
Research article

Coupled effects of treated wastewater and sewage sludge biochar on performance and resource efficiency of low-carbon cement mortar

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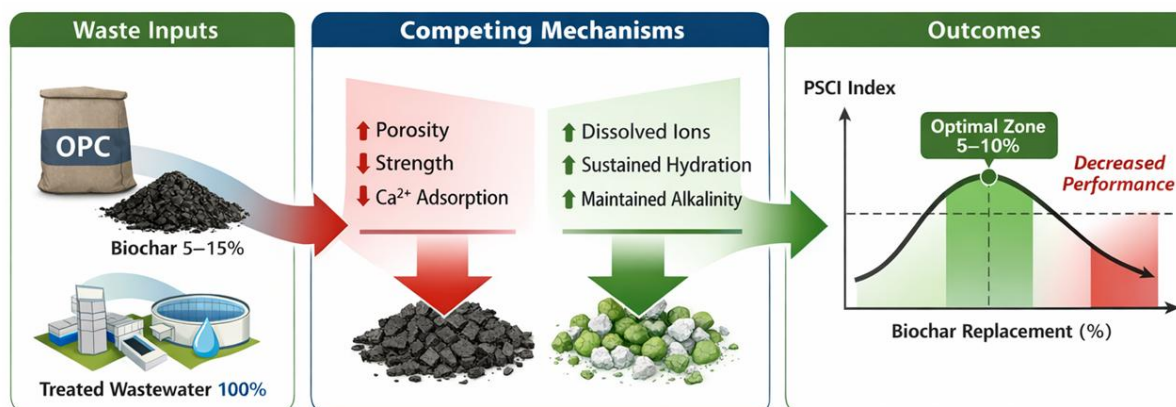
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Abstract: This work studied the properties of low-carbon cement mortars with biochar from sewage sludge replacing 5–15 wt% of ordinary Portland cement and treated wastewater instead of drinking water for mixing. The flowability, compressive and flexural strength, ultrasonic pulse velocity (UPV), and water absorption were measured to evaluate the effect of the two waste-derived components on fresh, mechanical, and transport properties. Workability and strength decreased with an increase in biochar dosage, particularly at 15% replacement, mainly due to a reduction in reactive binder availability and an increase in pore volume. Mortar mixed with treated wastewater, by comparison, approached the control strength and UPV at later ages despite a small early-age reduction. At 5%–10% biochar, the combined mixtures retained more of their performance than the 15% mixture, reflecting the competing effects of water retention and pore development. A Performance-Sustainability Coupled Index (PSCI) was therefore formulated from normalized engineering and resource-efficiency terms. Within the mixtures tested, OPC-SW had the most favorable overall PSCI, whereas 5% biochar produced the best balance among the biochar-containing mortars; this balance deteriorated as replacement increased to 10%–15%. Thus, the wastewater investigated here can serve as an alternative mixing source, but the biochar dosage must be controlled. The PSCI offers a comparative means of

screening waste-integrated mortars when performance retention and resource savings must be considered together.

Keywords: Ordinary Portland Cement (OPC); sewage sludge biochar (SSB); wastewater (WW); ultrasonic pulse velocity (UPV); water absorption (WA); performance–sustainability coupled index (PSCI)



Graphical abstract

1. Introduction

Portland cement production draws heavily on raw materials and energy and remains a major source of emissions. Cement manufacture is commonly assigned about 7%–8% of global CO₂ emissions [1], much of it arising from limestone calcination and the heat required for clinker production [2]. Concrete needs large quantities of suitable water in the mixing and curing processes. In this sense, related research topics are the decrease in demand for clinker, water reuse, and the search for possible uses of compatible wastes [3,4].

A mere evaluation of strength does not tell if a waste-modified mortar is a good option. Lowering the clinker content can save raw materials, but it may lead to a more porous structure, albeit with an acceptable load-bearing capacity, without reducing freshwater consumption. Recent assessments include mechanical performance [5], durability and environmental metrics [6], and resource requirements [7]. In a circular model for construction materials, it is important to simultaneously consider the reduction of clinker, water saving, and waste reuse [1,2,4,8–11].

Biochar is relevant here because its carbon-rich grains combine high porosity with a comparatively large surface area [12]. They can retain part of the mixing water, yet the same features may disturb packing and the early hydration environment. Gupta et al. [13], for example, reported that replacing 10%–15% of the binder lowered 28-day compressive strength by roughly 25%–40%. They associated the reduction with less C₃S and C₂S, additional capillary voids, and Ca²⁺ adsorption onto biochar surfaces, which may reduce the calcium available for C-S-H nucleation [14]. Beyond about 8% dosage, total porosity has been reported to increase by nearly 30%, with more pores in the 10–50 nm interval; both compressive and flexural strengths then declined [14].

At low replacement, however, biochar need not behave in the same way. Ahmad et al. [15] observed higher bound-water content and cumulative heat at 56 days when dosage did not exceed 5%.

Their calorimetry and thermogravimetric data suggest that water initially held by the particles was subsequently available to the hydrating binder [15]. That study established an internal-curing effect, but it did not investigate chloride transport, carbonation, or changes in mixing-water quality. Its findings, therefore, cannot by themselves describe the durability of a mortar containing both biochar and wastewater.

Table 1. Summary of previous studies and the research gap addressed.

Study	Materials used	Key focus	Key findings	Identified gap
[10]	Several wastewater types	Untreated industrial wastewater	Untreated wastewater produced strong pavers, and machine learning was used to predict performance.	The application of treated wastewater remains underexplored.
[13]	Biochar + OPC	Mechanical properties of biochar-modified mortar	Strength decreases with increasing biochar content because of dilution and increased porosity.	No approach to mitigate strength loss; interaction with alternative mixing water was not examined.
[16]	Wastewater + SCMs	Durability and microstructure	Acceptable durability performance was observed under controlled conditions.	Biochar and other porous carbon materials were not considered.
[17]	Biochar at low replacement levels	Internal curing and hydration	Low biochar content improved later-age hydration.	Durability evaluation was limited, and combined material systems were not investigated.
[18]	Treated wastewater	Effects on hydration and strength	Compressive strength was comparable to the control, with a minor early-age delay.	The study was limited to water substitution without integration with supplementary materials.
[19]	Sewage sludge biochar + cement composites	Microstructural effects	Biochar increased porosity and altered the pore structure.	Compensatory mechanisms for mitigating adverse effects were not investigated.
[20]	Waste-derived materials in cement	Sustainability assessment	Environmental benefits of incorporating waste-derived materials were demonstrated.	An integrated performance–sustainability assessment framework was lacking.
Present study	Sewage sludge biochar + treated wastewater	Coupled system behavior and sustainability	Identifies an optimal replacement range of 5%–10% for achieving balanced performance.	Investigates the coupled engineering performance of sewage sludge biochar and treated wastewater and introduces the PSCI framework for integrated performance–sustainability evaluation.

Freshwater demand has also motivated the use of treated wastewater in place of potable mixing water. Li et al. used municipal secondary-treated water with total dissolved solids in the range of 500–

900 mg/L and found that 28-day compressive strengths remained within $\pm 5\%$ of potable water controls, although early-age strength (7 days) was delayed by 7–10% [21]. They attributed this behavior to the dissolved ionic constituents present in the treated wastewater, although the underlying mechanisms remain subject to ongoing investigation. Silva et al. [16] extended such analyses to systems with supplementary cementitious materials (SCMs) and showed that treated wastewater could be used without detrimental effects on chloride migration coefficients or capillary absorption, provided that sulfate and chloride concentrations remained below threshold limits [16]. However, these studies were limited to evaluating treated wastewater as a single substitution parameter, without integration with other waste-derived materials such as biochar.

The studies summarized in Table 1 leave a fragmented evidence base. Work on biochar has mainly explained why strength and pore structure change, whereas work on wastewater has tested whether an alternative water source is acceptable. Few experiments bring these two materials into the same mortar. A second gap concerns evaluation: freshwater saving and cement replacement are normally reported separately from strength and transport measurements. This makes it difficult to decide whether a loss in one property is justified by gains elsewhere.

Three unresolved issues follow from Table 1. Strength loss becomes increasingly evident above low biochar dosages, and no broadly accepted mitigation route has emerged. Treated wastewater has performed satisfactorily when studied alone, but its contribution in a multi-waste mixture remains uncertain. Most importantly, little evidence is available on mortars containing both treated wastewater and biochar, including whether wastewater-borne ions alter the response of biochar-containing matrices.

