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The use of Biochar to reduce the carbon footprint of cement-based / Suarez-Riera, D., Restuccia, L., Ferro, G.A.. - In: PROCEDIA STRUCTURAL INTEGRITY. - ISSN 2452-3216. - 26:(2020), pp. 199-210. (1st Mediterranean Conference on Fracture and Structural Integrity, MedFract 2020 Athens (GR) 2020) [10.1016/j.prostr.2020.06.023].

Availability:
This version is available at: 11583/2853704 since: 2020-12-11T15:01:29Z

Publisher:
Elsevier

Published
DOI:10.1016/j.prostr.2020.06.023

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28 November 2026

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Procedia Structural Integrity 26 (2020) 199–210

Structural Integrity Procedia

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The 1st Mediterranean Conference on Fracture and Structural Integrity, MedFract1

The use of Biochar to reduce the carbon footprint of cement-based materials

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Abstract

The organic waste management is a most current topic, because its processing and degradation it is responsible for emissions of methane and other greenhouse gases, leading to serious environmental problems. Limited oxygen thermochemical processes, such as pyrolysis or gasification, have demonstrated the energy recovery potential of the treated biomass and its environmental benefits. However, the solid part of the process -Biochar- it is considered as a waste, as only its coarse ash can be used as soil improvers. Nevertheless, several researchers have explored its potential application as green filler in order to reduce the carbon footprint both of cement production and cement-based construction materials. In this work, Biochar microparticles were used both as a filler inside the cement paste and mortar composites and as a substitute for the cement powder inside the mixes. Based on previous work, this investigation has a twofold objective: to understand the full influence of the use of an optimized percentage of Biochar (2% with respect to the weight of the cement) either as a filler in the mixture or as a substitute for cement, while guaranteeing an improvement in the strength without losing ductility. The results showed that 2 wt% of Biochar's particles are sufficient to increase the strength and toughness of the cement and mortar composites and, in place of the cement in the mixture, can maintain the mechanical properties equal to those of the reference samples.

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Keywords: Biochar; Cement paste; Mortar; Mechanical properties; Carbon footprint

1. Introduction

In our society, cement is an essential product; however, its production is highly energy consuming and it has a severe impact on the environment. Global cement production is the third largest source of anthropogenic carbon dioxide emissions (Andrew, 2018). For this reason, there is a growing interest in finding sustainable solutions to

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10.1016/j.prostr.2020.06.023

reduce its carbon footprint and the utilization of raw materials (Imbabi, et al., 2012) (Miller, et al., 2018). In Recent Times, many opportunities for using alternative cements are based on different chemical compositions and binding phases and they are obtained using recycled resources and mineral waste (Suhendro, 2014), adding carbon nano/micro-particles obtained from polyethylene beads (CNBs) in cement matrix (Ferro et al., 2015) or micro-sized inert carbonized particles from hemp hurds (Ferro et al, 2014).

Currently Supplementary Cementitious Materials (SCMs) are widely used in concrete technology to partially substitute ordinary Portland cement (OPC). Their use leads to a significant reduction in CO_2 emissions per ton of cementitious materials which means no additional clinkering process involved (Lothenbach, et al., 2011) (Chen, et al., 2019).

On the other hand, population growth, urbanization, and living standards have resulted in a massive generation of waste around the world. Approximately one-third of the comestible parts of food produced for human intake, gets lost or wasted globally, which is about 1.3 billion ton per year (FAO, 2011). Other than food wastes, another significant type of waste is generated from the wood processing industry. Only Italy generated almost 3 million tons of wood waste according to Rilegno (2018). Regardless, food or wood waste translates into wasting the resources used in its production (land, water, energy, and inputs), generating unnecessary CO_2 emissions and causing serious management problems and costs for the states.

Recently, one of the solutions for managing the large amount of organic waste is the use of oxygen-free thermochemical processes such as pyrolysis or gasification since these allow the biomass's energy capacity to be recovered, in turn, these processes generate Biochar. The International Biochar Initiative (IBI, 2014) defines it as "a solid material obtained from the thermochemical conversion of biomass in a low oxygen environment", or rather, a carbonaceous waste from the thermochemical conversion process. Depending on the type of feedstock and preparation conditions used, biochar has the potential of reducing net greenhouse gas (GHG) emissions by about 870 kg CO2 equivalent (CO2-e) per ton dry feedstock (Roberts, et al., 2010). This material allows the transformation of agricultural waste, such as wood or municipal solid waste, crop residues, rice husks, quinoa and lupine residues, cassava rhizomes, tobacco seeds, oil mill and oil mill sludge, algae biomass and many others in ground transformers (Duku, et al., 2011) (Shackley, et al., 2011) (Taherymoosavi, et al., 2017) (Heredia Salgadoa, et al., 2018) (Tippayawong, et al., 2017) (Onorevoli, et al., 2017) (Yoon, et al., 2017) (Abdelhadi, et al., 2017) (Zhang, et al., 2018) (Yu, et al., 2017); therefore, it is mainly used as a soil amendment (Lehmann, et al., 2009) (Gonzaga, et al., 2018) (Thangarajan, et al., 2018) (Li, et al., 2017) (Agegnehu, et al., 2017) (Shi, et al., 2018).

