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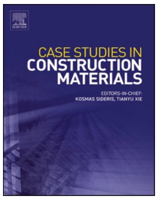

Short communication

Translating lab success to the field: Evaluating coffee biochar-enhanced concrete in real-world construction

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ABSTRACT

Building upon our pioneering laboratory research on coffee biochar in concrete, this study presents a world-first field trial, translating lab-based findings into real-world construction applications. Our previous experimental work demonstrated that biochar derived from pyrolysing spent coffee grounds (SCGs) at 350°C, when used as a partial replacement of fine aggregates, could enhance concrete strength by up to ~30 %. This field study evaluates the performance of coffee biochar-enhanced concrete under actual construction and environmental conditions. However, a major limitation was encountered in the production of coffee biochar, as the pyrolysis equipment of the commercial-scale biochar producer could not operate at the optimal 350°C temperature due to operational constraints. In this real-world application, we collaborated with a local council to translate the lab-based research work into a mainstream construction solution. To evaluate the performance of this biochar blended concrete, we carried out independent testing of the concrete slump, compressive strength of concrete and cored slab, flexural strength and concrete shrinkage and compared its performance against the control mix. The successful translation of this lab-based research into field applications showcases the potential of coffee biochar as a sustainable construction material that can transform coffee waste into a valuable resource for concrete applications with improved performance. It also highlights the current supply chain limitations that must be addressed before making it a mainstream construction material.

1. Introduction

Recent advancements in concrete technology have opened new avenues for incorporating industrial by-products and waste materials into construction applications [1–7]. Among these, the use of pyrolysed organic waste as a partial replacement for cement [8–10] and fine aggregates [11,12] has shown particular promise in laboratory settings. Our recent work on coffee biochar in concrete applications demonstrated that these organic waste forms can be transformed into high-value by-products for improving concrete performance [13]. This research garnered significant international media attention, underscoring its importance and potential impact [14–17].

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To better understand the broader context of biochar applications in concrete, recent reviews have highlighted biochar’s potential as a promising sustainable admixture in cementitious materials. The incorporation of biochar in cement-based materials has been found to enhance both mechanical and durability properties when used in appropriate amounts, while contributing to carbon sequestration [7,18–21]. Biochar’s effectiveness depends heavily on its physicochemical properties which are influenced by factors like feedstock source, pyrolysis conditions and temperature [7]. Higher pyrolysis temperatures generally lead to increased surface area and porosity beneficial for cement composites, though this comes with reduced biochar yield [7,22]. The porous nature and high specific surface area of biochar enable it to modify the pore structure of cementitious materials and act as an internal curing agent [23].

Building upon these fundamental properties, studies have demonstrated that biochar can serve multiple functions in cement-based materials - as a partial cement replacement, fine aggregate substitute, and pore structure modifier [24]. When incorporated at optimal dosages, biochar has been shown to enhance compressive strength, reduce permeability, improve thermal insulation properties and contribute to carbon dioxide capture and storage. However, higher replacement levels may adversely affect workability and mechanical properties due to biochar’s high water absorption capacity [7,18–21]. Therefore, proper optimization of biochar content and careful consideration of its properties are essential for achieving the desired performance enhancement in cementitious composites.

While these laboratory studies demonstrate promising results for biochar in concrete applications, translating laboratory-based research into real-world commercial applications is often challenging due to the high costs involved in infrastructure development and the potential financial implications of trial failures for end users. To bridge the gap between laboratory findings and practical implementation, a carefully designed and executed field trial is essential. We conducted our field trial in collaboration with a local council in Victoria, Australia, who proactively supported the implementation of our coffee biochar concrete in a footpath project within a local residential area in Gisborne, Victoria. This medium-scale construction project provided an ideal setting to evaluate the material’s performance under real-world conditions, allowing us to identify and address any potential challenges before progressing to larger structural projects.

