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16. Abstract

In portland cement concrete, biochar additions efficiently accelerate setting, increase the initial rate hardening, and promote the precipitation of secondary minerals to fill capillary pores, all key aspects of accelerated bridge construction. However, biochar has variable properties and performance in concrete, especially at early ages. We investigated how biochar surface area, composition, and water absorption influence the rheological properties, hydration rates, and strength development of fresh and hardened concrete material. Two different biochar sources were characterized for specific surface area, porosity, composition, and particle size distribution, and were used to partially replace portland cement in cement binders. The fresh hydration rates, rheological properties, and setting times were monitored by isothermal calorimetry, rotational rheometry, and Vicat penetration, respectively. With 5 w% biochar replacement, setting times were 25 % lower, 7-d compressive strengths were 25 % greater, and secondary mineralization rates were enhanced by 25 % relative to control materials without biochar. These results show that low-volume biochar additions in concrete can both accelerate bridge construction and can potentially provide a material with enhanced mechanical performance.

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Development of Concrete Materials Infused with Biochar for Bridge Applications

Final Report

July 2025

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CHAPTER 1. INTRODUCTION

1.1. Project Motivation

The motivation for this project is a recognition of the need for concrete materials that (1) enable accelerated ready-mixed construction methods and (2) have improved durability for lower repair and rehabilitation costs over the life of the bridge. Among recent trends in high-performance, sustainable construction materials, the incorporation of low dosages of biochar stands out as a potential means to meet these needs for accelerated bridge construction.

1.2. Research, Objectives, and Tasks

The primary objective of this research project is to determine the early-age structure-processing-property relationships of concrete containing moderate replacements of biochar. Quantifying these relationships will enable biochar-infused concrete to be used reliably and at higher volume fractions of replacement for portland cement. Within that objective, our specific goal in this project is to map the relationships among biochar dosage and properties (ash content, fineness, and porosity) to fresh flow properties (yield stress, shear-dependent viscosity, and thixotropy) and early-age mechanical properties and microstructure.

This objective was accomplished through the following research tasks.

Task 1 – Screen and characterize biochar sources: Use multiple complementary characterization methods to determine the properties of as-received biochars.

Task 2 – Map the rheological properties of pastes and mortars. Rotational rheometry was used to determine the influence of biochar type and dosage on flow curves and yield stress, using a design-of-experiments approach with biochar dosage, water-solids mass ratio, and superplasticizer dosage as factors.

Task 3 – Determine biochar influence on early-age hydration, carbonation, and mechanical properties. Isothermal calorimetry was used to track real-time hydration rates. Microthermogravimetry was used to quantify the extent of carbonate mineralization up to seven days of exposure, and mortar cube compressive strength measurements (ASTM C109) were used to characterize the mechanical integrity of the materials.

Task 4 – Final Report: A final report will be prepared meeting the RITA requirements for UTC funded projects. The content of the report will contain a detailed summary of the results from the preceding tasks and a recommendation for future phases of the project, if necessary.

1.3. Research Advisory Panel (RAP)

The project work and the developed survey were done in collaboration with the Research Advisory Panel (RAP). The following people participated in the RAP:

- Enad Mahmoud, Deputy Director, Materials and Test Division, TxDOT
- Andy Naranjo, Director, Rigid Pavement and Concrete Section, TxDOT

CHAPTER 2. INFLUENCES OF BIOCHAR CHARACTERISTICS ON EARLY-AGE HYDRATION AND FRESH PROPERTIES OF CEMENT

2.1. Materials

2.1.1. Raw Materials

Type I Ordinary Portland Cement (OPC) was used as the binder material, and two commercially available biochars were used as partial cement replacements. One biochar was derived from rice husk waste (referred to as RH-BC hereafter). The other biochar was produced from wood sawdust waste (referred to as SD-BC hereafter). A laboratory ball milling machine was used to grind the biochar as described in Figure 2.1. The ground RH-BC had an average particle size of 7.0 µm and SD-BC had an average particle size of 16.5 µm.

Figure 2.1 Biochar ball milling procedure, showing the as-received particle size distribution (left) and the ground size distribution after milling (right).