A further difficulty is how to judge a mixture that saves resources but loses part of its engineering performance. Published studies commonly list strength, porosity, or hydration results separately, which makes the overall trade-off difficult to interpret. Integrated assessment has consequently gained importance in resource-efficient infrastructure research [22,23]. In this study, the Performance-Sustainability Coupled Index (PSCI) brings the selected mechanical, durability-related, and resource-saving terms into one comparative value. It is intended to support mixture screening, not to replace the individual test results.

Against this background, we prepared mortars in which sewage sludge biochar replaced 5, 10, or 15 wt% of OPC, and treated wastewater replaced all potable mixing water. The test program covered flowability, compressive and flexural strength, UPV, and water absorption. We use these measurements to assess the effects of dilution and changes in engineering performance, while possible roles of pore characteristics, retained water, and dissolved ions are discussed in relation to the observed results and relevant literature. Finally, PSCI values are calculated to compare property retention with the quantities of cement and freshwater replaced.

2. Materials and methods

2.1. Raw materials

The ordinary Portland cement was supplied by Maple Leaf Cement Factory Pvt. Ltd., meeting the relevant ASTM requirements. ASTM C109 graded sand was used in every mixture so that changes in the measured response were not influenced by variations in the fine aggregate.

Treated water came from the plant-based unit operated by the Department of Agricultural Engineering at Bahauddin Zakariya University, Multan. Treatment in this unit consists of biological

filtration followed by phytoremediation. We collected the effluent in sealed containers and used it without further chemical adjustment, thereby retaining the composition produced by the unit. Table 2 lists the measured water-quality variables and the comparison values reported in [24].

Table 2. Measured wastewater quality and the corresponding desirable levels in ASTM C1602/C1602M.

Components	Units	Values	Desirable level (ASTM C1602/C1602M)
COD	mg/L	46	10
BOD	mg/L	37	5
TSS	mg/L	59	30
DO	mg/L	3.7	5
TDS	mg/L	197	500
TN	mg/L	140	Not specified (performance-based)
TP	mg/L	141	–

The TDS was within the ASTM C1602/C1602M limit, whereas COD, BOD, and TSS were above the respective limits, as shown in Table 2. After the biological and phytoremediation processes, the effluent was not totally free of organic substances and suspended particles. This distinction constrains the interpretation: the results are for a particular effluent after a particular treatment process, not for treated wastewater in general. Therefore, a resource for field application must be independently tested, as source water and treatment methodology may change the interaction with cement.

Sewage sludge was collected from the same treatment plant, dried to constant weight, and converted into biochar by slow pyrolysis in a muffle furnace under oxygen-limited conditions at 400–450 °C for 2 h. After natural cooling, the biochar was ground and sieved to obtain a uniform fine fraction suitable for incorporation into mortar mixtures. The biochar production process is illustrated in Figure 1. The chemical composition of the biochar was determined using X-ray fluorescence (XRF) spectroscopy, and the results of biochar and all types of cements, expressed as weight percentages of major oxides, are summarized in Table 3. A ternary plot showing Al_2O_3 -CaO-SiO₂ composition of the OPC and sewage biochar is presented in Figure 3. The particle size distribution of different materials is shown in Figure 2; the D50 of OPC and biochar is 21.0 and 12.0 μm , respectively.

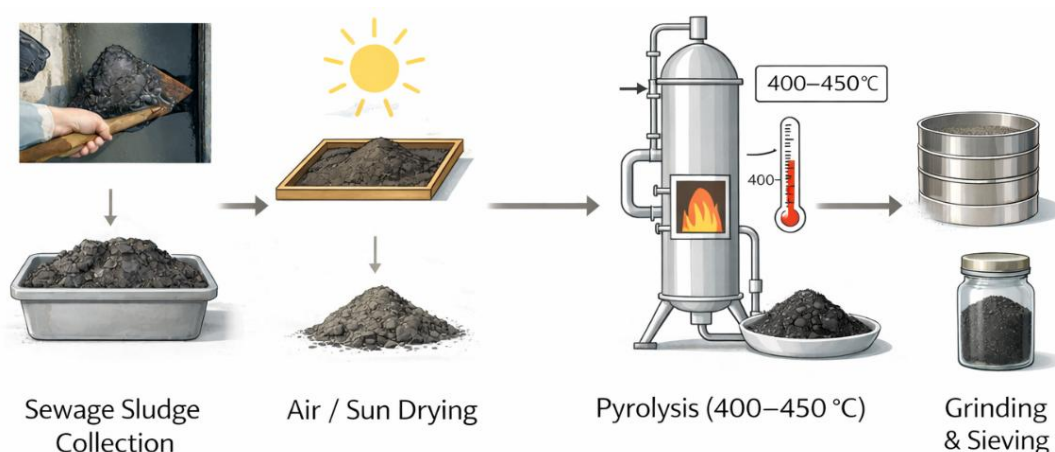
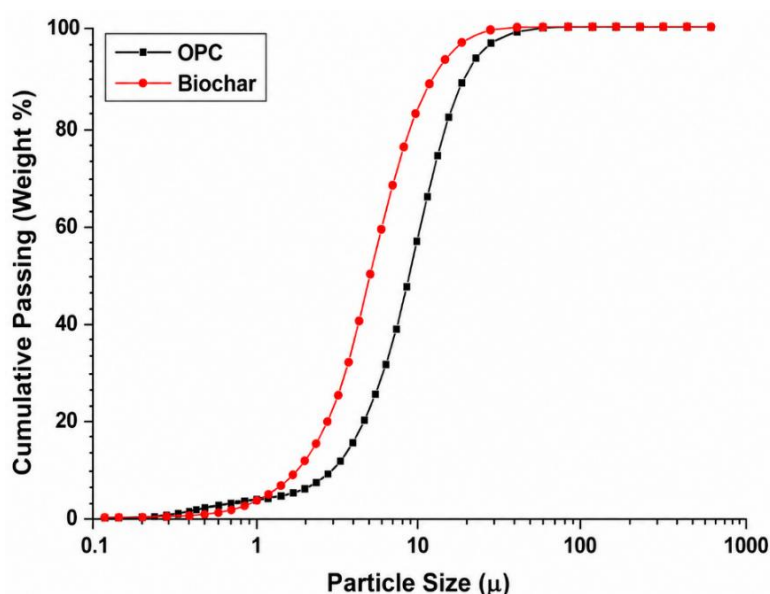


Figure 1. Collection and preparation of biochar.

Table 3. Chemical composition of biochar and sewage sludge-based binary OPC blends.

Oxide%	OPC-5SB	OPC-10SB	OPC-15SB	OPC	Biochar
SiO ₂	18.79	21.95	20.3	19.4	60.3
Al ₂ O ₃	4.37	5.3	4.84	4.8	11.49
Fe ₂ O ₃	3.63	3.94	3.8	3.5	4.42
CaO	53.84	50.23	50.22	61	5.37
MgO	1.14	1.4	1.25	2.7	2.39
K ₂ O	1	0.94	1.15	0.3	1.96
Na ₂ O	0.42	0.51	0.53	0.8	1.29
SO ₃	2.32	2.18	2.23		0.5
C ₃ S	10.9	19.2	5.86	55.97	0.01
C ₂ S	27.4	70.42	53.83	13.4	20.5
C ₃ A	5.44	7.39	6.39	6.74	—
C ₄ AF	11.05	11.98	11.58	10.78	—
LOI	—	—	—	2.5	20.5

**Figure 2.** Particle size analysis of OPC and sewage sludge biochar.

The column labels OPC-5SB, OPC-10SB, and OPC-15SB denote anhydrous binary blends of OPC and sewage sludge biochar (SB) containing 5, 10, and 15 wt% cement replacement, respectively, and do not involve treated wastewater (SW). The chemical composition of the biochar was determined using X-ray fluorescence (XRF) spectroscopy. The oxide composition and clinker phase composition of OPC were obtained from Maple Leaf Cement Factory. The C₃S, C₂S, C₃A, and C₄AF contents reported for OPC were calculated using the standard Bogue equations. The corresponding values for the OPC–biochar blends were calculated according to the respective biochar replacement levels and are therefore reported as calculated estimates rather than experimentally measured phase contents, as described in Table 3.

