The Efficiency Of Using Incinerated Organic Waste As An Alternative Aggregate For Concrete

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ABSTRACT

With the growth of the global population, two major problems have emerged. Firstly, a significant amount of domestic and industrial waste is discarded and placed in landfills. Secondly, there is a necessity for more construction and building materials. This research discusses the use of alternative green resources for construction materials taken from recycled organic waste, which represents more than 60% of the total waste generated by humans. Results showed that, after incineration at 750 °C, the reminder represented less than 15% of the original mass of the waste. The waste was separated into five groups: bottom ash (BA) powder, this part represented 5% of the reminder after incineration (for replacing cement); sand; and fine, medium and coarse aggregates. The powder underwent a pozzolanic reaction and the optimum replacement was 10% for the powder, 30% for the sand, and 10% for the fine, medium, and coarse aggregates. A higher compressive strength was applied to the medium aggregate replacement and a lower one for the fine aggregate. In general, BA can be used as an aggregate replacement as the powder undergoes a pozzolanic reaction and can used as a replacement for cement.

Key Words: Concrete, Municipal waste, Bottom ash, Mechanical properties, Relative Activation index.

INTRODUCTION

Sustainability, durability, cost-effectiveness, straightforward casting, robustness and other advantages affirm that concrete is the most abundant construction material globally (IEA, 2018); although, CO_2 emissions from the cement industry place a moral restriction on its use, as cement factories produce 7% of the total CO_2 emissions (Chen *et al.*, 2010). Additionally, the effort attributed to the reduction of waste, the limitations of natural resources and the employment of more sustainable concrete for construction issues have forced researchers to obtain an alternative green material for inexpensive, eco-friendly and green concrete with structural benefits. Bottom ash (BA), which is derived from the incineration of organic waste, is an industrial by-product originating from thermal power plants. It presents some ecological benefits as an alternative source for cement (Whittaker *et al.*, 2009; Abdullah *et al.*, 2017); aggregates (Elaqra *et al.*, 2019); road pavement (Aggarwal and Siddique, 2014); and glass and ceramics (Tang *et al.*, 2014).

According to the World Bank Group (2016), 2.01 billion tons of solid waste were generated by the worlds' cities, which is equal to 0.74 kilograms per person per day (Kaza *et al.*, 2018). This amount will reach 3.40 billion tons by 2050, with an expected increase of 70%. Table 1 depicts the global waste distribution.

Table 1. Distribution of waste in the world (Kaza *et al.*, 2018)

Type	Organic	Paper and cardboard	Plastic	Metal	Glass
Percentage (%)	43%	17%	12%	4%	5%

There are concerns about the Gaza Strip, which is a closed area (around 362 m^2), where the poulation has increased dramatically, a huge amount of solid waste has resulted without any, as shown in Table 2.

Table 2. The amount of waste in the Gaza Strip (ton/day) and predicted amounts in 2030 and 2040 (Maqadmh *et al.*, 2015)

Year	2013	2014	2015	2020	2030	2040
Total amount (ton/day)	1753	1813	1855	2097	2668	3023

Table 3 depicts the type of waste in the Gaza Strip and the distribution demonstrates that organic waste represents the majority of the waste.

Table 3. Distribution of waste in the Gaza Strip according to the type of waste (Abu El qomboz and Habil, 2013)

Waste	Organic	Sand	Paper	Plastic	Glass	Metal	Textile	Others
Percentile (%)	67%	10%	8%	7%	2%	2%	2%	2%

One lightweight green aggregate compared with cement or natural aggregates is bottom ash, as its density is governed by the origin of the waste. Organic, paper, plastic and textile wastes tend to maintain a mass below 1 g/cm.[3] Moreover, metal, glass and other heavy materials have a tendency to increase the density of BA (Siddique, 2010; Huang *et al.*, 2020). Another parameter that determines the type of replacement by BA is its size, where it varies according to the type of incinerator and the origin of the waste (Lynn *et al.*, 2016). The BA powder (smaller than 75 µm) generally represents approximately 3% of the total waste (Alhassan and Tanko, 2012).

The use of BA as cement is governed by its chemical composition because BA can have pozzolanic properties due to the presence of calcium aluminodisilicate (CAS_2) and aluminosilicate (AS) (Rémond *et al.*, 2002). Table 4 presents the chemical composition of ash in the existing literature. Its major composition is the same as cement; nonetheless, the amount of CaO is extremely small compared to cement, while the amount of SiO_2 is higher. The presence of chloride is considered a cement accelerator, the optimum is located at 10% and the BA undergoes a pozzolanic reaction especially during a long curing time (Rémond *et al.*, 2002).