Most Recently, biochar has been explored as a building material and there is an emerging trend of its use as concrete admixture as well as additive/replacement in cementitious composites (Khalid, et al., 2018). Gupta S. et al. (2018) used biochar derived from mixed food waste, rice and wood waste as carbon sequestering additive in mortar, obtaining similar results in mechanical strength by adding 1–2 wt% of biochar compared to control mix. Also, an increase of more than 20% in compressive and tensile strength was reached. Also, Gupta and Kua (2019) found that finer biochar particles guarantee an improvement of early strength and water tightness compared to normal biochar (with macro-pores) when biochar is used in cement mortar mixtures and recommend that biochar from wood waste can be used as filler material for improved strength development and water tightness of concrete constructions. Akhtar and Sarmah (2018) investigated the effect of biochar mixed with cement on the mechanical properties of concrete replacing the cement content up to 1% of total volume with three different types of biochar, such as poultry litter, rice husk and pulp and paper mill sludge biochar. Results showed that compressive strength was almost equal to that of reference one by using pulp and paper mill sludge biochar at 0.1% replacement of total volume. Regarding the flexural strength, 20% increment in comparison with the control specimens was found when poultry litter and rice husk biochar were added to the mixture at 0.1%. Zeidabadi et al. (2018) replaced a part of cement in concrete mixture with rice husk and bagasse biochar. Concrete samples containing 5% biochar had a compressive and tensile strength improvement by more than 50% and 78% respectively, compared to ordinary mix. Moreover, the samples in which 10% of biochar was used as a replacement showed a compressive strength improvement by more than 22% (with respect to the control concrete). In addition, Zhao et al. (2018) incorporated different percentages of biochar in vegetation concrete to study the trend in porosity, permeability and compatibility of plants. Discovering that the height of the plant, the length of the root and germination rate increased by more than 22% in the mixtures with approximately 2.30 wt% biochar, additionally, obtaining a slight increase in the compressive strength in comparison with the mixture without biochar. Khushnood et al. (2016) added peanut and hazelnut shells biochar to cement paste

by up to 1 wt%, obtaining an increase of the flexural strength and toughness with respect to plain cement, but also gaining an increase in electromagnetic radiation shielding effect when 0.5 wt% of biochar was used. Finally, Restuccia et al. (2017) reported an increase in fracture energy on cement paste samples after 28 curing days by more than 45% by addition of 0.8 wt% biochar, derived from hazelnut shell.

Despite the many benefits of using biochar in cementitious mixes, there is not yet an ideal mix design for its use, obtaining different results since not all biochar used became from the same source. In this paper, a 2 wt% of biochar used as a filler from gasification treatment waste has been investigated, also, its utilization as Ordinary Portland Cement replacement capacity in cement paste a mortar mixes.

2. Materials and methods

2.1 Cement, sand, superplasticizer and water

Portland cement type I, CEM1 52.5 R (Italcementi S.p.A.), CEN Standard sand, a natural siliceous sand consisting of rounded particles having a silica content of at least 98%, whose particle size distribution lies within specific limits according to UNI EN 196-1 (Societé Nouvelle Du Littoral), Superplasticizer Dynamon SP1 (MAPEI S.p.A), finally, deionized water was used for mixing procedure and tap water for curing were used.

2.2 Gray Borgotaro Biochar

Gray Borgotaro Biochar (GBB) was produced from wood chips through gasification, specifically, the equi-current fixed bed system "downdraft" which means that the direction of the fuel (wood) and the gas flow in the same direction at a temperature of about 700 ºC.

2.2.1 Gray B*orgotaro Biochar properties*

2.2.1.1 Potential of Hydrogen analysis (pH)

The pH of biochar was measured by preparing a homogeneous aqueous suspension according to a biochar weight ratio: water 1:10 and after 90 minutes of stirring the pH was measured using a Crison pH meter Basic 20.
As expected, the tested biochar sample was alkaline, probably due to the presence of organic functional groups, carbonates or inorganic alkalis. Results are reported in Table 1.

Table 1. Gray Borgotaro Biochar pH.

Sample	pH	pH 24h	pH 5 days
Gray Borgotaro Biochar	10.22	10.8	10.95

2.2.1.2 Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) was conducted using a Perkin Elmer Pyris 1 TGA instrument. During a typical experiment, the sample, about 2 mg, was placed in an aluminium crucible, the analysis was performed at a rate of 30 °C/min from 30 to 900 °C under N_2.