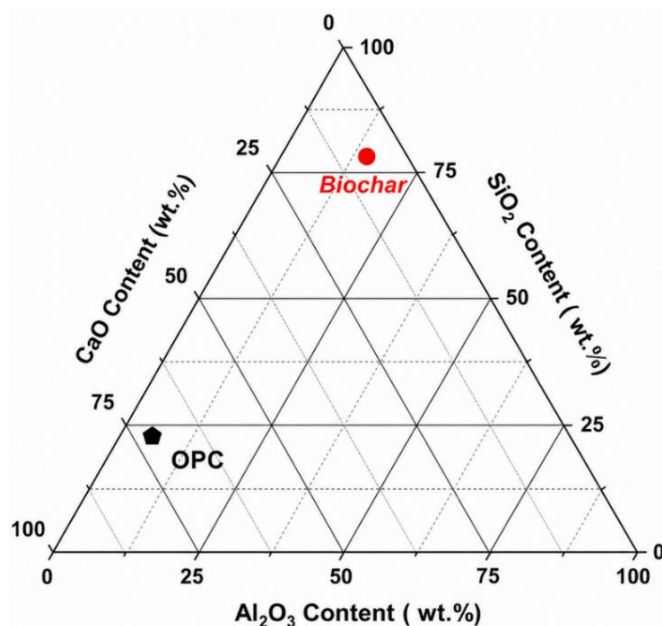


Figure 3. Ternary plot showing Al_2O_3 -CaO-SiO₂ composition w.r.t OPC.

2.2. Formulation of mortar blends

Mortars were prepared according to ASTM C109 [25]. Each batch had a ratio of 1 : 2.75 of cement to sand and a ratio of 0.50 of water to binder. These ratios were purposely set so that any changes in the response could be attributed to the waste-derived inputs and not to changes in the quantities of water or aggregate.

The reference mortar consisted of OPC and drinking water. The experimental batches were then treated with wastewater, biochar, or both, with wastewater replacing all mixing water supply and biochar replacing a stated fraction of cement. Several dosages were tested to follow the performance response to varying biochar content and to identify the point at which performance begins to deteriorate appreciably. Prior to mixing, the biochar assigned to a batch was lightly wetted with water from that batch. This step decreased its immediate absorption of free water and helped distribute the fine particles. The cement, sand, and the rest of the dry biochar were blended slowly. The liquid was added in installments and then mixed at a higher speed until the mortar looked uniform.

Fresh mortar was cast into cube molds of $50 \times 50 \times 50$ mm for compressive strength testing and prismatic molds of $40 \times 40 \times 160$ mm for flexural strength and ultrasonic pulse velocity measurements [26]. Specimens were compacted in layers to eliminate entrapped air and were subsequently sealed to prevent moisture loss during the initial curing period. After 24 h, specimens were demolded and cured in water at 20 ± 1 °C until the designated testing ages of 3, 7, and 28 days. Treated wastewater was used exclusively as the mixing water for the designated mixtures, whereas all specimens were cured in potable water until the specified testing ages.

Table 4. Mix proportion of binary and ternary blends.

Mix no.	Mix type	Acronym	OPC (kg/m ³)	Sand (kg/m ³)	Biochar (kg/m ³)	Fresh water (L/m ³)	Wastewater (L/m ³)	Biochar replacement (wt%)	w/b ratio
Mix-1	Single	OPC	2319	6377.3	0	1159.5	0	0	0.5
Mix-3	Single	OPC + SW	2319	6377.3	0	0	1159.5	0	0.5
Mix-2	Binary	OPC + SB	1971.2	6377.3	347.8	1159.5	0	15	0.5
Mix-4	Ternary	OPC + SW + 5SB	2203.1	6377.3	115.9	0	1159.5	5	0.5
Mix-5	Ternary	OPC + SW + 10SB	2087.1	6377.3	231.9	0	1159.5	10	0.5
Mix-6	Ternary	OPC + SW + 15SB	1971.2	6377.3	347.8	0	1159.5	15	0.5

Note: OPC = control mortar (potable water, no biochar); OPC + SW = mortar prepared with 100% treated wastewater and no biochar; OPC + SB = binary OPC–biochar mortar with 15 wt% biochar replacement (potable water); OPC + SW + 5SB/10SB/15SB = ternary mortars prepared with 100% treated wastewater and 5, 10, or 15 wt% biochar replacement, respectively. Biochar replacement (wt%) is the mass fraction of OPC replaced by biochar. w/b ratio is the total mixing liquid (fresh water and/or wastewater) divided by total binder mass (OPC + biochar).

2.3. Performance–Sustainability Coupled Index (PSCI)

We calculated PSCI as a screening tool, not a substitute for the measured results [27]. The calculation is based on three measured responses, which inform different aspects of mortar behavior. The compressive strength describes the load resistance, the UPV indicates the continuity of the hardened matrix, and the water absorption indicates the access through connected pores. Taking them together avoids a mixture scoring well simply because it maintains strength while its transport behavior deteriorates. Since no end use was specified, we gave them equal weight. The governing performance requirement might justify a different weighting for a given application. Equal weighting was used in this study because the three selected performance parameters were considered to have equal importance in the overall PSCI assessment, rather than assigning greater weight to any individual parameter based on a specific end-use application.

Equation (1) gives the form of PSCI:

$$\text{PSCI} = \left(\frac{f_c}{f_{c,\text{ref}}} \right)^\alpha \times \left(\frac{\text{UPV}}{\text{UPV}_{\text{ref}}} \right)^\beta \times \left(\frac{W_{A,\text{ref}}}{W_A} \right)^\gamma \times (1 + R_c + R_w) \quad (1)$$

In Eq. (1), f_c and $f_{c,\text{ref}}$ denote the compressive strengths of the mixture and OPC control, respectively; UPV and UPV_{ref} are the corresponding ultrasonic pulse velocities; and W_A and $W_{A,\text{ref}}$ are their water-absorption values. R_c is the fraction of OPC replaced by biochar, whereas R_w is the fraction of potable water replaced by treated wastewater. Parameters α , β , and γ specify how strongly the index responds to strength, matrix continuity, and durability-related behavior, respectively.

Each engineering term is normalized against OPC. Because greater absorption is undesirable, it enters as $W_{A,\text{ref}}/W_A$; under this form, reduced water uptake raises the score. Cement and potable water savings are introduced through $(1 + R_c + R_w)$. The base calculation sets α , β , and γ to unity, so none of the measured properties receives an additional mathematical weight.

The calculation included only the 28-day measurements. The measured values and their normalized forms are listed in Tables 5 and 6, and the resulting comparisons are shown in Figures 9

and 10. Hence, the reported values of PSCI are for six mixtures at a single age and under the assumptions of the present formulation. PSCI is neither a life-cycle assessment nor a reason to accept substantial deterioration in engineering performance. The basis for judging the suitability of a mixture, together with the underlying strength, is the UPV and absorption results.

3. Results and discussion

The discussion below keeps measured evidence separate from mechanistic interpretation. Flow, strength, UPV, and absorption came directly from experiments. Explanations involving hydrate formation, connected porosity, or pore-solution chemistry are instead inferred with support from earlier studies. As XRD, TGA/DTG, SEM, MIP, and pore-solution measurements were outside the experimental program, these explanations should be regarded as provisional.

3.1. Experimental setup

Fresh-state behavior was examined through flow spread, normal consistency, and setting time. Flow was measured according to ASTM C1437 [25]; the Vicat consistency and setting tests followed ASTM C187 and ASTM C191 [28]. Each condition was tested three times at 20 ± 2 °C; the values reported here are the arithmetic means.

Compressive and flexural tests were conducted after 3, 7, and 28 days. The compressive specimens were 50 mm cubes tested on a Shimadzu universal machine in accordance with ASTM C109 [28]. Three specimens were tested per mixture and age, and reported values are the arithmetic means. For flexure, $40 \times 40 \times 160$ mm prisms were loaded at the center, following ASTM C348 [29]. Loading continued at 2640 ± 110 N/min until failure, and the maximum load was used to obtain flexural strength. Reported values are means of three specimens.

Water absorption was measured at the same three ages using ASTM C642 [28]. Each 50 mm cube was weighed in the saturated surface-dry condition, dried for 24 h at 105 °C, and weighed again. Equation 2 was then used to calculate absorption.

$$\text{Water Absorption (\%)} = \frac{W_{\text{wet}} - W_{\text{dry}}}{W_{\text{dry}}} \times 100 \quad (2)$$

UPV was measured through $40 \times 40 \times 160$ mm prisms following ASTM C597. Coupling gel was placed between the transducers and the opposite prism faces. Velocity was obtained from the measured travel time and the known transmission length.