2.1.2. Mix Proportions and Fabrication

Each biochar replaced 5 w% of the cement. When desired, the biochars were pre-saturated before mixing with cement by pouring water equal to the biochar's water absorption capacity and sealing for three hours. The total water-to-solid mass ratio was fixed at 0.35 in both dry and pre-saturated biochar cases. A planetary mixer with a 5-quart capacity was used for the mixing process. The mixed biochar-cement paste was directly used for the fresh property measurement, and the cast samples were stored in a high humidity (RH 95% ± 5%) chamber at 23°C until the desired testing date.

2.2. Test Methods

The initial and final setting times of the biochar-cement paste were determined using an automatic Vicat machine following the ASTM C191 standard. The workability of biochar-cement paste mixtures was tested using the flow table according to ASTM C230. The flow table test was conducted twice for each paste mixture to measure fluidity, and the average value was reported.

The effect of biochar on hydration kinetics was investigated using an isothermal calorimetry test by measuring heat flow and cumulative heat of reaction over 72 h according to ASTM C1702.

The rheological behavior of biochar-cement paste was investigated using a rotational Brookfield RST-SST rheometer with a 40 mm height and 20 mm diameter vane setup in accordance with ASTM C1749. A paste volume of 140 mL was placed in a 150 mL beaker. Plastic viscosity and yield stress were inferred from shear-controlled flow curve measurements. The details of the

flow curve experiments are adopted from [1], and the resulting data are shown in Figure 2.2. The descending curve between 15 s^{-1} and 35 s^{-1} was selected to calculate the plastic viscosity and yield stress based on the Bingham model [1] and the hysteresis loop area was calculated to quantify the thixotropy of biochar-cement paste [2]. Two replicates were used, and the average values are reported.

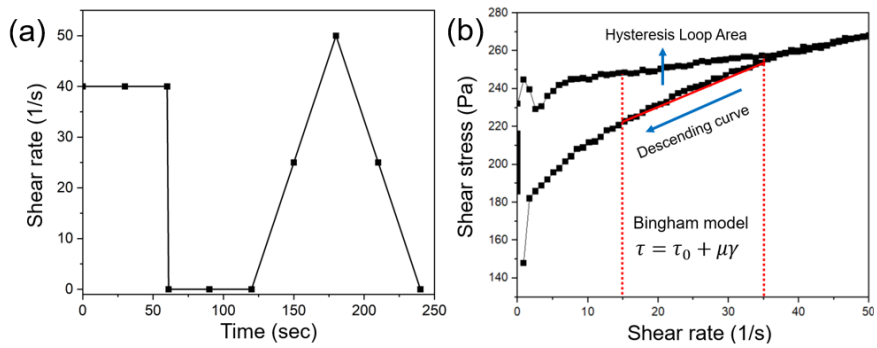

Figure 2.2 Rheological behavior test of biochar-cement paste; (a): flow curve test profile and (b) example result and calculation.

To evaluate the early-age mechanical properties of biochar-cement paste, compressive strength measurements were made at 3 d and 7 d of curing following ASTM C109 using 50 mm cube specimens. At each testing age, three cubes were measured per paste mixture, and the average values were reported.

2.3. Results and Discussion

2.3.1. Biochar Characterization

The physical characteristics of the biochars before and after the grinding process are described in Table 2.1. The specific surface area of SD-BC is significantly greater than that of RH-BC. After grinding, the specific surface area increases only marginally, which indicates that the finer pores provide the greatest contribution to the surface area. Additionally, the large specific surface area of SD-BC enables it to hold more water within its structure and on the surface of its particles, resulting in a higher water absorption capacity. Both RH-BC and SD-BC show a reduction of > 50 % in water absorption capacity after grinding, implying that the process may eliminate relatively larger pores that are more effective for storing water inside the biochar.

Table 2.1 Physical Characteristics of Biochars Before and After the Grinding Process.

Biochar (Raw/Ground)	Water Absorption (g/g)	Specific surface area (m^2/g)	Bulk density (kg/m^3)
RH-BC (Raw)	4.94	139.17	197.03
RH-BC (Ground)	2.14	196.35	462.48
SD-BC (Raw)	6.32	358.85	200.23
SD-BC (Ground)	2.77	379.08	540.0

The composition of both biochars obtained from XRF and elemental analysis are given in Table 2.2. The major difference between RH-BC and SD-BC is their SiO_2 content. RH-BC has a SiO_2 content of 96.2 wt%, while SD-BC has only 6.36 wt%. Previous studies [3, 4] have found that

high silica content is due to the biochar being derived from silica-rich feedstock, such as agricultural waste, together with a relatively high ash content.