To ensure unbiased and reliable results, we engaged an independent National Association of Testing Authorities (NATA) accredited laboratory to perform comprehensive testing. The assessment included slump tests, compressive strength measurements (for both concrete samples and cored samples), flexural strength tests, and concrete shrinkage evaluations. This rigorous approach enables a thorough comparison between the coffee biochar concrete and a control mix without the presence of coffee biochar.

In this paper, we report the findings from these independently conducted tests, highlighting the performance characteristics of coffee biochar concrete in a real-world application. Additionally, we discuss the limitations and challenges posed by current supply chain settings for biochar application in concrete. The field trial utilised the optimal concentration of coffee biochar that was identified in our previously published laboratory-based research [13], providing a direct link between controlled experiments and practical implementation.

2. Materials, mix designs, test methods, and field trial location

2.1. Materials

The materials used in this field trial included general blended cement (GBC – 52 % cement reduction with supplementary cementitious materials) [25], spent coffee grounds (SCGs) biochar, coarse and fine aggregates, and water. The biochar was supplied by a local producer using a continuous pyrolysis reactor, typically operated at higher temperatures. For the field trial, we requested a lower pyrolysis temperature. However, due to the equipment limitations, the company could only reduce the pyrolysis temperature to 450 °C. In addition, they used water to quench and cool down the biochar after the pyrolysis process. Both control and biochar blended concrete mixes were supplied by an independent ready-mix producing company contracted by the local Council for this field trial project.

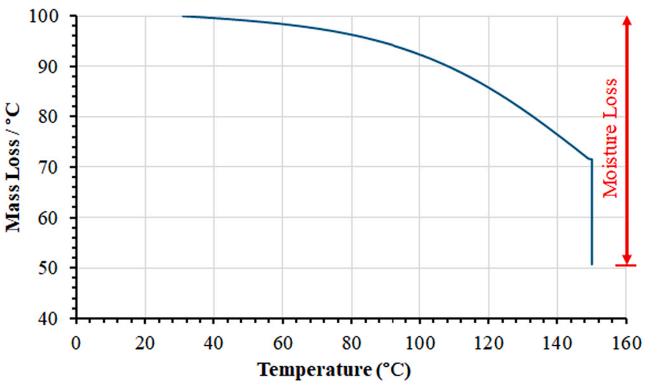

Fig. 1. Thermogravimetric analysis to ascertain the moisture content in the coffee biochar sample.

2.2. *Thermogravimetric analysis to identify the moisture content of biochar*

Thermogravimetric analysis (TGA) of coffee biochar was undertaken to ascertain the moisture content present in the biochar supplied for the field trial so that it can be compensated for in the actual concrete mix design TGA was carried out using Perkin Elmer STA 8000 equipment in nitrogen environment with a nitrogen flow rate of 20 mL/min. The sample was subjected to a controlled temperature program from 30 °C to 150 °C at a heating rate of 10 °C/min, followed by an isothermal hold at 150 °C for 30 minutes. The TGA curve (Fig. 1) exhibited a continuous mass loss profile characteristic of moisture desorption, with the initial mass decrease occurring gradually up to 150 °C, followed by a sharp vertical descent during the isothermal period. This vertical mass loss during the isothermal stage indicates the final dehydration of water molecules from the spent coffee grounds matrix. The total moisture content was determined to be approximately 50 % (w/w) of the initial sample mass, suggesting significant water retention capacity of the spent coffee grounds. The specific gravity of the wet biochar was calculated to be equal to 0.59.

2.3. *CHNS analysis of 450CBC*

The CHNS analysis was carried out on 450 CBC using PerkinElmer Series II CHNS analyser. The results are shown in Table 1.

2.3.1. *XRF analysis of 450CBC*

The elemental composition (Table 2) of 450CBC biochar sample was identified using the Bruker-AXS-S4-Pioneer XRF equipment.