3.2. Fresh properties of blends

Figure 4 shows that adding biochar reduced flow spread and raised the consistency demand. Its open pore system and large surface area take up part of the mixing water [30], leaving less free water to lubricate the cement and sand grains [31]. The mixture consequently develops greater interparticle resistance. The change became more apparent as the replacement level increased.

Water retention may also be associated with oxygen-containing surface groups that interact with water, which would be consistent with the higher demand of the fine, high-LOI biochar blends [32]. The new mixture was influenced by the treated wastewater of another group of constituents. Dissolved

calcium, magnesium, phosphate, and other species altered the ionic environment. Residual organics may have inhibited wetting or initial particle dispersion. The actions are potentially in conflict; ions can promote flocculation while organics may hinder contact between water and cement. Experimentally, the net effect on flow was small, with spreads measured with wastewater remaining close to the control [30]. The contribution to alkalinity or hydration later on is not verified here, but is plausible from the measured water composition and previous literature [33].

A small delay in setting was recorded after biochar addition. One possible cause is temporary retention of Ca^{2+} or OH^- at the particle surface during the early reaction period, although adsorption was not measured. The delay remained modest when wastewater was also used; despite its greater water demand, the biochar did not make the fresh mortar unworkable. Direct adsorption and early-age pore-solution measurements would be required to separate the contribution of each constituent.

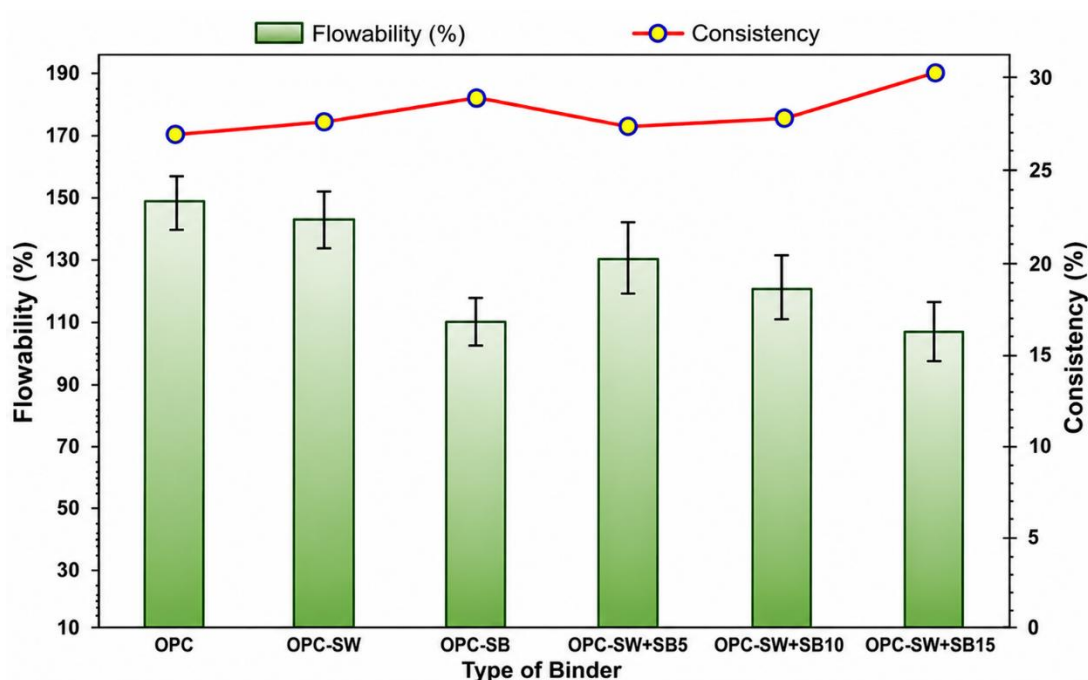


Figure 4. Flowability and consistency of the investigated mixtures.

3.3. Compressive strength development

Figure 5 presents compressive strength at 3, 7, and 28 days. The OPC control followed the expected age-dependent increase. Continued clinker hydration produced a progressively stronger C–S–H framework and, with it, greater load-bearing capacity [34,35]. The remaining mixtures are compared with this reference below.

The use of treated wastewater as a complete replacement for potable water resulted in compressive strength values comparable to the control at later curing ages, although a slight reduction was observed at early ages [36]. This initial reduction may be associated with the presence of residual organic matter, which can temporarily influence cement dissolution and delay early hydration reactions [37]. However, the recovery of strength at later ages suggests that the dissolved ionic constituents present in the treated wastewater may contribute to influencing the pore solution environment and supporting continued

hydration [10]. Within the scope of this study, these effects do not appear to adversely influence long-term strength development.

Strength fell when cement was replaced by sewage sludge biochar [17]. Part of this loss is unavoidable dilution: less clinker is present to form load-bearing hydrates [38]. Packing is also affected because the porous, irregular particles add voids and do not fit the matrix as efficiently as cement [4]. Surface adsorption offers a further possible contribution. Functional groups and pores can retain ions from the cement solution [30,39], potentially changing the Ca^{2+} supply available for C–S–H formation. The present data cannot quantify this chemical contribution because pore-solution composition was not measured. Dilution and increased porosity, therefore, provide a more directly supported explanation for the observed strength loss.

Among the wastewater-biochar mortars, the 5% and 10% mixtures were stronger than the 15% mixture. This establishes a dosage effect within the tested series, with the highest biochar content giving the lowest load capacity. It does not, however, prove that wastewater improved the 5% or 10% mixtures: potable-water counterparts at these two dosages were not included. The clearest interpretation is that dilution and connected pores became dominant at 15% [40]. A restricted replacement range is therefore more suitable where cement saving must be achieved without a large reduction in strength [41].

ANOVA provided only partial statistical support for the strength differences. The mixture effect was significant at 7 days ($F = 3.37$, $p = 0.04$), but not at 3 days ($F = 1.31$, $p = 0.33$) or 28 days ($F = 1.26$, $p = 0.35$). These tests were based on two or three replicates per mixture and consequently have low power. We therefore treat the 3- and 28-day differences as descriptive trends, even where their direction agrees with the proposed material response.

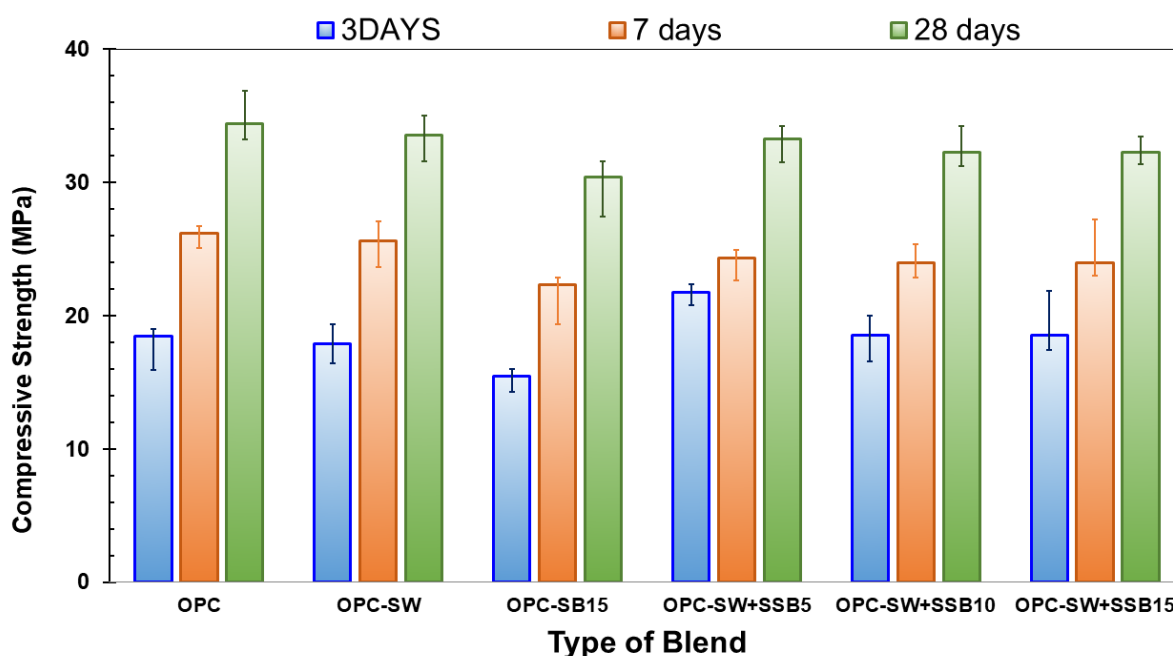


Figure 5. Compressive strength of the OPC, binary, and ternary mixtures at 3, 7, and 28 days.