Table 2.2 Chemical and elemental composition results of RH-BC and SD-BC.

	RH-BC (wt%)	SD-BC (wt%)		RH-BC (wt%)	SD-BC (wt%)
SiO_2	96.2	6.36	C	37.70	86.98
K_2O	1.44	22.7			
P_2O_5	0.83	2.75	H	1.01	0.9
CaO	0.65	56.7			
MgO	0.29	3.06	N	0.24	0.18
Al_2O_3	0.28	1.09			
MnO	0.14	4.96	O	61.05	11.94
SO_3	0.07	1.09			
Others	0.10	1.29	Total	100	100

2.3.2. Pozzolanic reactivity of biochar

The pozzolanic reactivities of RH-BC and SD-BC were compared using cumulative isothermal heat release results and CH consumption as shown in Figure 2.3. The RH-BC shows much higher heat release (378.56 J/g) compared to SD-BC (77.29 J/g) up to 160 h, suggesting that RH-BC's higher SiO_2 content enables more dissolution and reaction with CH. The heat release of SD-BC, in contrast, is similar to that of limestone (21 J/g) and quartz (82 J/g) [3], which implies that SD-BC can be considered pozzolanically inert. In contrast, RH-BC has a similar heat release to fly ash (327 J/g [5]). In Figure 2.3 (b), RH-BC exhibits much higher CH consumption due to the reaction between CH and SiO_2 from the biochar, whereas SD-BC shows only marginal CH consumption during the test period.

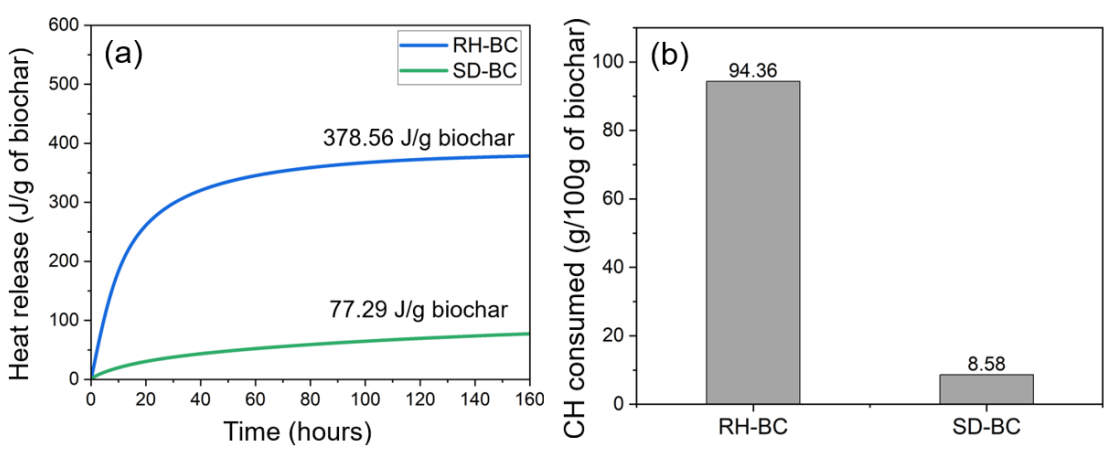

Figure 2.3 Pozzolanic reactivity of RH-BC and SD-BC (a): cumulative heat release, (b): amount of CH consumption.

2.3.3. Biochar morphology

The morphologies of the raw and ground biochars are shown in Figures 2.4. Both RH-BC and SD-BC clearly have a cellular structure with cylindrical pores. However, grinding appears to largely destroy the cellular structure. The changes in biochar's physical characteristics by grinding indicate that grinding significantly reduces its water absorption capacity. However, ground biochar still can absorb more than twice its mass in water. Furthermore, despite the elimination of visible micropores during grinding, there is only a slight increase in the specific surface area. This suggests that micropores and mesopores continue to play a significant role in determining the specific surface area. Additionally, the ground RH-BC exhibits an irregular and rough surface, as seen in Figure 2.4(b), whereas the ground SD-BC displays sharp and angular surfaces, as shown in Figure 2.4(d).