2.3.2. *XRD analysis of 450CBC*

The XRD analysis of dried and finely ground powder of 450CBC was carried out using Bruker Axs D4 Endeavor XRD equipment. The XRD data was collected between 5° and 70° 2theta using a step size of 0.1° and a count time of 0.5 sec per step to ascertain the mineralogical composition of 450CBC. Fig. 2 shows the x-ray diffractogram and identified mineralogical compositions of 450CBC.

2.3.3. *SEM analysis of 450CBC*

SEM analysis of 450CBC was carried out using FEI-Quanta200ESEM at 100x and 250x magnification levels (Fig. 3) for the visual identification of their surface microstructure characteristics. Thermal decomposition of coffee grounds due to pyrolysis created a porous structure within the particles.

2.3.4. *Particle size distribution*

The particle size distribution of 450CBC was obtained using the Malvern particle size analyser “Malvern Mastersizer 3000”. The results are presented in Table 3.

2.4. *Mix designs*

Two different concrete mixes (Table 4) were used for the field trial: the control and the biochar mix containing 27.7 kg of wet biochar per m^3 of concrete. N25 grade concrete mix was used with 310 kg/m^3 of GBC content (containing 52 % of SCM content), 1053 kg/m^3 of coarse aggregates (≤14 mm maximum size), 890 kg/m^3 of fine aggregates, and a water/cement ratio of 0.63. The original optimum dry biochar content used in the lab work was 14 kg/m^3. To account for the water content and higher specific gravity (0.59) of the wet coffee biochar, the biochar content in the coffee biochar blended concrete mix was 27.7 kg/m^{3,} which was used as a replacement of sand (S.G = 2.62) by volume. The target slump of the concrete mix was 80 mm.

2.5. *Test methods*

Both the control and coffee biochar blended concrete samples were tested for their slump (fresh concrete) as per AS1012.3.1:2014 [26], 7 and 28-days compressive strength of concrete as per AS1012.9:2014 [27], 28-day compressive strength of the concrete samples cored from the test footpath slab tested as per AS 1012.9:2014 [19], 28 days flexural strength as per AS1012.11:2000 [28] and concrete shrinkage test as per AS1012.13:2015 [29]. All tests on hardened concrete samples were carried out on three replicates and the average values are presented with error bars. The results are presented as mean values with the error bars present.

2.6. *Field trial location*

The field trial was conducted in Gisborne in the Macedon Ranges, located about 50 kilometres (north-west of Melbourne CBD, Australia. Fig. 4(a) shows the fresh concrete being finished, and 4(b) shows the aerial view of the finished concrete slabs.

Table 1
CHNS analysis of 450CBC samples.

Material	Carbon (weight%)	Hydrogen (weight%)	Nitrogen (weight%)	Sulphur (weight%)
450CBC	67.5 ± 0.45	3.2 ± 0.04	3.5 ± 0.02	0.3 ± 0.05

Table 2
Elemental composition of 450CBC.

Elements	Percentage Composition
Magnesium (Mg)	0.92 %
Aluminium (Al)	0.20 %
Silicon (Si)	0.96 %
Phosphorous (P)	0.63 %
Sulphur (S)	0.22 %
Chlorine (Cl)	0.28 %
Potassium (K)	11.30 %
Calcium (Ca)	3.91 %
Titanium (Ti)	0.03 %
Chromium (Cr)	0.01 %
Manganese (Mn)	0.10 %
Iron (Fe)	0.46 %
Nickle (Ni)	0.01 %
Copper (Cu)	0.06 %
Zinc (Zn)	0.04 %
Rubidium (Rb)	0.02 %
Strontium (Sr)	0.03 %

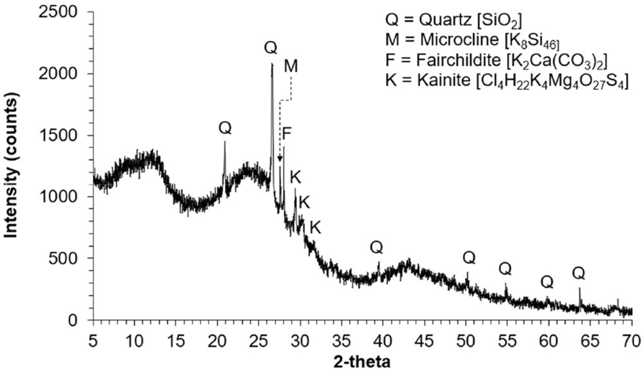

Fig. 2. XRD analysis of 450CBC.