3.4. Flexural strength development

Flexural strength generally increased with age, as shown in Figure 6, but did not reproduce the compressive ranking exactly. This is expected because bending failure is influenced strongly by a local defect, the paste–aggregate interface, and the point at which a crack first develops.

The OPC specimens developed the highest flexural strength, in keeping with their more continuous paste and stronger paste–aggregate interface [40]. The wastewater mortar was slightly weaker at early age. Residual organics may have delayed some initial hydration [6], but the gap narrowed with curing. Most biochar mixtures also showed lower flexural strength. Under bending, porous and relatively compliant biochar particles may act as local weak points, while their irregular geometry can disturb the interfacial transition zone [17]. At 5%, these effects were limited, and retained water may have supported local hydration as curing progressed [42]. Although the 10% wastewater-biochar mixture marginally exceeded the 5% mixture at 28 days, the difference is too small to establish a favorable dosage effect. Flexural response is sensitive to flaw position and specimen heterogeneity [6]. At 10%–15%, pores and weak interfaces are likely to outweigh internal curing [43]. Dosage should therefore be chosen from both compressive and flexural evidence where cracking matters.

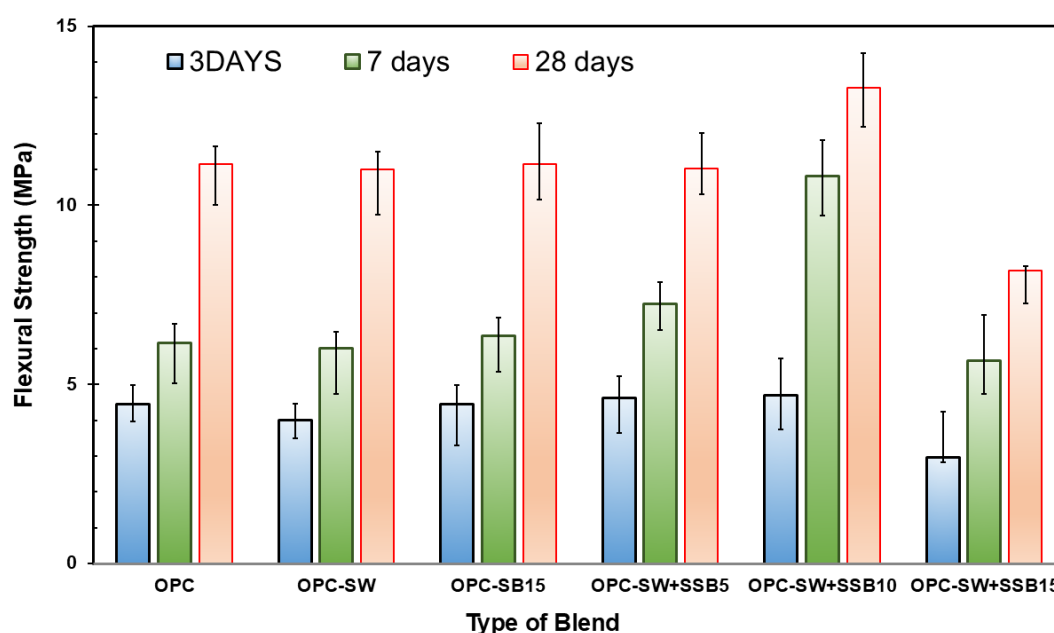


Figure 6. Flexural strength of the OPC, binary, and ternary mixtures at 3, 7, and 28 days.

3.5. Ultrasonic pulse velocity (internal quality and transport-indicators)

Figure 7 reports UPV, which was used as an indirect measure of internal continuity. A pulse travels faster through a continuous solid skeleton than through a matrix interrupted by pores or microcracks [44]. The measurement is therefore useful for comparison, although it does not identify the type or size of a defect.

The OPC specimens recorded the greatest velocities, as expected for the mixture with the most continuous hydrated matrix [44]. Wastewater specimens approached these values at the later ages. Within the sensitivity of the test, complete water substitution did not create a persistent break in the

transmission path [10]. The organic matter and dissolved solids measured in the water therefore produced no evident UPV penalty under the present curing conditions.

Velocity declined as the biochar fraction increased. Pores within the biochar and voids introduced around its irregular particles interrupt the solid path followed by the pulse [45]. The same structural changes also reduce the area available to transfer compressive stress, which explains why the UPV and strength trends moved in the same direction.

At 5% biochar, the wastewater mixture retained a comparatively continuous matrix, and its UPV reduction was modest. Dissolved ions in the water may have contributed, but the experiment did not measure the proposed chemical pathway [46]. Raising biochar to 10% and 15% produced a clearer loss of velocity, consistent with a more heterogeneous internal structure [17]. Thus, the dosage effect is supported by UPV, whereas the suggested wastewater mechanism remains provisional.

Taken together, UPV data identify biochar dosage, rather than water substitution alone, as the main source of lost internal continuity. More biochar produced a less efficient pulse path, in agreement with the strength results.

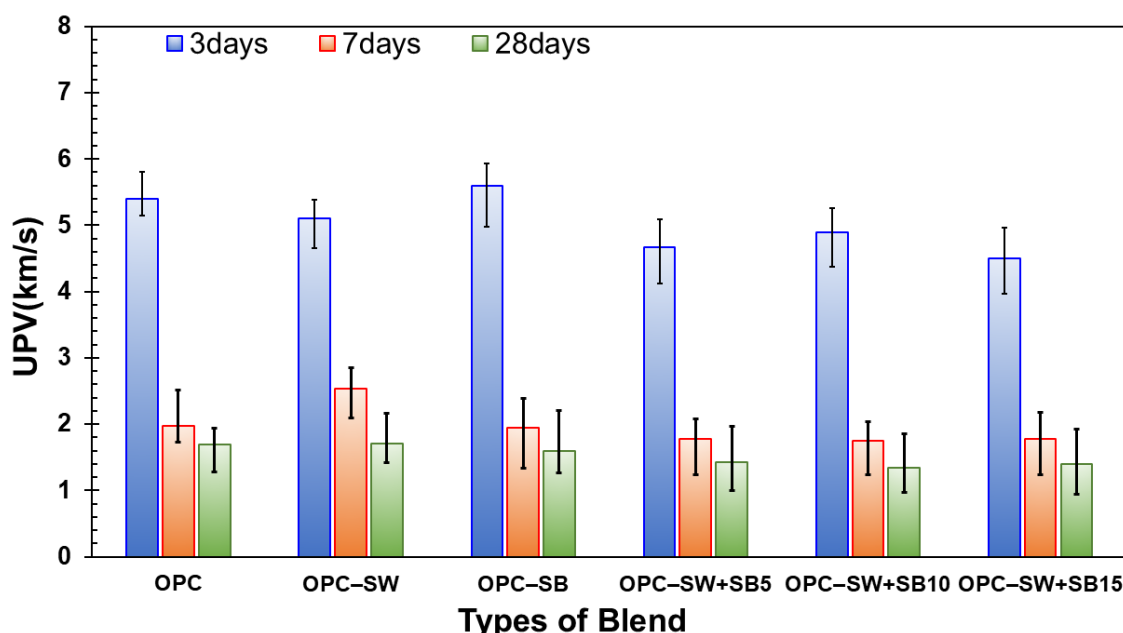


Figure 7. UPV of the investigated mixtures at 3, 7, and 28 days.

3.6. Water absorption

To determine the transport properties and the pore structure characteristics of the mortar systems, water absorption was assessed. The water absorption results are presented in Figure 8. Being a durability-related parameter, water absorption is an indicator of the resistance to fluid ingress of the material, which is directly interconnected with pore size distribution, connectivity, and general densification of the matrix.

The control mixture displayed rather low absorption of water values, which declined slightly with the age of curing as a result of further hydration and gradual improvement of the capillary pore network.

The trend is in line with traditional cementitious systems, in which the development of hydration products like C-S-H leads to pore filling and lower permeability [47].