The sample from Gray Borgotaro appears to be thermally stable (Figure 1). The thermostability of a biochar depends on the temperature at which it was generated, in fact, with the increase of temperature, more stable carbon forms with a high heat resistance originate inside the material (HoKim, et al., 2012). Considering this, it can be corroborated that Gray Borgotaro Biochar sample was produced by thermoconversions occurring at high temperatures.

To verify if the residual % weight is due to more stable forms of the carbon formed during the gasification, TGA were carried out in air because the organic compounds, in contrast to the inorganic ones, tend to give combustion reaction in the presence of oxygen.

In fact, the thermogram (Figure 1) of the sample analysed showed a lower % in residual weight due to the combustion of the most stable forms of carbon. As regard, instead, the unburnt fraction, this could be attributed to the presence of inorganic compounds or metals.

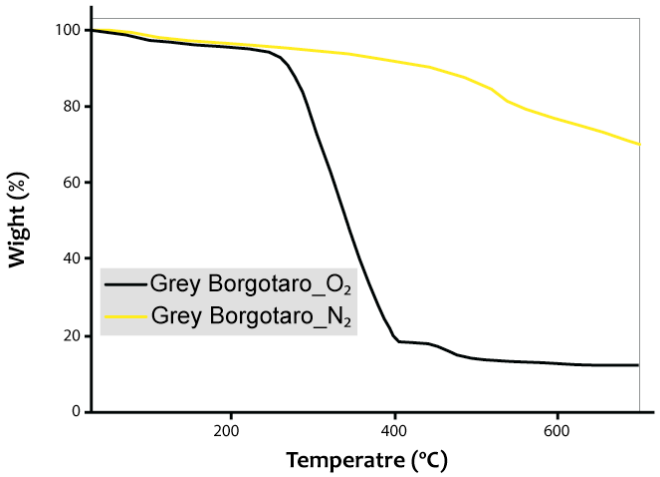

Fig. 1. TGA. Thermogravimetric analysis was conducted under the flow of N_2 and O_2.

Table 2. Quantity of heavy metals calculated by inductively coupled plasma mass spectrometry (ICP-MS).

Metals and not metals in ICP	Unit	Value	Method
Arsenic As	mg/Kg	0.364	IPC-MS-PT-IPC mass
Cadmium Cd	mg/Kg	1.94	IPC-MS-PT-IPC mass
Chrome Cr	mg/Kg	6.35	IPC-MS 12m-IPCmass
Iron Fe	mg/Kg	1310	M05/IPC-OES-IPC optical
Magnesium Mg	g/100g	1.52	M05/IPC-OES-IPC optical
Mercury Hg	mg/Kg	< limit	IPC-MS-PT-IPC mass
Nickel Ni	mg/Kg	59	IPC-MS-PT-IPC mass
Lead Pb	mg/Kg	11.3	IPC-MS-PT-IPC mass
Potassium K	g/100g	6.07	M05/IPC-OES-IPC optical
Copper Cu	mg/Kg	57.2	M05/IPC-OES-IPC optical
Sodium Sa	g/100g	0.115	M05/IPC-OES-IPC optical
Zinc Zn	mg/Kg	230	M05/IPC-OES-IPC optical

2.2.1.3 Mass Spectrometry with Inductively Coupled Plasma (ICP-MS)

ICP-MS (Mass Spectrometry with Inductively Coupled Plasma) is an elemental and isotopic inorganic analysis technique capable of determining and quantifying most of the elements of the periodic table in a linear dynamic range of 8 orders of magnitude (ng/L - mg/L) in addition to being able to carry out the determination of the elements in a multielement analysis that provides the composition of the sample analysed. It can also carry out the quantification of the isotopic composition and studies of the stability of trace isotopes.

2.2.1.4 Particle size distribution analysis

The particle size distribution analysis on the biochar was made using the Fritsch Laser Analyzer 22 compact laser. For this purpose, the sample-holding cell was filled with the suspension liquid, manually operating the stirring and carrying out a measurement of the reference blank. Then the sample was introduced into the sample cell in small increments by means of a pipette up to a sample dilution percentage of 7%.

The results obtained (Figure 2) show that more than half of the particles are below 8µm, which makes it possible to establish a standard procedure for the use of Biochar in cement mixtures and guarantee repeatability.

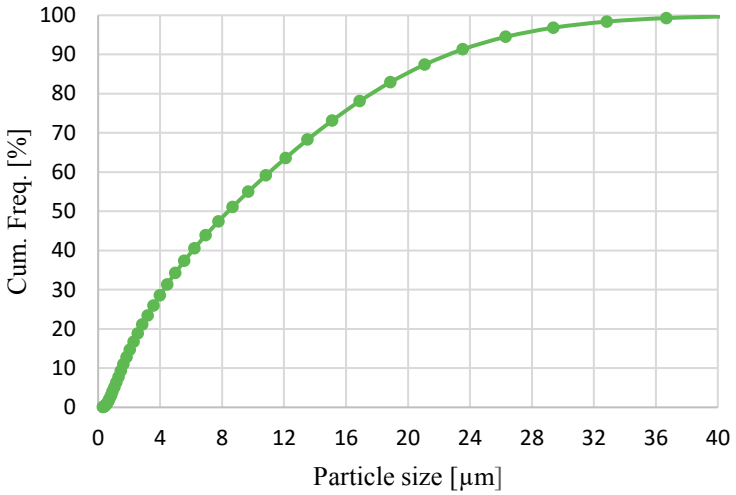

Fig. 2. Particle size distribution of Gray Borgotaro Biochar.