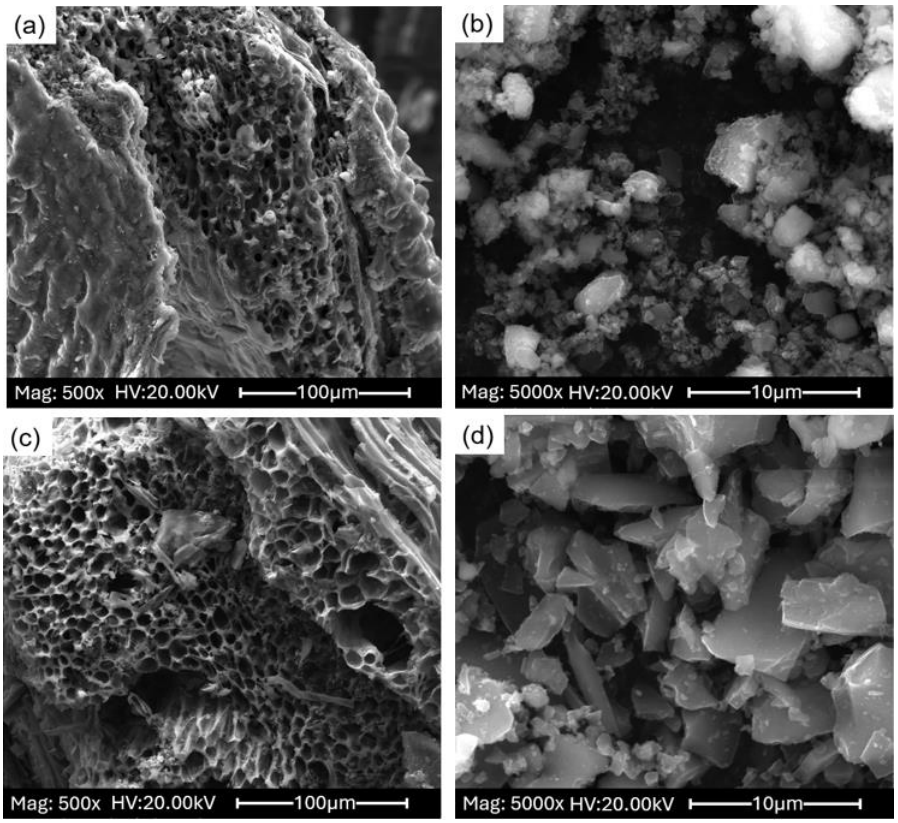

Figure 2.4 SEM images of (a) raw RH-BC (b) ground RH-BC, (c) raw SD-BC, and (d) ground SD-BC.

2.3.4. Paste Setting Time and Workability

Figure 2.5(a) shows the initial and final setting times of pastes made with either of the two different biochars when added in either dry or pre-saturated condition. Regardless of biochar type and saturation condition, all pastes have similar initial setting times, but shorter final setting times compared to the control (cement only). The reduced final setting time in biochar-cement mixes may result from the combined effects of accelerated hydration due to the enhanced total solid volume fraction through biochar incorporation. The fine particles and high porous structure of biochar can absorb water, reducing the volume of free water in the paste. In addition, the fine

particle size of biochar can fill the space between cement particles and thereby increase the packing density. Pre-saturating either of the biochars corresponds with a delayed setting time compared to dry biochar. The absorbed water near the pre-saturated biochar surface could help dispersion by lubricating the cement particles, leading to more uniform water distribution and prolonged setting time.

The fluidity results are summarized in Figure 2.5(b). Pastes that incorporate either RH-BC or SD-BC, regardless of their saturation state, have lower fluidity than the control. The reduced workability is primarily due to biochar's water absorption capacity, which decreases the amount of available mixing water. Furthermore, the pre-saturated amount of water can reduce the effective mixing water and affect fluidity significantly.