Mortar mixed only with treated wastewater absorbed approximately the same amount of water as the control, and in some cases, slightly less. Continued hydration in the presence of dissolved ions is one possible explanation [48], but no microstructural test was conducted to verify it. More importantly, the residual organics and suspended solids listed in Table 2 did not produce a measurable absorption penalty during the test period. This finding applies to the sampled effluent and should not be transferred to wastewater of a different origin or treatment history.

Compared with the water-source effect, the influence of biochar on absorption was distinct: values increased at every test age [49]. Biochar contributes its own accessible pore volume and high surface area [50], while cement replacement reduces the amount of hydrate available to refine the capillary network. Its irregular particles may also create open or weak zones near the paste–particle interface [51]. The rise with dosage is therefore consistent with greater pore connectivity, although this experiment cannot separate the contributions of these processes.

In the ternary series, absorption rose only moderately at 5% biochar but more strongly at 10% and 15% [50]. The 15% result deserves particular attention. At 28 days, OPC-SW+SB15 absorbed about 14.7%, compared with approximately 11.0% for the biochar-only OPC-SB mixture—roughly one-third more. Wastewater, therefore, did not mitigate the high-dose response. The combination of dissolved material and an already open biochar-modified matrix may have increased water access, but this cannot be established from absorption alone. MIP or SEM analysis is required before assigning a specific mechanism to this reversal.

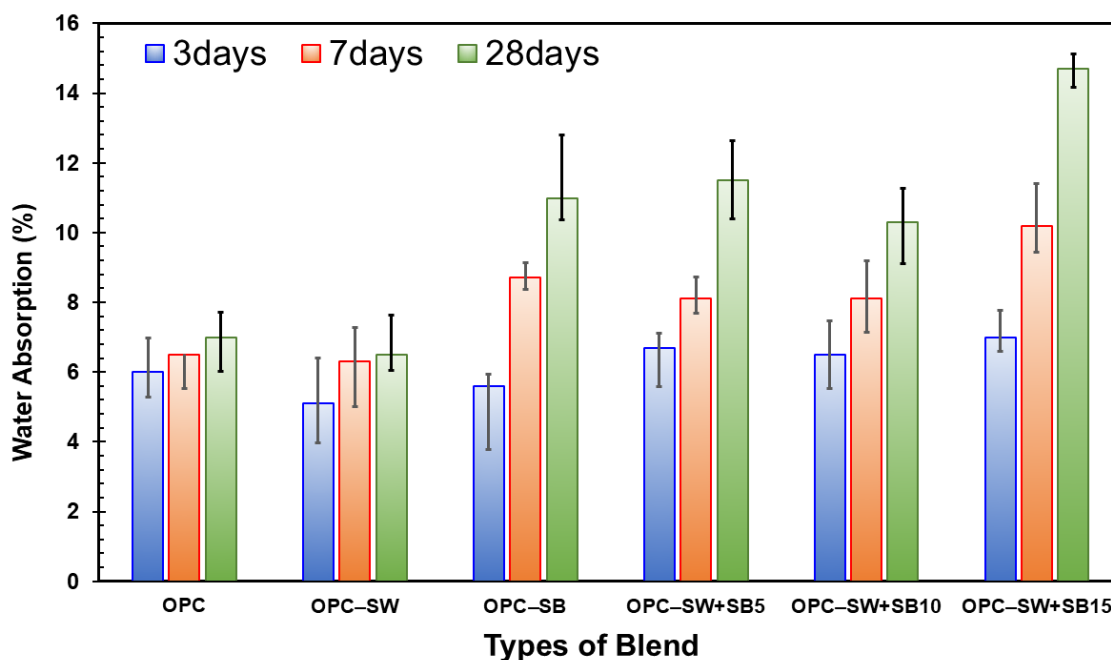


Figure 8. Water absorption of all blends at 3,7 and 28 days.

On the whole, the water absorption findings suggest that treated wastewater used on its own (OPC-SW) does not compromise transport properties relative to the control, but its use in combination with biochar does not consistently mitigate biochar-induced porosity: partial mitigation is observed at

5%–10% biochar replacement, while at 15% replacement, the combination is associated with higher water absorption than biochar alone. The use of biochar, therefore, implies a trade-off between the positive changes in sustainability and the enhancement of porosity, and this trade-off is not uniformly improved by treated wastewater across all replacement levels. It is therefore necessary to control biochar content to sustain reasonable levels of durability-related performance.

3.7. Performance–Sustainability Coupled Index (PSCI)

PSCI was calculated to place engineering retention and resource efficiency on the same comparative scale. Tables 5 and 6 and Figure 9 provide the normalized 28-day inputs, resource factors, and resulting index values, allowing each calculation to be checked.

Figure 9 also reports a simpler Sustainability Index (SI), the arithmetic mean of the four normalized engineering performance ratios shown in the same figure: $SI = [(f_c/f_{c,ref}) + (F_f/F_{f,ref}) + (W_{Aref}/W_A) + (UPV/UPV_{ref})] / 4$, where F_f and $F_{f,ref}$ are the flexural strength of the mixture and control, respectively, and the remaining terms are as defined in Section 2.3 for the PSCI. Unlike the PSCI, SI omits the $(1 + R_c + R_w)$ sustainability term and, as such, isolates the net effect of biochar and treated wastewater on measured engineering performance alone.

To examine the influence of weighting assumptions on PSCI ranking, a sensitivity analysis was performed by varying the relative importance of the selected performance parameters (α , β , γ) and, separately, the strength of the sustainability term $(1 + R_c + R_w)$. For the equal-weight case ($\alpha = \beta = \gamma = 1$), PSCI values were 1.00 (OPC), 2.14 (OPC-SW), 0.53 (OPC-SB), 1.12 (OPC-SW + SB5), 1.06 (OPC-SW + SB10), and 0.78 (OPC-SW + SB15) (Table 6). Under a strength-dominant scenario ($\alpha = 2$, $\beta = 1$, $\gamma = 1$), corresponding values were 1.00, 2.10, 0.47, 1.09, 1.00, and 0.71; under a durability-dominant scenario ($\alpha = 1$, $\beta = 1$, $\gamma = 2$), values were 1.00, 2.31, 0.30, 0.75, 0.72, and 0.37. The ranking order of the mixtures was unchanged in both cases. Because the sustainability term $(1 + R_c + R_w)$ contributes a large, all-or-nothing credit for full wastewater substitution, its own strength was tested separately by rescaling it to $(1 + \lambda R_c + \lambda R_w)$ for $\lambda = 1.0, 0.5$, and 0.25 ; OPC-SW retained the highest PSCI, and 5% biochar retained the highest PSCI among the biochar-containing mixtures, at every λ tested. This indicates that the ranking is driven primarily by genuine differences in engineering performance between mixtures rather than by the specific weight assigned to any single term, and that application-specific weighting strategies, while permissible within this framework, are unlikely to reverse the overall trend identified here.

OPC-SW ranked first by PSCI because its engineering values remained near the control, while all potable mixing water was replaced. The result does not mean that OPC-SW was mechanically superior to OPC. It means that, under the index definition, a small performance difference was accompanied by a large freshwater saving. Individual strength, UPV, and absorption values must therefore be checked alongside the index [52]. The later-age strength and UPV data support this interpretation because both remained close to the reference.

Biochar produced a different balance. At 5% replacement, the saving in cement was accompanied by only a modest loss in the measured properties, and PSCI remained relatively favorable. The index fell at 10% replacement and more strongly at 15%, showing that dilution and associated porosity more than offset the additional cement savings. The order of the ternary series was consistent: the 5% mixture was rated higher than the 10% and 15% mixtures. Given this evidence, a 5%–10% interval is more defensible than going for the largest possible substitution. PSCI is useful as it combines retained

performance, cement reduction, and freshwater reuse in one metric [53,54]. But this is a screening tool; it does not address long-term durability and life-cycle burdens [52].

Table 5. Raw 28-day measurements used as inputs for the PSCI calculation.