2.2.1.5 BET

The specific area and porosity of the biochar was determined by the adsorption isotherm and desorption of nitrogen (N_2) at 77.35 ºK (liquid nitrogen temperature) by the Brunauer, Emmett and Teller method (BET) (Brunauer et al., 1938). The nitrogen adsorption–desorption isotherms were determined at liquid nitrogen's boiling point using a Tristar II Krypton 3020.

From the nitrogen adsorption curve of the biochar, it was possible to observe that there is a high nitrogen adsorption which translates a high specific area of 28.06 m^2/g, also, the size of the pores is 32.73 Å or, 3.27nm. These conditions facilitate any access to adsorption of water (Gray, et al., 2014).

2.2.1.6 Water retention capacity

According to Gupta et al. (2018) water retention by biochar makes it a potential material in cementitious matrix thanks to their morphology and surface pores, furthermore, Gray et al. (2014) reported that micro-pores and pyrogenic nano-pores provide site for adsorption of aqueous solutions.

Water retention capacity was determined according the method used by Gupta et al. (2018), 30g of biochar were dried in a continuous airflow oven at 70.3ºC for 24 hours before performing the test to eliminate moisture that might be present in the powder, then, three containers were prepared with 10g of Biochar and 100g of distilled water previously weighted. The three specimens were subsequently sealed and allowed to stand for 48 hours, subsequently each solution was subjected to a vacuum filtering process (with cellulose filter) until there was no free water flow. The weight of the soaked biochar was then subtracted from the weight of dry biochar, consequently the mass of water absorbed in the biochar was calculated.

The water retention capacity expressed as the mass of absorber water per gram of dry biochar was calculated as 2.17g of water for each gram of dry biochar.

2.2.1.7 Scanning electron microscope (SEM)

The morphology of samples was observed through a SEM EDS microscope by Zeiss, at 20 kV and increased by more than 6K. SEM images of the feedstock and biochar are shown in Figure 3. It can be observed that the biochar maintain part of the biomass fibrous structure, also is clearly seen to be porous in all the SEM images. The porous structure of char could be derived from the porous structure existing in raw biomass or was formed during the gasification process. The surface of the Gray Borgotaro Biochar showed a high porosity. This corroborates the results obtained in the BET analysis, mentioned before. Additionally, the presence of organic particles, unidentified inorganic and filamentous compounds were found.