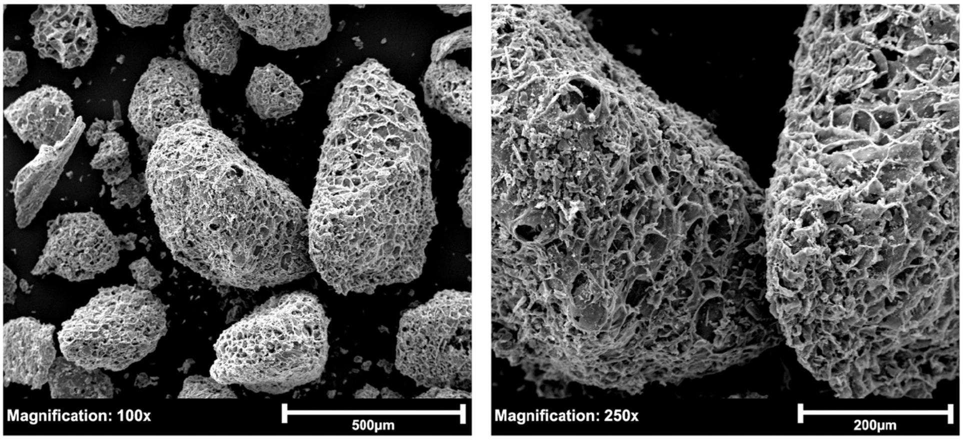

Fig. 3. SEM images of 450CBC at 100x and 250x magnification levels.

Table 3
Particle size distributions of 450CBC.

Materials	D_{10}	D_{25}	D_{50}	D_{75}	D_{100}
450CBC	34.7 μm	134 μm	232 μm	308 μm	759 μm

Table 4
Concrete mix designs.

Concrete Mix	GBC	Coarse Aggregate	Fine Aggregate	Biochar	Water
Control	310 kg/m^3	1053 kg/m^3	890 kg/m^3	-	195 L
450CBC	310 kg/m^3	1053 kg/m^3	767 kg/m^3	27.7 kg/m^3	181 L*

[*] Note: the water content was compensated for the water absorbed by the wet biochar

Fig. 4. (a): Finishing of fresh concrete footpath slab. Fig. 4(b): Aerial view of the field trial location (Howey Street, Gisborne, Victoria, Australia).

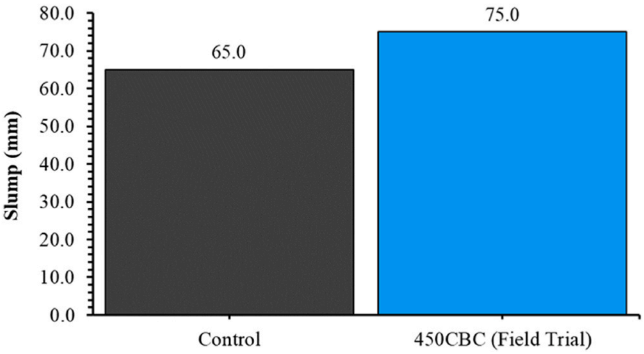

Fig. 5. Slump test results.

