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The influence of industrial biochar on mortar composites' mechanical properties

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Abstract

CO2 emissions have reached record levels in recent years, and the construction and materials production industries significantly contribute to greenhouse gas emissions. To address this environmental issue, architectural design and civil engineering are trying to adopt strategies such as using less toxic and harmful building materials, controlling energy consumption throughout the structure's life cycle, and implementing new materials such as biochar, a byproduct produced through thermochemical processes that involve limited oxygen, such as pyrolysis or gasification, that have been shown to have the ability to recover energy from treated biomass and provide environmental benefits. This study examines the effects on the mechanical strength of the substitution of cement for biochar in mortar composites. The results show that substituting 1-5% of biochar does not significantly affect mortars' compressive performance, in case of cementitious conglomerates characterized by compressive strength around 50 MPa. Interestingly, results show that the fracture energy can increase up to 30% compared with the reference mortar, without biochar. The results presented in this study justify the use of this material to produce mortars for structural applications.

Keywords: structural mortar; biochar; eco-friendly building materials; fracture energy; compressive strength; flexural strength

1. Introduction

In the last 30 years, global CO2 emissions increased by more than 50%, reaching almost 32 billion tonnes, contributing to climate change and adversely affecting ecosystems (International Energy Agency, 2021). According

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to the Global Alliance for Buildings and Construction, the construction and building sector is responsible for approximately 40% of energy-related CO2 emissions (Nasir et al, 2017). Cement manufacturing, the most widely used construction material globally, accounted for about 36% of CO2 emissions from construction activities and roughly 8% of overall anthropogenic CO2 emissions (Habert et al, 2020). Achieving carbon neutrality goals at a global scale will require significant efforts to develop and promote the use of carbon-negative construction materials through innovative design and unprecedented actions. The failure to recycle more than 40% of the waste produced by the United States, United Kingdom, Germany and Australia combined, amounting to approximately 82 million tons per year, has emerged as a significant environmental concern (Basu, 2013). On the other hand, the European Union (EU) has been attempting to tackle the issue of waste for a significant period by implementing regulations and promoting the reusing and recycling of materials. Several industries are also taking steps to address this problem, especially concerning wood production processes where its continuous accumulation in unmanaged conditions poses a significant threat to the surrounding environment (Alabduljabbar et al, 2020). In order to deal with this problem, it is possible to convert wood waste into products that have a higher value, thereby promoting an environment that is sustainable and less contaminated, i.e., energy recovery through thermochemical processes like gasification or pyrolysis (Basu, 2013). These procedures have a high potential for transforming biomass waste into liquid biofuel or syngas; notwithstanding, a new waste is generated, the biochar. However, this type of charcoal has gained attention in recent years for its potential to sequester carbon and improve soil quality (Agegnehu et al, 2017); additionally, the construction industry has started to consider its implementation in recent years. Moreover, the amount of carbon from the original biomass stored in biochar can be over 60%, depending on the feedstock and preparation methods used. This can decrease net greenhouse gas emissions by 530-570 kg of carbon dioxide per metric ton of dry feedstock (Roberts et al, 2010). Thus, adding filler sourced from biomass to cement-based materials can significantly enhance the sustainability of construction materials, leading to a significant advancement in improving the environmental impact of building materials. Some research has demonstrated that using biochar can enhance the mechanical properties of construction materials (Restuccia et al, 2016), mainly, it is beneficial to increase the fracture energy (Falliano et al, 2020) and could be useful in 3D concrete printing processes (Falliano et al, 2022). Some researchers (Choi et al, 2012) observed a 10-12% increase in the compressive strength of mortar when replacing up to 5% of the cement with biochar made from wood waste. This increase was due to the internal curing properties of the water released from the biochar pores. This hydration occurred even when the external curing conditions were wet or dry. According to Gupta et al., adding 1-2% biochar can control the free water-cement ratio in the cement mixture, which can enhance hydration and increase the mechanical strength, flexibility, and durability of cement mortar and concrete by up to 20% and 50%, respectively, in comparison to the reference (Gupta et al, 2018a), (Gupta et al, 2018b). Suarez-Riera et al. found that incorporating 1% and 2% of biochar in cement paste mixes increased flexural strength by up to 24% and 15%, also, achieving fracture energy improvements by almost 40% when 2% was used as filler in mortar specimens (Suarez-Riera et al, 2020), (Suarez-Riera et al, 2022). Despite the numerous advantages of incorporating biochar into cement-based mixes, an optimal mixture design has not yet been achieved, as different results have been obtained due to variations in the source and production method of the biochar used. This study examines the impact of using industrial biochar in mortar samples to evaluate its influence on mechanical properties.