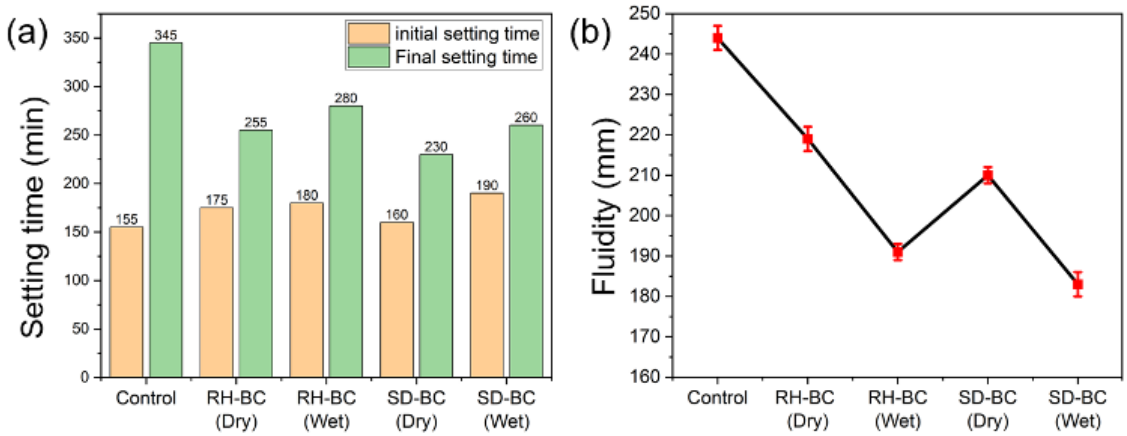

Figure 2.5 (a) Setting time results and (b) fluidity measurements of biochar-cement pastes. The estimated uncertainty in the setting time with a standard deviation of 12 min for the initial setting and 20 min for the final setting is based on the ASTM C191-21 precision statement.

2.3.5. Hydration Kinetics of Biochar-infused Cement Paste

The effect of biochar types and pre-saturation conditions on the hydration of biochar-cement pastes was investigated by isothermal microcalorimetry and described in Figure 2.6. The first peak in the pastes with biochar corresponds to the dissolution of the tricalcium silicate (C_3S), which occurs earlier than in the paste without biochar. This suggests an enhancement in hydration rate catalyzed by the finer particle size and greater surface area of biochar, relative to cement particles, that provides favorable sites for nucleation and growth of hydration products [6, 7].

In both RH-BC and SD-BC, dry biochar enhances the peaks compared to pastes with pre-saturated biochar, and RH-BC exhibits a slightly higher peak than SD-BC. The dry biochar absorbs water in the initial stage and may provide additional nucleation sites for C-S-H. In Figures 2.6(c) and 2.6(d), the difference in total heat release was negligible regardless of biochar type and pre-saturation condition. This implies that the pozzolanic reactivity of biochar may not be a key parameter in controlling early-age cement hydration; instead, physical characteristics such as particle size and surface area are more important controlling factors for early-age hydration.

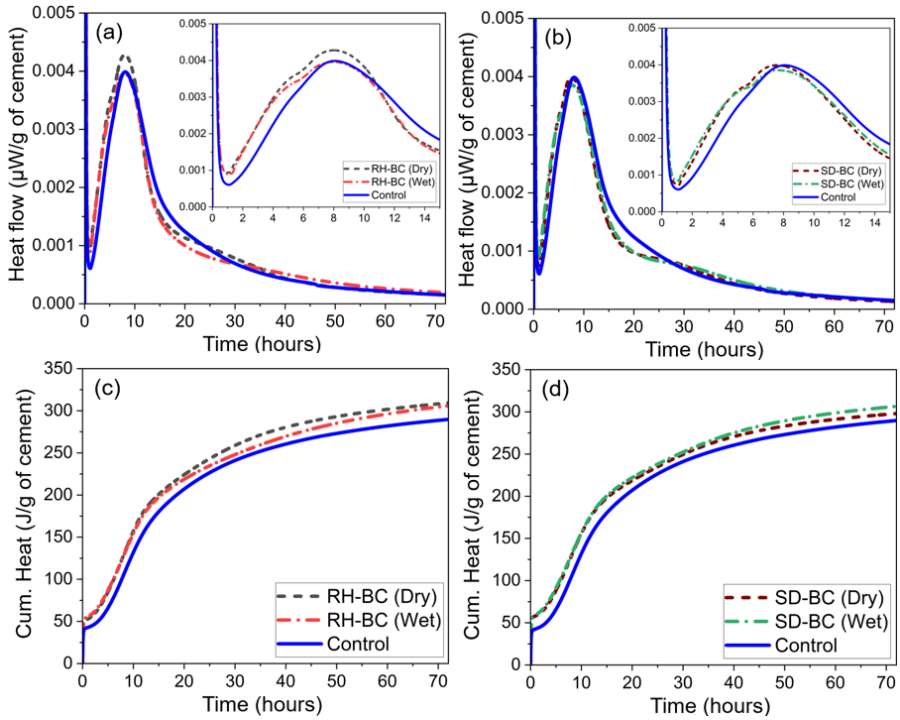

Figure 2.6 Isothermal calorimetry results of biochar-infused cement paste.