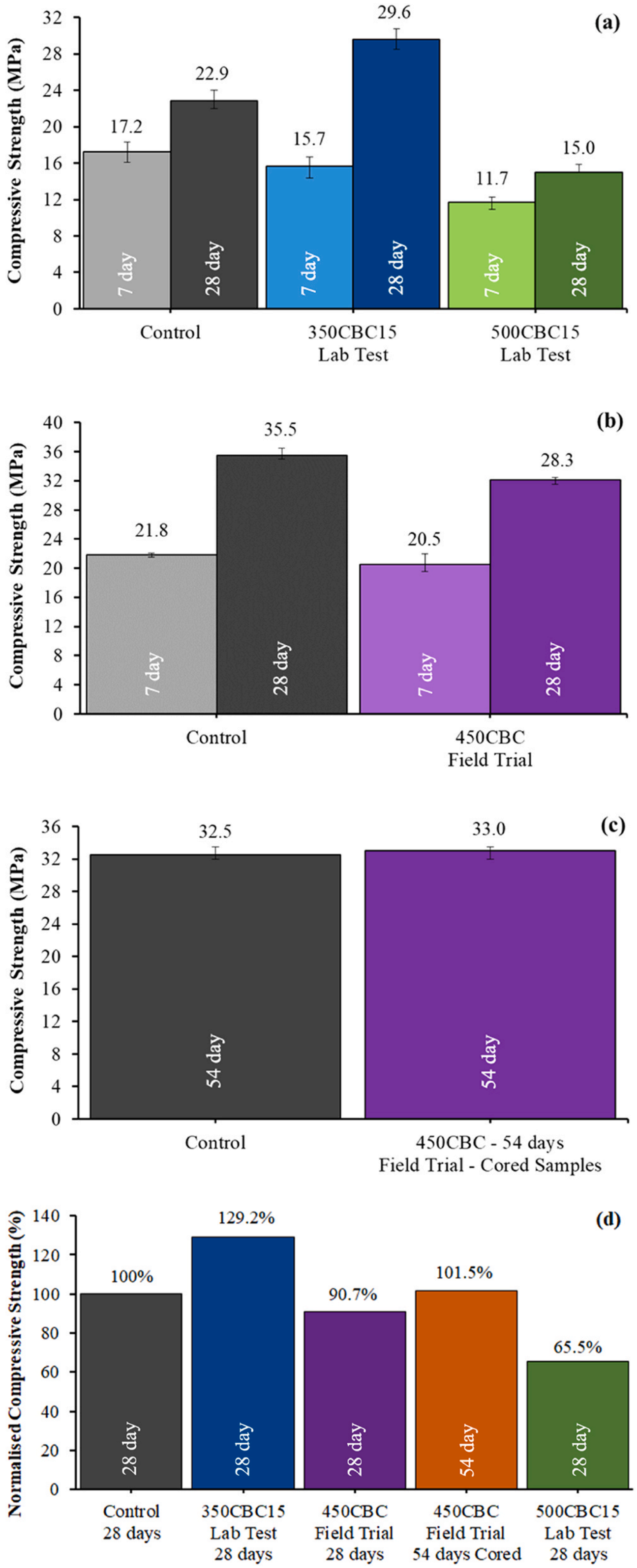

Fig. 6. Compressive strength results of (a) 350CBC15 and 500CBC15 from existing lab tests (published work) [13], (b) coffee biochar field trial tests, (c) coffee biochar field trial tests (samples cored from concrete slab extension at 54 days of curing), and (d) normalised strength results relative to the control mix (including lab test [13]).

3. Results and discussion

3.1. Concrete slump test

Even though the water content of the wet biochar was compensated by reducing the equivalent water from the concrete mix design, the biochar blended concrete mix showed a higher slump compared to the control mix (Fig. 5). Previous studies have consistently reported that the incorporation of biochar typically reduces concrete workability and slump values due to its high water absorption capacity and porous nature [7,18]. However, interestingly, in our field trial, despite compensating for the water content of the wet biochar by reducing the equivalent water from the concrete mix design, the biochar blended concrete mix showed a higher slump (75 mm) compared to the control mix (65 mm). This contrasting behaviour could be attributed to two potential mechanisms: (i) the pre-saturated state of the biochar pores with water during the quenching process may have created a lubricating effect at the interfacial zones between aggregates and cement paste, and (ii) the saturated biochar particles may act as 'water reservoirs' that temporarily release some absorbed water during mixing and concrete placement, enhancing the immediate workability. This observation suggests that the water absorption and workability effects of biochar in concrete can be significantly influenced by its pre-treatment conditions and moisture state at the time of mixing, offering potential strategies for workability control in biochar-modified concrete.