2. Materials and methods

The main materials used for preparing the mortar specimens are Portland Cement (C) type I 52.5R, tap water (W), superplasticizer (SP), CEN standard sand, and industrial biochar (BC). The biochar used in this investigation was provided by Nera Biochar SRL, a wood-chip-derived product that comes from cleaning green areas and wood processing waste. This company's wood chips biomass comes from a controlled supply chain obtained by a fast pyrolysis process. The biochar structure is made up of more than 75% carbon. A ball milling machine was used to ground and achieve the expected BC particle size distribution in dry condition since the biochar used comes in the form of pellets. First, 100 g of biochar were put into a ceramic jar with medium-sized spheres. Afterward, the container was put into the machine for 7 hours using a feet rate of 60 rpm. Finally, the ground biochar was collected. Previous studies suggest that a smaller average size of the biochar particle produces a better interaction with the cement matrix; when the particle's surface area increases, the interaction between the particles and the surrounding cement matrix increases (Gupta et al, 2017). The particle size distribution analysis was carried out using a Malvern Mastersizer 3000 Aeros S machine. Table 1 shows the granulometry obtained for five samples. Biochar can store water thanks to its morphology, making it a material with great potential for retaining liquids in cement paste and mortar mixtures, being a key point in the internal curing of the mixture.

The process for calculating the water retention capacity of BC is based on the method proposed in (Gupta et al, 2018b). First, two BC samples were taken, each of 10 g, and placed in a ventilated oven at 90ºC for 24 hours; in this way, the BC natural and acquired humidity is eliminated before testing. Each of the 10 g biochar samples were filled with 100 g of distilled water, then sealed and left to stand for 48 hours. A vacuum filtration test was prepared, in which a funnel with a cellulose filter (Whatman 150 mm Ø) was used to extract all the surface liquid mass. Taking the weight of the wet and filtered biochar, then subtracting the dry biochar's weight, the compound's fluid retention capacity is obtained. The water retention capacity expressed as the mass of absorber water per gram of dry biochar was calculated as 0,94 ± 0.02 g of H_2O/g of dry biochar. Compared to other studies in the relevant literature, the biochar used in this study is characterized by much lower water retention capacity. This condition could be due to the low porosity and shape of the chip, which does not allow very high absorption capacities.

Table 1. Results of the granulometry analysis of the used biochar (BC)

Specimen No.	Sample preparation	Dx(10)	Dx(50)	Dx(90)	Dx(100)	Average [µm]
1	Ball Milling Ceramic (7 Hours) + Sieving 180 Micron	1.80	7.92	24.10	85.7	
2		1.75	7.85	24.30	75.9	Dx (10) 1.78
3		1.79	7.87	24.40	75.9	Dx (50) 7.88
4		1.76	7.90	23.70	86.2	Dx (90) 23.96
5		1.81	7.87	23.30	111	

Seven types of mortar specimens were prepared following the mix design reported in Table 2, according to the procedure established by the standard UNI EN 196-1. The mixtures were prepared with a water-to-cement ratio of 0.5 (remaining constant even when the BC was used to substitute the cement powder) and a cement-to-aggregate ratio of 1:3. The fine aggregate used was CEN standard sand certified in EN 196-1, agreeing with ISO 679:2009.

Table 2. Mix proportions

Mix ID	Description	Cement [g]	Water [g]	Sand [g]	Biochar [g]
OPC	Plain Cement mortar	450	225	1350	0
BC 1% - FI	1% BC in the mix as filler	450	225	1350	4.5
BC 1% - SO	1% BC in the mix as cement substitution	445.5	225	1350	4.5
BC 3% - FI	3% BC in the mix as filler	450	225	1350	13.5
BC 3% - SO	3% BC in the mix as cement substitution	436.5	225	1350	13.5