Mix	CS (MPa)	FS (MPa)	WA (%)	UPV (km/s)
OPC	34.37	11.15	7	1.69
OPC+SW	33.53	11	6.5	1.71
OPC+SB	30.4	11.15	12.50	1.59
OPC+SW+5SB	33.26	11.03	10.50	1.42
OPC+SW+10SB	32.28	13.28	10.3	1.34
OPC+SW+15SB	31.43	8.18	14.7	1.4

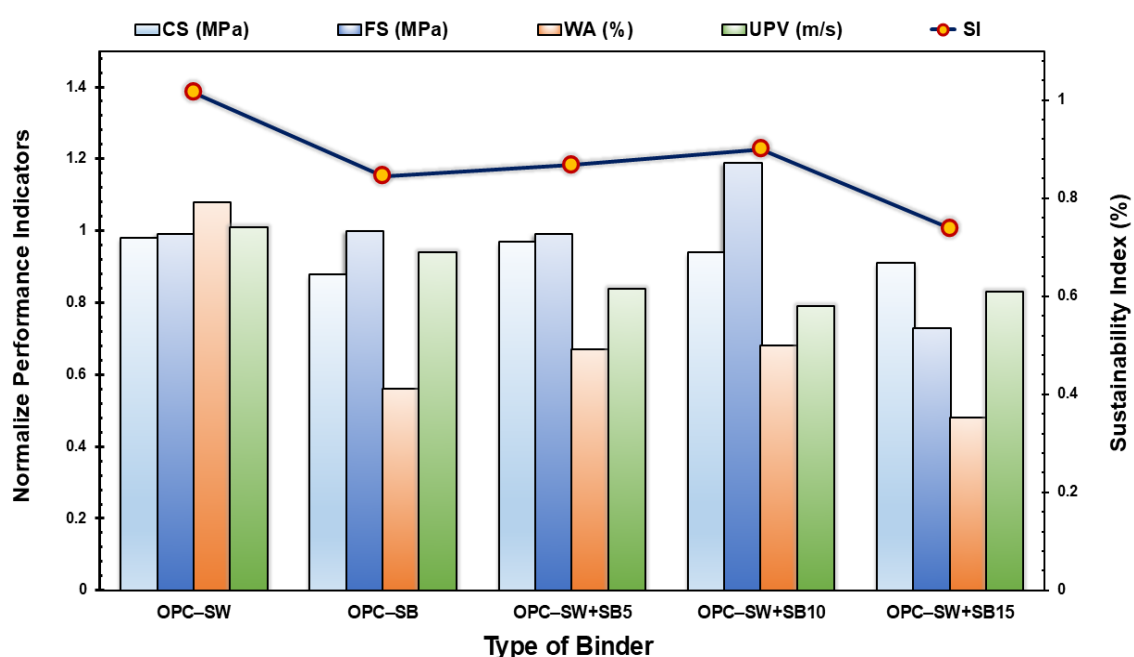


Figure 9. Normalized 28-day property ratios (CS, FS, WA, and UPV), together with PSCI, for each mortar mixture.

4. Analytical discussion on coupled mechanisms and system behavior

Biochar and wastewater affected different parts of the mortar. The addition of biochar altered the quantity and distribution of solids and mixing water, and the wastewater altered the chemistry of the liquid phase. Their combined response was dependent on the biochar content, and the results do not support a common synergistic mechanism for all mixtures.

4.1. Coupled hydration and ion availability

Surface adsorption offers one possible chemical account of the response. Sufficient retention of Ca^{2+} or OH^- by biochar could disturb early C-S-H nucleation and help explain the weaker mixtures at high dosage. Ions carried by the wastewater may partly oppose that effect by sustaining alkalinity and

conductivity in the pore solution [33]. The low-dose behavior is consistent with such compensation, but consistency is not confirmation. Since neither pore-solution composition nor hydrate assemblage was measured, the proposed ionic effect remains a working hypothesis.

4.2. Microstructural evolution and pore network development

The measurements provide firmer support for a physical explanation. Biochar adds pore space, and replacing cement removes clinker that would otherwise generate pore-filling hydrates. The combined result is a less continuous load-bearing skeleton. With increasing dosage, UPV fell, and absorption rose, which is consistent with progressive loss of continuity. With 15% biochar, any favorable contribution from the wastewater was too small to offset the structural penalty.

4.3. Internal curing and localized hydration

Biochar may later release some of the water retained during mixing near still-unhydrated cement grains. This local supply could have contributed to the recovery observed at 5%–10% replacement. Once biochar content increased further, however, clinker dilution and discontinuity of the matrix became more influential; at 15%, internal curing was insufficient to offset the added pore volume.

4.4. Performance–transport relationship

All three response measures describe a consistent deterioration. Mixtures with lower compressive and flexural strength also transmitted the ultrasonic pulse more slowly and absorbed more water. The relationship is physically plausible because a connected pore network both reduces the solid area available to transfer stress and opens pathways for cracking and moisture movement.

Table 6. Input measurements and corresponding 28-day PSCI calculations used in the performance-resource comparison.

Mix	CS/CS _{ref}	UPV/UPV _{ref}	WA _{ref} /WA	R _c	R _w	(1+R _c +R _w)	PSCI
OPC	1	1	1	0	0	1	1
OPC+SW	0.98	1.01	1.08	0	1	2	2.139
OPC+SB	0.88	0.94	0.56	0.15	0	1.15	0.533
OPC+SW+5SB	0.97	0.84	0.67	0.05	1	2.05	1.119
OPC+SW+10SB	0.94	0.79	0.68	0.1	1	2.1	1.06
OPC+SW+15SB	0.91	0.83	0.48	0.15	1	2.15	0.78

4.5. System-level trade-off and PSCI interpretation

The PSCI calculations (Table 6 and Figure 10) provide a comparative assessment of engineering performance alongside the corresponding cement and potable-water substitution levels.

- OPC–SW records the highest PSCI overall, reflecting the combination of engineering performance comparable to the control and complete potable-water replacement. Among the biochar-containing mixtures, the 5% replacement level provides the most favorable balance between engineering performance retention and resource efficiency.

- At 15% biochar replacement, the additional sustainability contribution is outweighed by reductions in engineering performance, resulting in a marked decrease in PSCI.

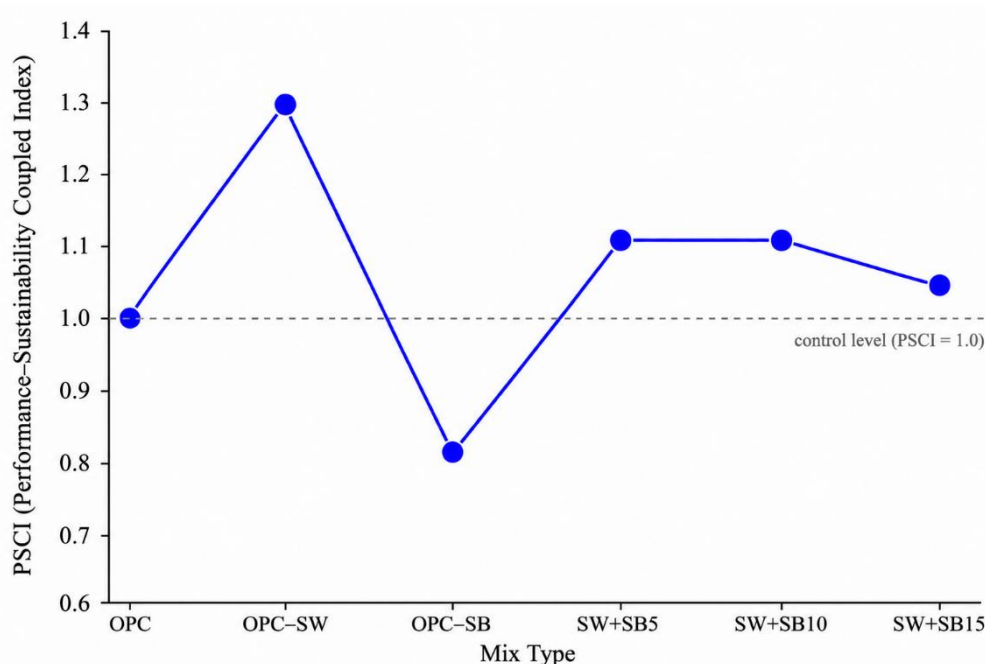


Figure 10. Performance–Sustainability Coupled Index (PSCI) of the investigated mortar mixtures, illustrating the balance between retained engineering performance and resource substitution relative to the control mixture.

4.6. Implications for material design

The results show that a moderate level of biochar addition (5–10) using treated wastewater can result in considerable environmental benefits without a significant level of performance loss. The strategies that can be adapted to reduce the structural constraints in the presence of higher biochar contents include optimization of particle size, surface modification, or additional cementitious materials.