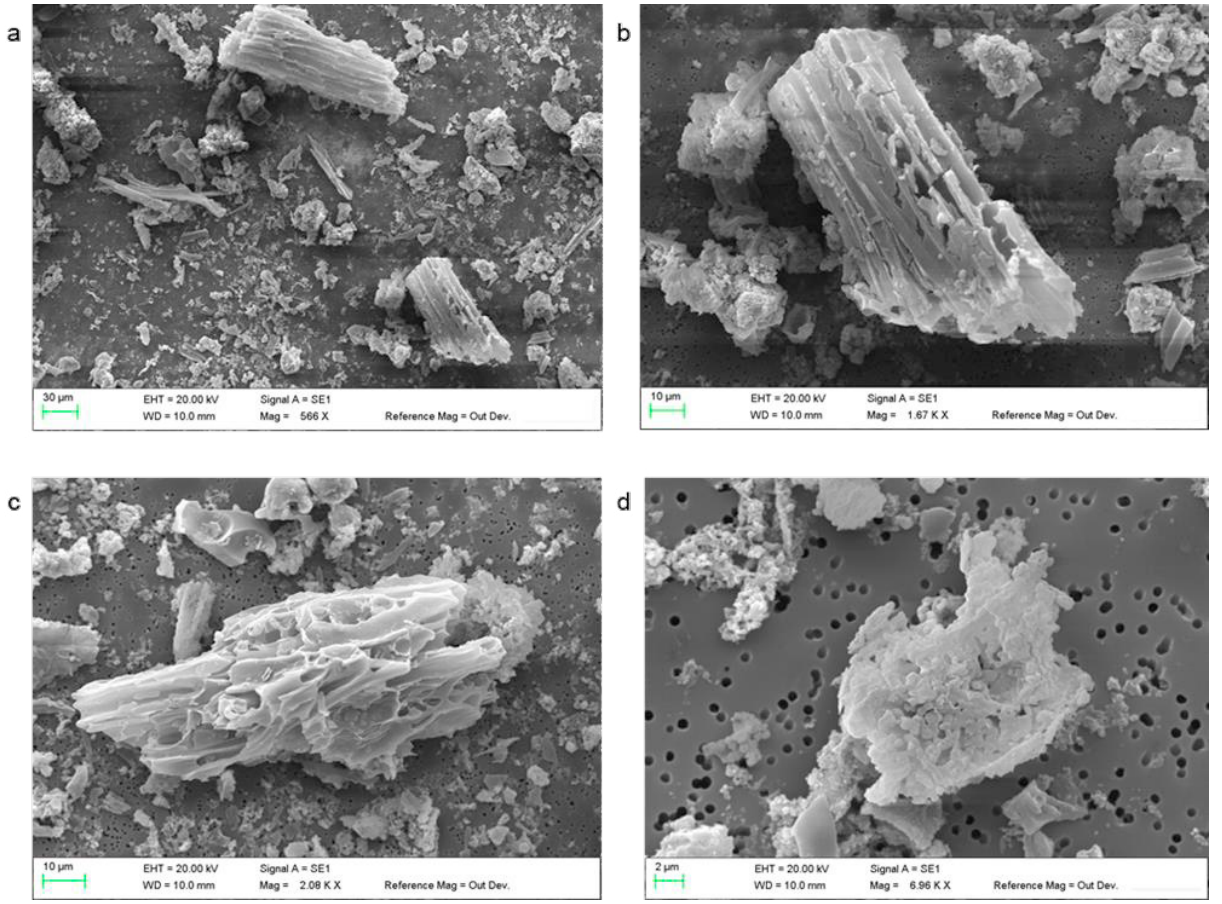

Fig. 3. (a) FESEM of Gray Borgotaro Biochar, 566X zoom; (b) FESEM of Gray Borgotaro biochar, 1670X zoom; (c) FESEM of Gray Borgotaro Biochar, 2080X zoom; (d)FESEM of Gray Borgotaro Biochar, 6960X zoom.

2.3 Mixing procedure and preparation of specimens

2.3.1 Cement paste specimens

Five types of cement paste specimens were made (Table 3), in four of them an optimized percentage of 2% of Biochar was used. In two cases the biochar was used as filler and incorporated into the mixture in two different ways: in the first two cases (C BC 2% and C BC 2%_S) the biochar was previously mixed with the water-superplasticizer (W-S) solution or with the powder of cement before making the mixture. In the remaining two cases, the Biochar was used as a cement substitute, using the above-mentioned incorporation methods. The mix design was based on the experience of previous studies carried out by Cosentino (2017), Restuccia, et al., (2016), Restuccia, (2015). All mixtures were prepared with a water/cement ratio of 0.35.

The materials mentioned above used in the preparation cement paste mixtures were weighed, following the indicated quantities in Table 3, after weighing the materials, water and superplasticizer were mixed manually for approximately 30 seconds, to this solution was successively added the biochar. The mixture C BC 2%_S and C BC 2%_S_Sost, the biochar was mixed manually with dry cement for approximately 5 minutes until a homogeneous mixture was obtained.

Continuing the process, the aqueous solution was transferred to a plastic mixing vessel. All the mixtures were carried out at a temperature of about 25 °C with at 440 rpm for 3 minutes, in the first 1.5 minutes the cement was added gradually to the liquid part, in the following half it was continued mixing, after 3 minutes, the speed of the agitator was increased to 630 rpm and the mixing continued for another 3 minutes, investing a total of 6 minutes of mixing.

Table 3. Mix proportions of different components in different types of cement paste mix.

CEM Mix	Description	Cement [g]	w/c	Water [g]	SP1	SP1 [g]	Biochar [g]
OPC	Plain cement paste	460	0.35	161	1%	4.6	-
C BC 2%	Paste with 2% of Biochar mixed in water	460	0.35	161	1%	4.6	9.2
C BC 2%_S	Paste with 2% of Biochar mixed in cement	460	0.35	161	1%	4.6	9.2
C BC 2%_Sost*	Substitution of 2% of cement (respect to BC 2%) with Biochar mixed in water.	225.4	0.35	80.5	1%	2.3	4.6
C BC 2%_S_Sost*	Substitution of 2% of cement (respect to BC 2%_S) with Biochar mixed in cement	225.4	0.35	80.5	1%	2.3	4.6

*The amount of water and superplasticizer was calculated based on the sum of the cement + Biochar

The mixture, once finished, was poured slowly to avoid air confinement in stainless steel mold, that has a 4 specimens' capacity of 20x20x80 mm. Subsequently, the specimens were placed in a humid environment at room temperature (24 ± 1 ° C) with relative humidity of not less than 90%. After 24 hours, the specimens were demoulded, named and submerged (curing process) in water for 7 days before being removed for the mechanical test. Totally, 32 specimens were made.

Once the maturation in water was finished (7 days), a U-shaped cut of 6mm depth was made in the middle of the orthogonal face of the pouring surface of the specimens using the TR100S Remet cutter with a 2mm thick diamond edge blade.