Three prismatic specimens 40 × 40 × 160 mm were cast for each series. After 24 hours, the samples were demolded and put into a water tank for curing. Once the curing time was finished, in particular 28 days, a u-notch of 12 mm depth and 2 mm width was made in each sample using a Miter saw BRILLANT 220, which was made in the middle of the orthogonal face to the pouring surface of all the specimens, following the geometry and dimensions recommendations reported in the Japan Concrete Institute Standard JCI-S-001. A single-column Zwick Line-Z010 testing machine with a 50 kN load cell device and the clip-on strain gauge to measure the crack Mouth Opening Displacement (CMOD) was used to test each notched specimen. The span adopted was 120 mm, and the test speed of 0.03 mm/min has been set. The evaluation of the flexural strength was carried out according to equation 1.

$$\sigma_{f,max} = F_{max} \cdot \frac{3L}{2bh^2} \quad [MPa] \tag{1}$$

Where F_{max} is the force on the prism at the failure time, L is the span (distance among the supports) equal to 120 mm, b is the specimen depth, and h is the net ligament height equal to 40 mm and 28 mm, respectively. The fracture energy was determined in accordance with the Japan Concrete Institute Standard JCI-S-001, according to equation 2.

$$G_F = \frac{0.75W_0 + W_1}{A_{lig}} = G_{F0} + G_{Fcorr} \quad [N/mm] \tag{2}$$

Where A_{lig} is the area of the nominal ligament equal to 1120 mm^2, W_0 $[N \cdot mm]$ is the area below the CMOD curve up to the rupture of the specimen and W_1 $[N \cdot mm]$ is the work done by deadweight of specimen and loading, evaluated according to equation 3.

$$W_1 = 0.75\left(\frac{l}{L}m_1 + 2m_2\right)g \cdot CMOD_c \quad [N \cdot mm] \tag{2}$$

Where l is the loading span (distance among the supports) equal to 120 mm, L is the total length of the specimen equal to 160 mm, m_1 $[kg]$ is the mass of the notched specimen, m_2 $[kg]$ is the mass composed by the arrangement for the evaluation of the displacement placed on the beam until it breaks, without being attached to the testing machine, g is the gravity acceleration, and $CMODc$ is the crack mouth opening displacement at the rupture. Besides the flexural strength, the halves of the prism broken were tested in compression in accordance with UNI EN 196-1 standards.

3. Results and discussions

Figure 1 and Figure 2 represent, respectively, the results in terms of flexural strength (σf) and fracture energy ($\mathrm{G}f$) of cementitious composites with BC used as a filler and as cement replacement, at 28 days. The Load-CMOD curves are shown in Figure 3. It can be recognized that the batches in which BC has been used led to a slight reduction at early age in terms of flexural strength except for 1 wt% substitution.

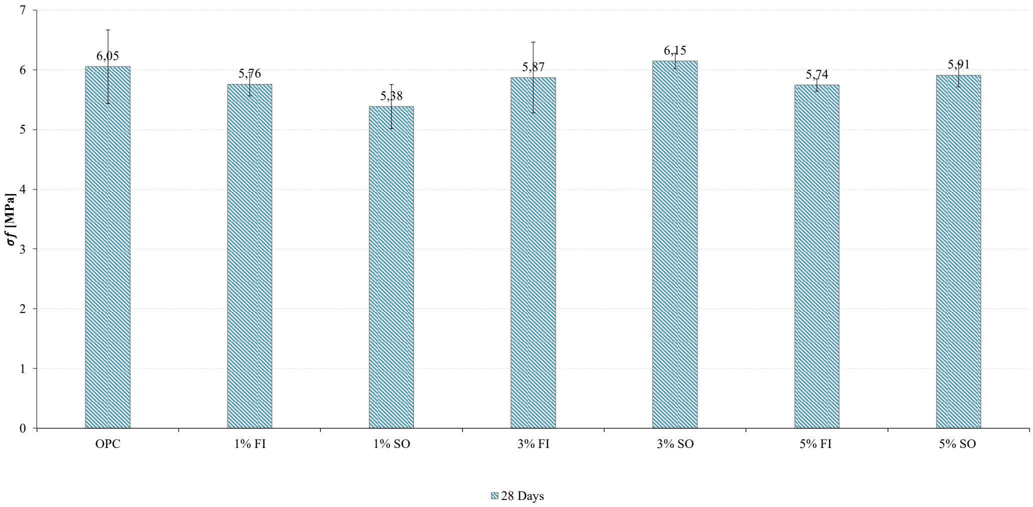

Fig. 1. Flexural strength - Average value and error bar for each batch at 28 days.