2.3.6. Rheological Behavior

The rheological characteristics of biochar-cement pastes obtained from flow curve tests are summarized in Figure 2.7. Yield stress is increased by incorporating biochar regardless of the pre-saturation condition. We speculate that the higher specific surface area and water absorption capacity of the biochar are the main reasons for yield stress enhancement. Use of SD-BC leads to higher yield stress in both dry and pre-saturated conditions than when RH-BC is used. This is because SD-BC has higher specific surface area and water absorption capacity, so less free water is available in the mixture. At a constant water to solid mass ratio, the pre-saturated biochar further reduces the effective water in the early-age mixing, demonstrated by the higher yield stress than dry biochar cases.

Figure 2.7(a) also shows that using pre-saturated biochar leads to lower plastic viscosity than when dry biochar is used. Pre-saturated biochar does not need to cannibalize free water during mixing, so the presence of water on the biochar surface may promote a more uniform distribution of biochar and may reduce friction among the cement particles and biochar. Pastes with pre-saturated biochar also have lower plastic viscosity than even the biochar-free control paste, whereas pre-saturated biochar cases show reduced fluidity compared to control as described in the previous section. This indicates that the pre-saturated biochar in the mix can compensate for the loss of workability under continued shear conditions, thereby enhancing its potential for practical use without compromising workability.

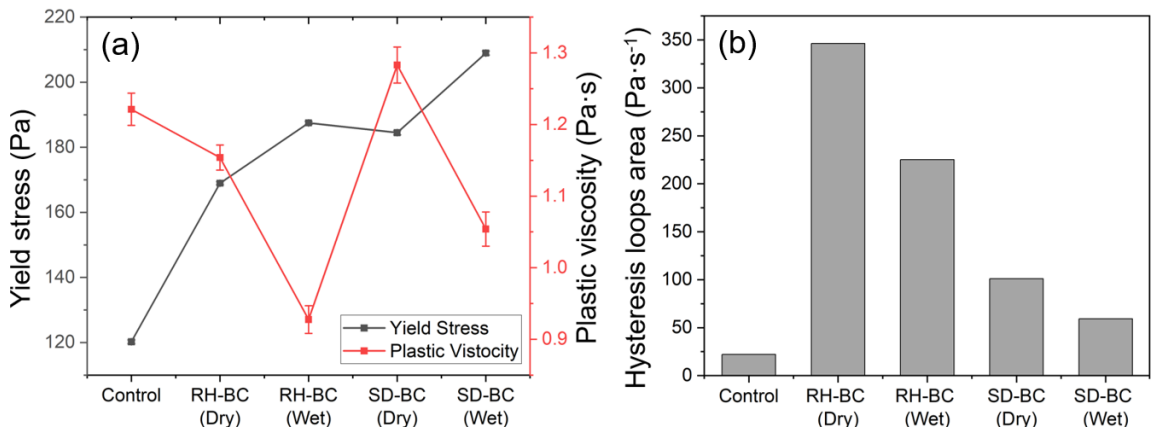

Figure 2.7 Rheological behavior of biochar-cement pastes (a) yield stress and plastic viscosity (b) thixotropy (hysteresis loop area) results.

In Figure 2.7(b), the biochar-infused cement pastes have higher thixotropy—measured as the area inside the hysteresis loop formed from ascending and descending shear rates— compared to the control, and the pastes with RH-BC have greater hysteresis than those with SD-BC whether dry or pre-saturated biochar is used. Although it requires further examination to make a definite explanation for the differences observed, the relatively finer particle size of RH-BC may facilitate greater interaction with cement particles than SD-BC, which can then lead to a more pronounced formation and subsequent breakdown of the microstructural network under shear, resulting in more evident thixotropic behavior. Due to its physical characteristics, incorporating biochar affects the rheological properties of cement paste. Moreover, biochar's pre-saturation condition can potentially reduce plastic viscosity, which may be beneficial for practical implementation. However, more in-depth rheological analysis with changing variables should be undertaken to better determine the impact of biochar for specific target applications.