3.2. Compressive strength results of concrete

Fig. 6(a) shows the test results of 15 % coffee biochar concrete mixes from the laboratory experiments [12]. It compares the concrete samples containing biochar produced at two different temperatures, 350 °C (350CBC15) and 500 °C (500CBC15). There is an 8.7 % reduction in concrete strength at 7 days and ~30 % increase at 28 days with 350CBC15; however, 500CBC15 showed a 32 and 34.5 % reduction in compressive strength at 7 and 28 days, respectively. These findings align partially with Tan et al. (2020) [30], who found that lower pyrolysis temperatures (400–500°C) generally performed better than higher temperatures, though their optimal dosage was much lower at 1–3 % and their lower temperature was higher than the optimum pyrolysis temperature of our lab based study [13].

Fig. 6(b) shows the test results from the field trial. The biochar used in this field trial was produced at 450 °C temperature. The biochar blended concrete mix showed ~6 and 9.3 % reduction compared to the control mix at 7 and 28 days, respectively. The relative performance of field trial biochar produced at 450 °C was significantly better than the one we tested in our lab that was produced at 500 °C temperature (Fig. 6(d)). This is most likely because of two reasons: (i) reduction in the pyrolysis temperature, i.e., 450 °C temperature compared to our earlier 500 °C which showed inferior performance in our lab work [13] and (ii) saturation of the pores of biochar with water, which helps in internal curing of concrete. Similar results in the improvement of strength properties with the water-saturated biochar have been reported by Gupta et al. [31]. However, the effect of pyrolysis temperature presents an interesting contrast with recent findings by Chen et al. (2024) [32], who reported that biochar pyrolysed at 500°C was most beneficial for compressive strength improvement during accelerated carbonation curing (ACC), achieving increases of up to 9.8 % and 7.8 % at early and later stages, respectively.

This apparent discrepancy in optimal pyrolysis temperature can be attributed to several factors. First, the curing conditions differ significantly - our study employed standard curing while Chen et al. (2024) focused on ACC conditions. Second, as highlighted by Murali and Wong (2024) [20], the type of biomass used to produce biochar significantly influences its performance in concrete. The coffee-based biochar in our study may have different optimal pyrolysis conditions compared to other biomass sources.

Fig. 6(c) shows the 54-day test results from the field trial concrete samples cored out of the concrete footpath slab extension. These results show relatively better results than the concrete samples collected from the fresh concrete at the time of the pour and cured offsite at the lab facility. This indicates that beyond 28 days of curing, the water saturation within the biochar particles helps in the further hydration of cement particles, resulting in an improvement in concrete strength relative to the control mix.

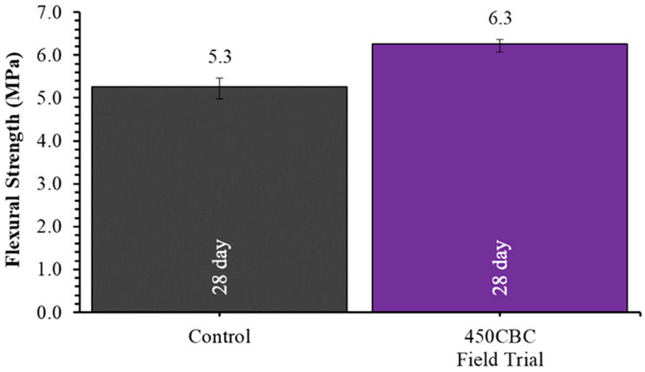

Fig. 7. Flexural strength results of field trial concrete samples.