Cement substitution with 3 wt% was associated with a slight increase of flexural strength of mortar by 2%; moreover, the highest percentage of cement substitution (5 wt%) was associated with a reduction of 2.3% concerning the plain mortar. A similar finding is reported by (Tan et al, 2020): the addition of 3% and 5% of pyrolyzed biochar at 500 °C caused a drop in flexural performance by around 10 and 20%, correspondingly at 28-

days. However, results revealed an advantageous effect of biochar addition in terms of fracture energy (Figure 2 and Figure 3). Using 3 wt% as filler, 3 wt% as cement replacement, and 5wt% of BC led to an increase of more than 17%, 31% and 26%, respectively, at 28 days compared to the reference, increasing the tortuosity of the failure path of the sample due to small agglomerations of biochar that attract the trajectory of the crack path. Adding fine biochar particles led to better packing and a more compact matrix, which can efficiently transfer stress by composite action (Restuccia et al, 2017). Also, BC particles improve interlocking between filler and matrix, leading to higher resistance to crack propagation and strength development (Gupta et al, 2018a).

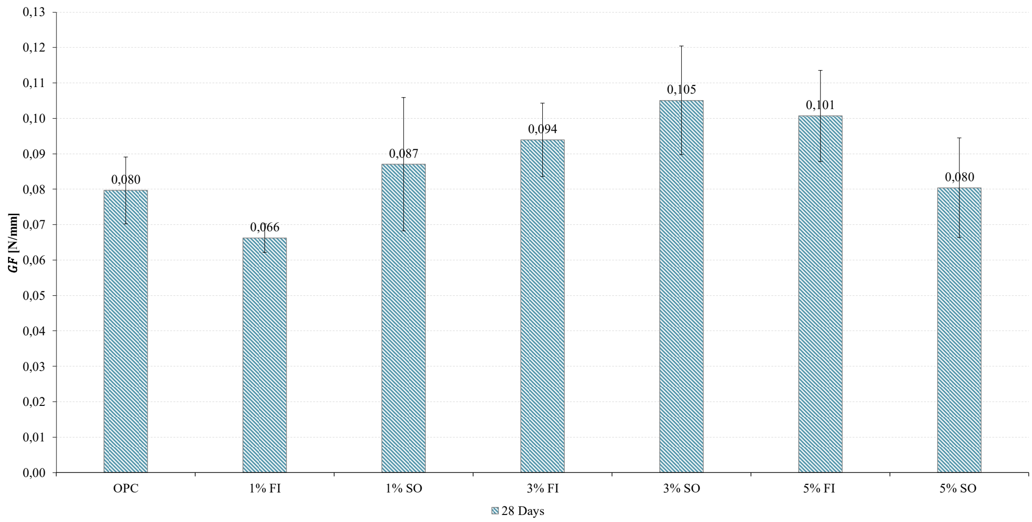

Fig. 2. Fracture energy - Average value and error bar for each batch at 28 days.

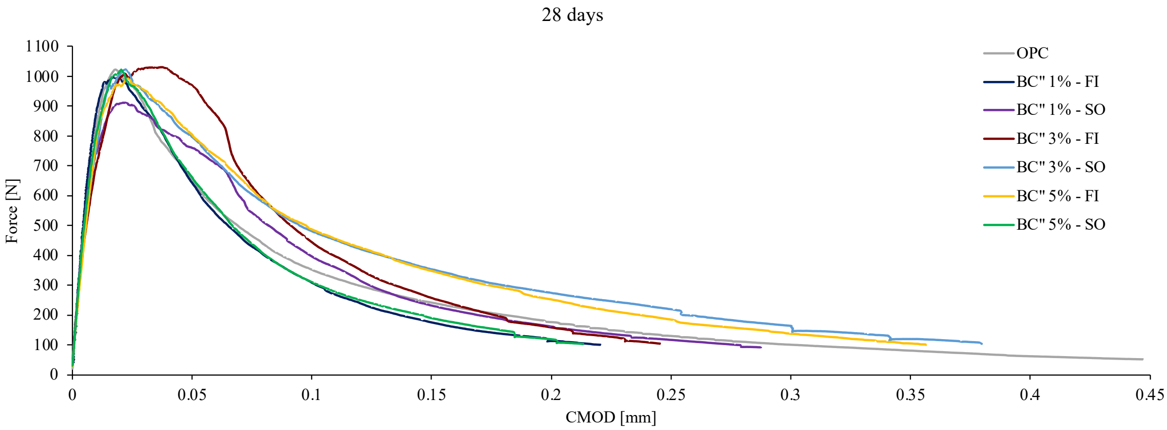

Fig. 3. Load-CMOD curves of mortar specimens at 28 days.