2.3.2 Mortar specimens

Five types of samples were prepared, of which four of them with the addition of GBB. An optimized percentage of 2% of Biochar was used, in two cases the biochar was used as filler and incorporated into the mixture in two different ways, in the first two cases (M BC 2% and M BC 2%_S) the Biochar was previously mixed with the water or with the powder of cement before making the mixture. In the remaining two cases, GBB was used as a cement substitute, using the above-mentioned methods of incorporation.

All mixtures were prepared with a water-to-cement ratio of 0.50 and a cement-to-aggregate ratio of 1:3. All the materials were weighted according to the amounts required in the mix design (Table 4) and mixed according to the UNI EN 196-1:2016. First, deionized water and cement were mixed for 30 seconds. Then, the sand was gradually poured into the solution within the first 30 seconds of the mixture. In the next 30 seconds, all the materials were mixed at high speed, after that, the mixer was stopped for 90 seconds: in the first 30 seconds, the material residues remaining on the bowl walls were removed, then the mixture was let stand. After the break, the mixer was reactivated at high speed for another 60 seconds. At the end of the mixing phase, the cement mixture was slowly transferred into

Table 4. Mix proportions of different components in different types of mortar mix

CEM Mix	Description	Cement [g]	Sand [g]	w/c	Water [g]	Biochar [g]
OPC	Plain Mortar	450	1350	0.5	225	-
M BC 2%	Mortar with 2% of Biochar mixed in water	450	1350	0.5	225	9
M BC 2%_S	Mortar with 2% of Biochar mixed in cement	450	1350	0.5	225	9
M BC 2%_Sost*	Substitution of 2% of cement (respect to BC 2%) with Biochar mixed in water.	441	1350	0.5	225	9
M BC 2%_S_Sost*	Substitution of 2% of cement (respect to BC 2%_S) with Biochar mixed in cement	441	1350	0.5	225	9

*The amount of water was calculated based on the sum of the cement + Biochar

the steel mold, made up of 3 40x40x160mm prismatic specimens, carefully avoiding air entrainment, subsequently, the specimens were placed in a humid environment at room temperature (24 ± 1 ° C) with relative humidity of not less than 90%. After 24 hours, the specimens were demoulded, named and submerged (curing process) in water for 7 days before being removed for the mechanical test. Totally, 15 specimens were made.

Once the maturation in water was finished (7 days), a U-shaped cut of 12mm depth was made in the middle of the orthogonal face of the pouring surface of the specimens using the TR100S Remet cutter with a 3mm thick diamond edge blade.

2.4 Mechanical tests

2.4.1 Three points bending test in Crack Mouth Opening Displacement

The three points bending test (TPB) was carried out for each notched sample which was considered optimal for the test, using a single column displacement-controlled testing machine Zwick Line-Z010, with load cell of 1 kN.

The test was performed by controlling the CMOD (Crack Mouth Opening Displacement) with a strain gauge and the test speed of 0,005 mm/min was adopted. The span adopted was 70 mm.

To evaluate the flexural strength of the specimens, Modulus of Rupture (MOR) was used:

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

2.4.2 Determination of fracture energy G_F by the JCI-S-001 standard

Stable bending tests on notched samples are much easier to perform, particularly, The Japan Concrete Institute Standard document (JCI-S-001), describe the simplest possible test to determine G_F is the three-point bending test on a notched beam (the fracture energy, G_F, measures the amount of energy absorbed until the sample breaks into two parts). Specimens shall be beams of rectangular cross section with a notch at the mid-length to a depth of 0.3 times the beam depth as shown in Figure 4.

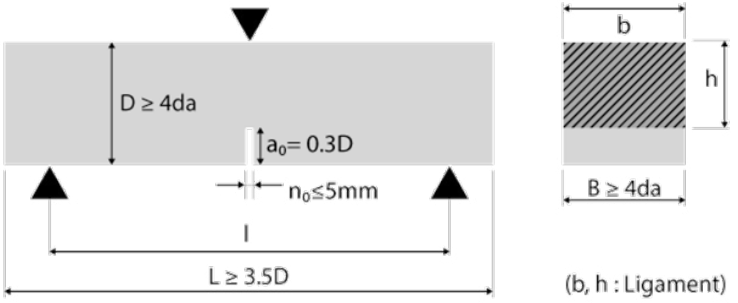

Fig. 4. Notched beam geometry.