3.3. Flexural strength results of concrete

Fig. 7 shows the flexural strength test results of the field trial concrete samples of control and biochar blended concrete mixes. The biochar blended concrete mix showed an 18.9 % increase in the 28-day flexural strength compared to the control mix. This can most likely be attributed to (i) Microstructure modification: Biochar particles may act as micro-fillers, potentially reducing some voids and creating a more intricate pore network, resulting in the improvement in stress distribution under flexural loading, (ii) Biochar's high porosity can lead to improved internal curing by retaining water and releasing it gradually during the hydration process. This could result in better hydration product formation, especially beneficial for the interfacial transition zone, which plays a crucial role in flexural strength.

Looking at these results in the context of existing literature, the 18.9 % improvement in flexural strength in our field trial presents an interesting contrast to several previous findings. For instance, Gupta et al. [33] reported that incorporating 5 % biochar from food and rice wastes actually led to 14 % and 18 % reductions in flexural strength, respectively, which they attributed to cement dilution effects and biochar particle accumulation. Similar negative impacts on flexural strength with higher biochar content were observed by Khushnood et al. [34], Ahmad et al. [35] and Falliano et al. [36].

The positive results in our field trial are more aligned with findings from Muthukrishnan et al. [37], who demonstrated that rice husk biochar could enhance flexural strength in mortar mixtures containing rice husk ash as a replacement of Portland cement. They attributed this improvement to biochar's pore-filling effect, which creates stronger linkages between concrete components and increases composite flexibility. Cosentino et al. [38] observed similar positive effects when using biochar as a nanomaterial.

Gupta and Kua [39] found that moist curing is crucial for biochar-modified cementitious composites, as air curing resulted in decreased flexural strength. Their subsequent research [31] further confirmed that moist curing produces more effective results than air curing for biochar-incorporated composites.

3.4. Shrinkage test results of concrete

Fig. 8 shows the shrinkage test results of the field trial concrete samples of control and biochar blended concrete mixes. The coffee biochar blended concrete mix shows a consistent improvement in the shrinkage properties. This improvement in the shrinkage properties could most likely be from the following potential reasons:

(1) Internal curing effect: Biochar's ability to absorb and release moisture could create a buffering effect, helping to maintain more stable moisture conditions within the concrete. This could lead to reduced differential shrinkage and overall improved dimensional stability. In addition, this water is then gradually released during the curing process, acting as an internal curing agent. This mechanism can lead to more complete hydration of cement particles and reduce self-desiccation, thereby minimising shrinkage. A similar reduction in concrete shrinkage due to the internal curing of concrete has been reported by several authors [40–42].

(2) Pore structure modification: Biochar particles likely alter the concrete's pore structure, potentially leading to a more refined and disconnected pore network [43]. This can reduce the capillary tension in the pore system, which is a primary driver of drying shrinkage [44].

The observed reduction in shrinkage with coffee biochar-blended concrete aligns with several studies in the literature, though the mechanisms and extent of improvement vary depending on biochar characteristics and dosage. Mo et al. [45] reported a 16.3 % reduction in autogenous shrinkage (from −580 to −485 microstrain) when using biochar as 2 wt% cement replacement at 180 hours, with an associated 5.5 % increase in internal relative humidity. Their findings support our hypothesis regarding the internal curing mechanism, as they demonstrated that biochar's internal curing effect not only reduced shrinkage independently but also enhanced the shrinkage compensation effect when combined with expansive additives. Furthermore, they found that this improvement in shrinkage properties came without compromising compressive strength, indicating biochar's potential as an effective shrinkage-reducing admixture.