2.3.7. Early-age Compressive Strength

Figure 2.8 illustrates the early-age compressive strengths of biochar-cement pastes. All specimens show similar compressive strength, ranging between 47.75 MPa and 52.66 MPa at 3 d of curing, regardless of biochar incorporation. However, at the 7 d of curing, RH-BC showed significant strength improvements up to 76.68 MPa, while the compressive strength of control and SD-BC reached up to 61.33 MPa and 66.95 MPa, respectively.

As discussed in the previous section on hydration kinetics, the finer particle size of RH-BC, rather than its pozzolanic reactivity, helped enhancing cement hydration, leading to the production of more hydration products and could densify the microstructure to produce greater strength compared to pastes with SD-BC.

In general, the minimum water-to-cement mass ratio (w/c) for cement to complete its hydration is known to be about 0.4. Dry biochar can absorb water as it is mixed with cement, resulting in a lower effective w/c. The higher water absorption capacity of SD-BC compared to RH-BC implies that it needs *less additional* mixing water than RH-BC to achieve equivalent total w/c ratios when pre-saturated biochar is used. In turn this lower volume of free water during mixing reduces the mean interparticle spacing during mixing, with corresponding implications for the rheological properties, even though the absorbed water can be released from the biochar

afterward. The results imply that the total water-to-solid ratio in biochar-induced mixes must be considered with both minimum effective water content and water absorption capacity of biochar.

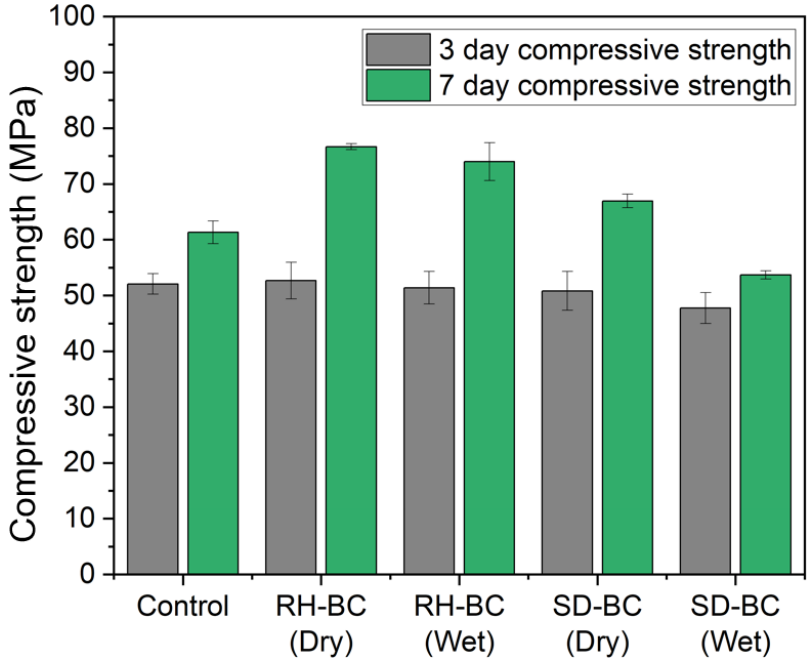

Figure 2.8 Compressive strength of 3-day and 7-day biochar-cement pastes.

CHAPTER 3. CONCLUSIONS AND RECOMMENDATIONS

Our research on biochar-infused concrete supports the hypothesis that biochar can be used as a partial replacement of Portland cement to create a cementitious binder for concrete that has 25 % earlier setting times and 25 % higher compressive strength at 7 d than a binder comprising only portland cement. The specific results have been shown to be predictable functions of particle size distribution and wetting condition, especially as related to producing lower plastic viscosity and reduced thixotropic characteristics in the fresh material.

The scope of this project was limited to a single biochar dosage, so we do not yet have data on how the mixture proportions and curing conditions influence the results. To advance the technology readiness level (TRL) of biochar-infused concrete for bridge applications, more data are needed on the influence of gas concentrations and biochar dosage on the biochar consumption rate and extent, initial and final setting times, compressive strength, and the rates and extent of secondary mineral precipitation.

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