The fracture energy was evaluated from the follow expressions:

$$G_F = \frac{0{,}75\ W0+W1}{Alig} = G_{F0} + G_{Fcorr} \quad [N/mm^2] \tag{2}$$

$$W1 = 0.75 \left(\frac{l}{L} m_1 + 2m_2\right) g \cdot CMODc \quad [N \cdot mm] \tag{3}$$

3. Results and discussions

3.1 TPB Results

The results of flexural strength of cement paste and mortar specimens are shown in Figure 4. The error bars are showing the variation in the values from average values. On the one hand, the cement paste samples result shows

how the use of 2% biochar (mixed in the water-superplasticizer solution) outcomes in an improvement of more than 15% compared to pure cement, however in the case where the GBB was mixed with the cement powder, a decrease in strength is observed by 8%. In the cases where the cement was replaced with the microparticles, there was a resistance loss of almost 30% and 40% in cases where the biochar was previously mixed with water and with the cement powder respectively. On the other hand, for the mortar specimens, it is possible to appreciate how the use of 2 wt% of GBB represents a slight loss of resistance of 2%, nonetheless, when the Biochar is previously mixed in the cement powder, the flexural strength drops less than 1%. Moreover, in the cases where biochar was used as a cement substituent, there was a quite slight decrease of strength of only 2% regardless of whether the biochar was mixed with water or cement powder previously. This situation is in line with the results reported by Ahmad et al. (2015), that reported slight reduction in fracture strength due to addition of biochar derived from coconut shell. However, it is to be noted that influence of Biochar on flexural strength is also dependent on the feedstock it is derived from. For example, Restuccia and Ferro (2016) reported about 47% increase at 7 days in flexural strength due to addition of Biochar derived from hazelnut shell.

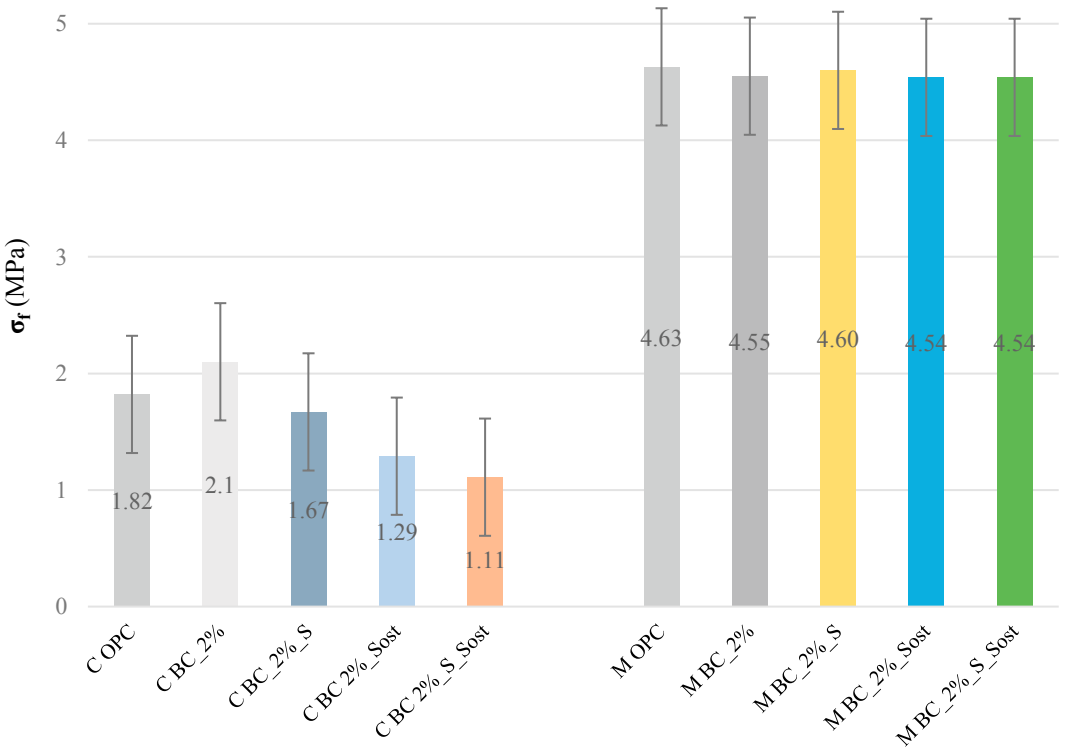

Fig. 5. Flexural strength [MPa] - Average value for each batch, 7 days.

3.2 Fracture energy (G_F) behavior

Starting from the three-point bending test it was possible to study the fracture energy of the experimental samples with the introduction of GBB into the cement paste and mortar. The 7-days fracture energy results of cement paste and mortar specimens containing Biochar are shown in Figure 5. On the one hand, it is evident the increase in the fracture energy of the cement paste specimens with respect to the reference, by more than 60% and 150% in the case where the Biochar powder was used as a filler (C BC 2%_S and C BC 2% respectively). However, the most encouraging results are the cases where the cement was substituted obtaining more than 100% and 8% increase in the case in which 2 wt% of Biochar was used and mixed in the water-superplasticizer solution and with the cement powder respectively.