However, the literature presents some contrasting results that warrant discussion. While our results show consistent improvement in shrinkage properties, Sirico et al. [46] found that 5 % biochar addition did not significantly alter shrinkage compared to plain concrete specimens. This divergence might be attributed to differences in biochar properties and preparation methods. Interestingly, Rashid et al. [47] observed even more dramatic effects with Junglee Keekar biochar, but in the opposite direction - reporting substantial shrinkage increases of 96 % and 60 % at 7.5 % and 10 % concentrations respectively, particularly after 25 days. The more moderate improvements observed in our study with coffee biochar suggest that biochar source and characteristics significantly influence shrinkage behaviour, with some types potentially increasing rather than decreasing shrinkage.

The timing and progression of shrinkage behaviour in our results merit comparison with previous findings. Gupta et al. [48] showed that all biochar mixes exhibited higher initial shrinkage (during the first 4 days) compared to plain mortar, with 1 % BC300 and BC500 increasing early shrinkage by 26 % and 12 % respectively. The increased shrinkage effect diminished after 4 days, with shrinkage increments ranging between 6 % and 12 % for most mixes, and 1 % BC500 even showing a slight reduction compared to plain mortar. This contrasts with our coffee biochar specimens, which demonstrated consistent improvement throughout the 56-day period (Fig. 8), highlighting how the source material and pyrolysis conditions can significantly influence shrinkage behaviour.

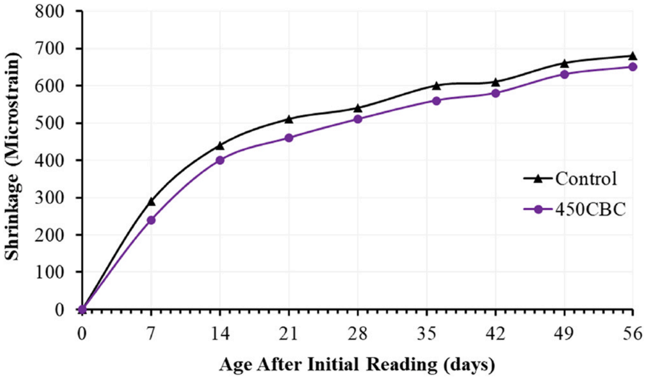

Fig. 8. Concrete Shrinkage results of field trial samples.

4. Conclusions

Test results from the field trial have been promising, showing better performance compared to our laboratory findings of 500CBC coffee biochar concrete, noting that the pyrolysis of spent coffee grounds for the field trial was carried out at 450 °C temperature.

However, the major limitation of this field trial was the significant reduction in the strength properties of coffee biochar blended concrete when compared to our best-performing lab test results of 350CBC biochar concrete. This was due to the inability of the biochar-producing company to operate its pyrolysis equipment at the optimal low temperature of 350 °C.

Based on the test results, the following conclusions can be drawn:

(1) Slump test: Wet coffee biochar improved concrete workability despite water content compensation in the mix design, suggesting beneficial effects on fresh concrete properties.
(2) Concrete compressive strength: Biochar performance was strongly influenced by pyrolysis temperature, with 350°C showing optimal results compared to 500°C. The field trial biochar (450°C) exhibited intermediate performance, with continuous strength improvement up to 54 days due to water-saturated biochar's enhanced hydration effects.
(3) Flexural strength: The biochar-modified concrete showed an 18.9 % increase in 28-day flexural strength through combined effects of microstructure modification and internal curing, optimising both pore network and hydration product formation.
(4) Shrinkage test: Biochar incorporation improved dimensional stability through enhanced internal curing and pore structure modification, leading to better moisture regulation and reduced shrinkage potential.

CRediT authorship contribution statement

Shannon Kilmartin-Lynch: Writing – review & editing, Visualization, Validation. **Rajeev Roychand:** Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chun-Qing Li:** Writing – review & editing, Visualization, Supervision. **Mohammad Saberian:** Writing – review & editing, Visualization, Validation, Investigation, Data curation. **Jie Li:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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