Figure 4 show the results obtained from compressive strength (σc) at 28-days of standard-cured specimens incorporating various dosage of biochar. When talking about compressive strength, the results show a non-positive behavior; the addition of biochar contributed to this loss of strength, going against the trend or the expected results; in fact, (Chen et al, 2022) found that the addition of 3% of biochar improved the compressive strength by almost 20% of absolute strength increment after 28 days. After 28-days of curing, no improvement due to biochar addition was found, being the case of BC 5% as filler or cement substitute, the worst scenario in which the compressive strength decreases around 10% respect the reference. On the one hand, a reduction in strength due to adding a high amount of biochar can be linked to low density and higher porosity of mortar (Gupta et al, 2018c). On the other hand, regarding the cement substitution scenarios, a possible cause of the compressive strength reduction is that the biochar has no hydration products. Therefore, more replacement of biochar to cement induces less amount of overall calcium silicate hydrate (C-S-H) products, which play the main act in compressive strength. Thus, compressive strength performance reduction. However, a 1% dosage of biochar had a relatively minor effect on compressive strength in which the BC 1% - SO performance increases by 3% with respect to the mortar without biochar. Nevertheless, the strength found in this work is well accepted by the American standards and European standards that regulate the strengths and capacities of a batch of mortar samples.

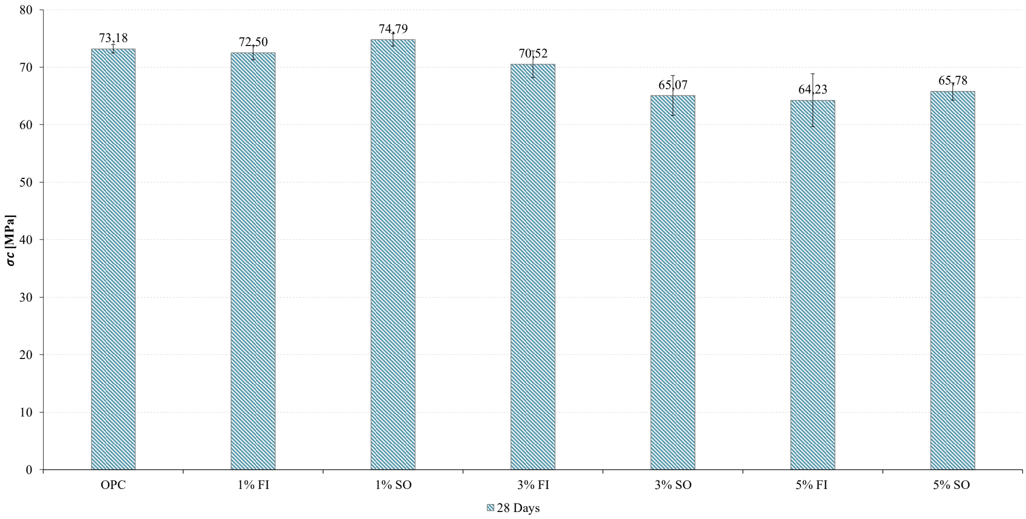

Fig. 4. Compressive strength - Average value and error bar for each batch at 28 days.

3. Conclusions

This research was motivated by previous studies where other types of biochar were used to increase the mechanical capacity of cement-based composites. The impact of industrial biochar as filler and partial cement replacement in the range of 1, 3 and 5 wt% on the cement mortar mechanical performance was investigated in this study. After analyzing the properties provided by the biochar content in cement-based mixtures, it is possible to conclude that this type of industrial biochar has no relevant impact in mechanical properties when used in mortar mixes, although it gives rise to non-negligible increases in fracture energy, due to the increased tortuosity of the failure path. When 1% of BC is added to the mortar mix, the mechanical properties are similar regarding the reference, with slightly better performance. However, biochar can be used as a replacement material for cement, maintaining good mechanical performance but saving cement costs and its environmental impact, which will be significant at large building scales. It is highlighted that biochar, in many cases, is considered a potential waste, then its cheap implementation brings benefits to mortar and especially to the environment due to carbon sequestration. It is expected that the current and past research will continue to motivate the scientific field and future research on building materials, meeting quality standards and improving the mechanical properties of cement-based composites.

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