On the other hand, In the case of mortar samples, the graph illustrates an important G_F increase by almost 40% and more than 30% in the cases where 2 wt% of GBB was mixed in water and in a dry manner respectively (MBC 2% and MBC 2%_S) compared to M OPC specimens. With respect to the Biochar used as a cement substitute, there was a slender increase of 2% when the carbonaceous powder was mixed with the cement powder and a G_F loss of 6% when it was mixed in water solution. The increase in the fracture energy provided by the Biochar to the cementitious pastes and mortars, is due to the generation of a more articulated and tortuous fracture trajectory and, therefore, much less linear than the typical brittle fracture of the cement-based materials. This explains the variation in post-peak behavior of the material and the increase in the ability to absorb energy before breaking.

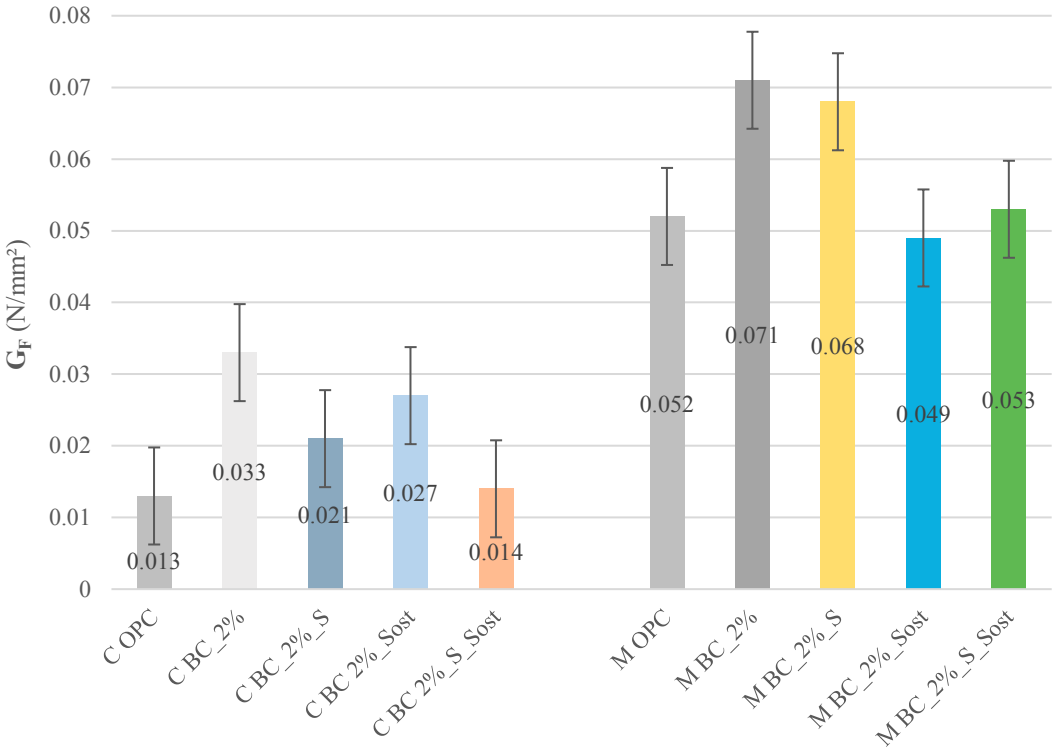

Fig. 6. Fracture energy [N/mm²] - Average value for each batch, 7 days.

4. Conclusions

The ignorance of the amount of waste that is generated every day, its environmental impact and the cost of its treatment, certainly does not help to deal with the problem of waste. The use of pyrolysis or gasification processes considerably reduce the environmental impact compared to ordinary incineration. Its implementation improves waste management, reduces toxic emissions, contaminations associated with the elimination of biomass (on water and soil) and allows an important energy recovery.

Nowadays, lower environmental impact construction materials are demanded. This work explored the possibility of using 2% of Biochar (with respect the weight of cement) as a filler and as cement substituent in cementitious composites (cement paste and mortar), in order to improve its mechanical properties and reduce its carbon footprint. In this study, the Biochar used was obtained through a standardized process of gasification of wood waste.

The results of the mechanical tests showed that the addition of Biochar increased the flexural strength and generate a ductile behavior with respect to the typical brittle behavior of the pure cementitious paste, especially when 2% of Gray Borgotaro Biochar was implied. The flexural strength increase in more than 15% and fracture energy more than 150% higher at 7 days, so it is concluded that the biochar acts as a micro-reinforcement in the

cement paste which helps to deflect the trajectory of the fracture, generating multiple fractures, which is the same, a ductile failure. In relation to the specimens where the cement was replaced by biochar, it was possible to obtain a great increase in the fracture energy even when the flexural strength was lower compared to the reference.

Regarding the mortar specimens evaluated, there was a considerable increase in fracture energy which translates into an increase in ductility of a fragile material. In addition, even if the specimens with less cement do not exceed the improvement achieved by those where the cement was not replaced the inclusion of biochar still guarantees acceptable strengths for various structural and plastering applications. Moreover, using biochar in cementitious materials is beneficial in terms of waste reduction and environmental sustainability.

In future, further studies should be conducted in exploring the application of Biochar from different types of food or wood waste and its influence in concrete mixtures.

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