*, vol. 21, no.
838 July, p. e03591, 2024, doi: 10.1016/j.cscm.2024.e03591.
- 839 [106] S. Kushwah et al., "Mixture of biochar as a green additive in cement-based materials for carbon dioxide
840 sequestration," *J. Mater. Sci. Mater. Eng.*, 2024, doi: 10.1186/s40712-024-00170-y.
- 841 [107] Y. Shao and H. El-hassan, "CO₂ Utilization in Concrete".
- 842 [108] J. Lehmann, "Energy Balance and Emissions Associated with Biochar Sequestration and Pyrolysis
843 Bioenergy Production," *Environ. Sci. Technol.*, vol. 42, no. 11, pp. 4152–4158, 2008.
- 844 [109] S. Joseph, N. R. Scott, and J. Lehmann, "Life Cycle Assessment of Biochar Systems : Estimating the
845 Energetic , Economic , and Climate Change Potential," *Environ. Sci. Technol.*, vol. 44, pp. 827–833, 2010.
- 846 [110] P. D. Dissanayake, S. You, and al, "Biochar-based adsorbents for carbon dioxide capture : a critical
847 review," *Renew. Sustain. Energy Rev.*, vol. 119, no. November 2019, 2020, doi: 10.1016/j.rser.2019.109582.
- 848 [111] S. Sohi, E. Krull, E. Lopez-Capel, and R. Bol, A Review of Biochar and Its Use and Function in Soil, vol.
849 105. 2010. doi: 10.1016/S0065-2113(10)05002-9.
- 850 [112] M. J. Antal and M. Grønli, "The Art , Science , and Technology of Charcoal Production," *Ind. Eng. Chem.*
851 *Res.*, vol. 42, pp. 1619–1640, 2003.
- 852 [113] M. Zamanian, M. Mortezaei, B. Salehnia, and J. E. Jam, "Fracture toughness of epoxy polymer modified
853 with nanosilica particles: Particle size effect," *Eng. Fract. Mech.*, vol. 97, no. 1, pp. 193–206, 2013, doi:
854 10.1016/j.engfracmech.2012.10.027.
- 855 [114] L. Restuccia, A. Reggio, G. A. Ferro, and R. Kamranirad, "Fractal analysis of crack paths into innovative
856 carbon-based cementitious composites," *Theor. Appl. Fract. Mech.*, vol. 90, pp. 133–141, Aug. 2017, doi:
857 10.1016/j.tafmec.2017.03.016.
- 858 [115] W. Liu, S. Xu, and K. Li, "Utilizing bamboo biochar in cement mortar as a bio-modifier to improve the
859 compressive strength and crack-resistance fracture ability," *Constr. Build. Mater.*, vol. 327, pp. 1–27, 2022, doi:
860 <https://doi.org/10.1016/j.conbuildmat.2022.126917>.
- 861 [116] Rodier L. et al, "Utilization of bio-chars from sugarcane bagasse pyrolysis in cement-based composites,"
862 *Ind. Crops Prod.*, vol. 141, 2019, [Online]. Available: <https://doi.org/10.1016/j.indcrop.2019.111731>.
- 863 [117] H. Lee, S. Yang, S. Wi, and S. Kim, "Thermal transfer behavior of biochar-natural inorganic clay
864 composite for building envelope insulation," *Constr. Build. Mater.*, vol. 223, pp. 668–678, Oct. 2019, doi:
865 10.1016/j.conbuildmat.2019.06.215.
- 866 [118] K. Tan, X. Pang, Y. Qin, and J. Wang, "Properties of cement mortar containing pulverized
867 biocharpyrolyzed at different temperatures," *Constr. Build. Mater.*, vol. 263, p. 120616, Dec. 2020, doi:
868 10.1016/j.conbuildmat.2020.120616.
- 869 [119] S. Yang, S. Wi, J. Lee, H. Lee, and S. Kim, "Biochar-red clay composites for energy efficiency as eco-
870 friendly building materials: Thermal and mechanical performance," *J. Hazard. Mater.*, vol. 373, pp. 844–855, Jul.
871 2019, doi: 10.1016/j.jhazmat.2019.03.079.

872 [120] C. E. Brewer et al., “New approaches to measuring biochar density and porosity,” *Biomass and Bioenergy*,
873 vol. 66, pp. 176–185, 2014, doi: 10.1016/j.biombioe.2014.03.059.

874 [121] E. Zhou et al., “Synergistic effect of graphene and carbon nanotube for high-performance electromagnetic
875 interference shielding films,” *Carbon N. Y.*, vol. 133, pp. 316–322, 2018, doi: 10.1016/j.carbon.2018.03.023.

876 [122] R. A. Khushnood, S. Ahmad, L. Restuccia, and C. Spoto, “Carbonized nano / microparticles for enhanced
877 mechanical properties and electromagnetic interference shielding of cementitious materials,” *Front. Struct. Civ. Eng.*,
878 no. January, 2016, doi: 10.1007/s11709-016-0330-5.

879 [123] C. Liu, M. Han, J. Lin, W. Liu, J. Liu, and Z. Zeng, “Wood biomass-derived carbon for high-performance
880 electromagnetic wave absorbing and shielding,” *Carbon N. Y.*, vol. 208, no. March, pp. 255–276, 2023, doi:
881 10.1016/j.carbon.2023.03.067.

882 [124] B. Dai, X. Shao, Y. Ren, G. Wang, C. Pei, and Y. Ma, “Electromagnetic performances of composites with
883 promising carbons derived from bacterial cellulose,” *Mater. Lett.*, vol. 82, pp. 188–190, Sep. 2012, doi:
884 10.1016/j.matlet.2012.05.094.

885 [125] C. Wan, Y. Jiao, T. Qiang, and J. Li, “Cellulose-derived carbon aerogels supported goethite (α -FeOOH)
886 nanoneedles and nanoflowers for electromagnetic interference shielding,” *Carbohydr. Polym.*, vol. 156, pp. 427–
887 434, Jan. 2017, doi: 10.1016/j.carbpol.2016.09.028.

888 [126] F. Natalio, T. P. Corrales, Y. Feldman, B. Lew, and E. R. Graber, “Sustainable Lightweight Biochar-Based
889 Composites with Electromagnetic Shielding Properties,” *ACS Omega*, vol. 5, pp. 32490–32497, 2020, doi:
890 10.1021/acsomega.0c04639.

891 [127] J. Xi, E. Zhou, Y. Liu, W. Gao, J. Ying, and Z. Chen, “Wood-based straightway channel structure for high
892 performance microwave absorption,” *Carbon N. Y.*, vol. 124, pp. 492–498, 2017, doi:
893 10.1016/j.carbon.2017.07.088.

894 [128] Comité Européenne de Normalisation, “EN 14647 Ciment d’aluminates de calcium - Composition,
895 spécifications et critères de conformité,” 2007.

896 [129] Comité Européenne de Normalisation, “EN 15743+A1 Ciments sulfaté - Composition, spécifications et
897 critères de conformité,” 2011.

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