The results support the technical possibility of combining sewage sludge-derived biochar with treated wastewater in mortar, but several limitations define how far the findings can be extended.

To start with, the interaction mechanism between biochar and treated wastewater is not determined using physical and chemical methods, but through macroscopic performance indicators. The parameters of pore solution chemistry, calcium ion concentration, and fine-phase assemblage were not directly quantified. Thus, the proposed compensatory influence of dissolved ions in treated wastewater on biochar-induced imbalance of hydration must be viewed as a possible process and not a proven fact. Additional investigations that include methods like thermogravimetric analysis (TGA), X-ray diffraction (XRD), and extraction of pore solutions are required in the future to confirm the chemical interactions.

Second, the durability test in the research is restricted to water absorption and ultrasonic pulse velocity. Despite the fact that these parameters have valuable information on pore structure and internal integrity, they do not provide a complete picture of long-term durability performance. Critical areas that include resistance to ingress of chloride, carbonation, sulfate attack, and drying shrinkage were not studied and are still a key question to be explored, especially with regard to structural use.

Third, the treated wastewater utilized in this study had physicochemical properties that are beyond desirable limits recommended by ASTM standards, especially organic content (COD, BOD) and suspended solids. Although no notable negative outcomes were noted within the limits of the given research, the variations in the contents of wastewater in various treatment systems can affect reproducibility and long-term functionality. They should also consider standardization of the quality of wastewater or pre-treatment requirements.

Fourth, biochar properties are strongly determined by the type of feedstock and the conditions of the pyrolysis. These results are only applicable to biochar made using sewage sludge in controlled conditions at 400–450 °C. The change in production parameters can have a substantial impact on the surface chemistry, porosity, and adsorption behavior of the material and, hence, its reaction with cement hydration.

Lastly, the mechanical performance results indicate that increasing the biochar replacement level beyond 15% increases porosity and reduces strength. This suggests that the proposed system is more suitable for non-structural or low-load applications at higher replacement levels. Among the biochar-containing mixtures, the most favorable balance between engineering performance and sustainability was observed within the 5%–10% biochar substitution range. Future studies should be aimed at optimizing mix design, surface alteration of biochar, and hybrid material systems to increase the scope of such a green cementitious material blend.

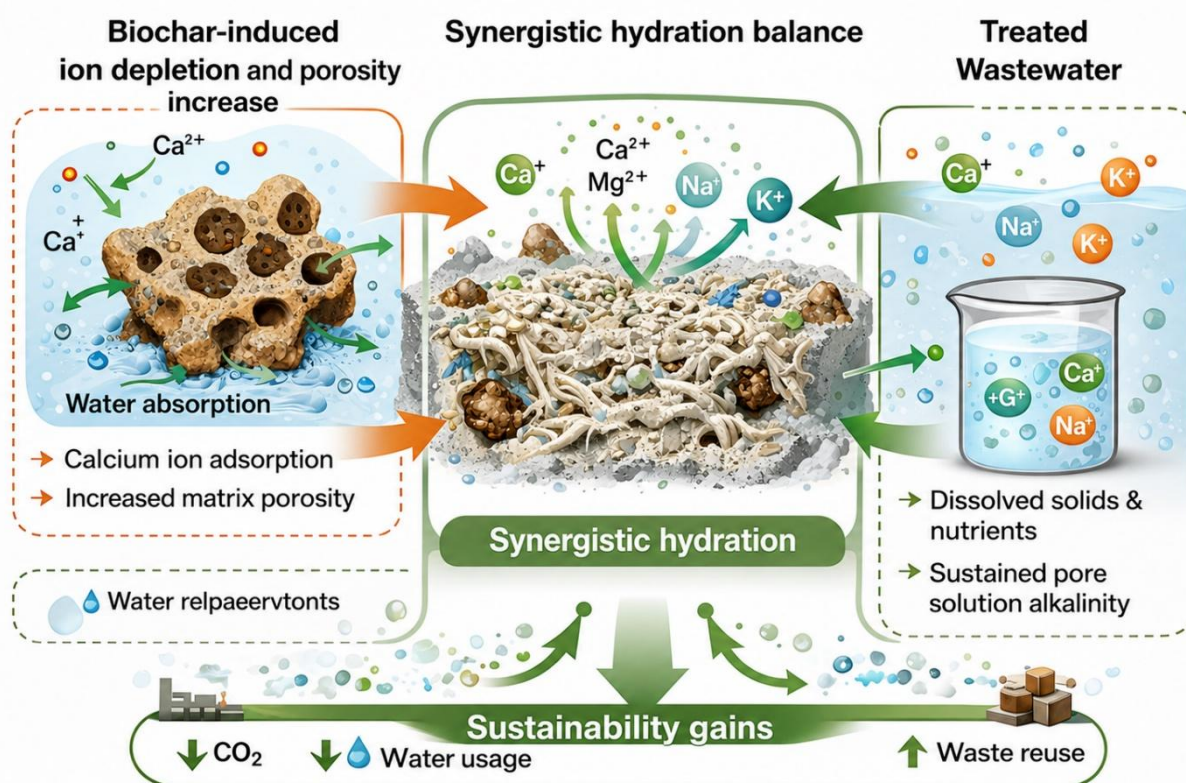


Figure 11. Treated wastewater partially mitigates biochar-induced hydration imbalance, enabling performance–sustainability optimization in low-carbon cement systems.

4.7. Environmental sustainability of sewage-derived materials in cement systems

Using sewage sludge and treated effluent in cement mortar addresses two resource problems at the same time. Pyrolysis converts sludge into a usable carbon-rich solid and reduces the quantity requiring disposal, while its incorporation in mortar can retain part of that carbon in the cementitious matrix. Replacing potable mixing water with treated effluent also creates a reuse route that is particularly relevant in water-stressed regions. The environmental value of the system therefore lies in avoided disposal, lower consumption of virgin resources, and circular use of municipal residuals; a full life-cycle assessment is still required to quantify those benefits.

Figure 11 summarizes the proposed pathways: ion adsorption and added porosity associated with biochar, dissolved ions and alkalinity supplied by the wastewater, and the balance between hydration response and resource saving. The scheme is interpretive rather than direct microstructural evidence.

5. Conclusions

Taken together, the experiments show that treated wastewater and sewage-sludge biochar can be combined in mortar, although increasing replacement does not yield a proportional benefit. The conclusions are limited to the materials, proportions, and curing conditions examined:

- The observed trends are consistent with changes in pore characteristics and matrix continuity, although these mechanisms were not directly characterized in the present study.
- Complete substitution of potable mixing water with the tested effluent still produced later-age properties close to those of the OPC mortar.
- The principal engineering loss was associated with increasing biochar content. Increasing its dosage reduced the clinker fraction and was accompanied by lower strength and UPV and greater water absorption, which may be related to changes in pore characteristics.
- An apparent coupled benefit occurred only at low biochar contents and did not persist as the dosage increased.
- PSCI makes the performance-resource trade-off visible, but it is intended for preliminary screening rather than as a complete measure of sustainability.
- Among the mixtures containing biochar, 5–10 wt% replacement retained the strongest engineering response while still lowering OPC consumption.

The ternary mixtures compared favorably within this experimental set, but 5% and 10% potable-water biochar controls were not included. It is therefore not possible to attribute their response specifically to compensation by wastewater. Confirmation will require direct measurements of hydration, pore architecture, and solution chemistry, supported by longer-term durability testing.

Author contributions

Nosheen Blouch: Conceptualization, Methodology, Investigation, Data curation, Writing—original draft. Muhammad Farhan Hanif: Conceptualization, Supervision, Formal analysis, Validation, Writing—review & editing. Muhammad Fateh Haider: Methodology, Investigation, Validation. Shazia Noor: Formal analysis, Visualization, Writing—review & editing. Maaz Ansari: Investigation, Data curation. Areeba Amjad: Investigation, Data curation. Muhammad Shahid Nawaz: Resources, Writing—review & editing.

Use of AI tools declaration

The authors used AI-assisted tools to refine the language and improve the readability of this manuscript. The authors reviewed and edited the resulting text and take full responsibility for the final content.

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Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Environmental and safety considerations

The experimental work involved cementitious materials and wastewater handling under controlled laboratory conditions. All procedures were conducted following standard laboratory safety and environmental guidelines to minimize potential risks or environmental harm.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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