Table 4. Chemical composition of BA compared to cement

	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	Na_2O	C1
Elaqra and Rustom (2018) Cement	66.69	18.84	6.3	3.72	2.66	0.61	0.5	0	0
Rémond *et al.* (2002) BA	16.4	27.2	11.7	1.8	3	2.5	5.8	5.9	7.2
Keppert (2012) BA	19.4	33.5	15.8	8.4	9.3	2	1.9	3.6	1.1
Tang *et al.* (2014) BA	21.9	39.3	10.1	12.7	3.7	0	0	0	0.8

Throughout the mixing, the use of BA decreases workability, because it demands more water due to its higher water absorption in comparison to natural aggregates (Li *et al.*, 2012; Aggarwal and Siddique, 2014). In general, as the BA replacement increases, the compressive strength attains the optimum and then it decreases; meanwhile, the value is still less than the control.

Used as a sand replacement by up to 15%, the optimum is located at 5%; the compressive strength is stable after 28 days and the control increases by 20%. This occurs due to the large amount of sulfate and chloride, which has a negative effect on the concrete (Keppert, 2012). Van der Wegen *et al.* (2013) replaced the coarse aggregate with 20% of BA and the results demonstrated that the compressive strength was 84% of the control at 28 days and 90% at 90 days. In contrast, Abbà *et al.* (2017) tried a 50% replacement of the coarse aggregate with BA and an increase of the w/c in order to have the same slump. The results revealed an increase in the compressive strength by up to 102% after 28 days. A replacement of up to 50% of the fine aggregate by BA with the same w/c demonstrated a lower slump and compressive strength. At 28 days, the compressive strength for 10% BA had 96% of the control, while 50% had 43% of the control (An *et al.*, 2017).

The aim of this research is to use BA obtained from the incineration of organic waste collected from municipal waste. It will be air dried, oven dried, and then incinerated at 750 °C, in order to obtain the BA for the replacement of cement, sand, and fine, medium and coarse aggregates. It is noted that the incineration process was done in the laboratory. Samples will be prepared with different amounts of replacement in order to evaluate them mechanically using compression tests. The activation index will be used to examine the pozzolanic activity of the powder.

EXPERIMENTAL AND TESTING PROGRAM

The experimental program is composed of the following steps:

Step 1. Obtain an alternative aggregate from domestic waste by applying the following steps:

1. Collect the solid municipal waste
2. Separate the organic component from the solid waste
3. Air dry the samples at 35 °C
4. Oven dry the sample at 105 °C
5. Burn the dried waste at 750 °C
6. Separate the alternative aggregate into four sizes (smaller than 75 µm powder, sand smaller than 600 µm, fine and coarse aggregates)

Step 2. Chemical analysis andinvitsigate the physical properties of the alternative aggregate.

Step 3. Mix concrete specimens according to the replacement of the natural sand, aggregate and cement, and conduct curing until test data is obtained.

Step 4. Density calculation and mechanical testing (compressive test) in order to evaluate the effect of the replacement.

MATERIALS

Cement

Local CEMII 42.5 N, SVL was used in this study. Table 8 shows the chemical composition of the cement used.

Aggregates

Natural sand and aggregate were used in this study from a local crushing site. Figure 1 depicts the particle size distribution of the natural sand and the aggregate according to the ASTM C136/C136M-14. The local sand was smaller than 0.6 mm, and the fine aggregate size was between 0.6 mm and 10 mm. The medium aggregate was between 10 mm and 20 mm in size and the coarse aggregate was larger than 20 mm. The curve depicts a positive grade distribution, where the cumulative curve is located between the maximum and minimum percentage.

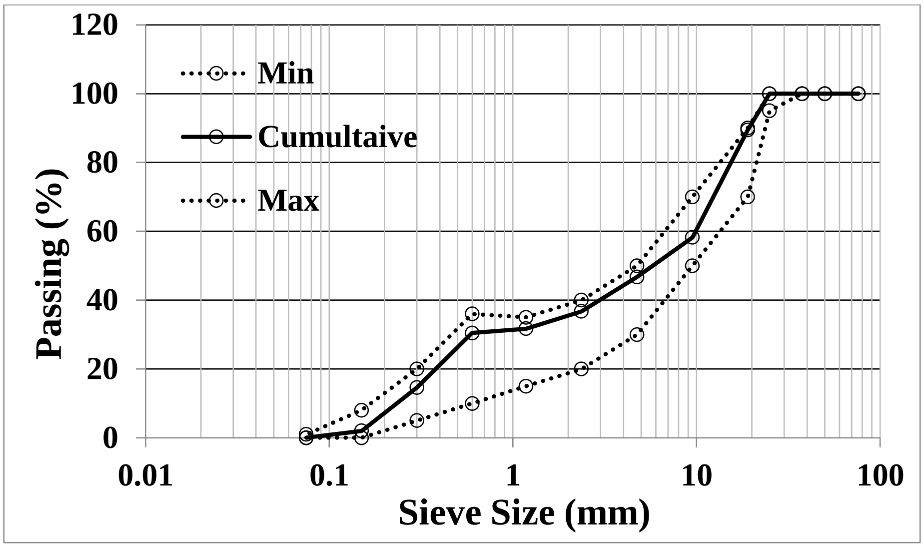

Figure 1. Cumulative particles' size distribution of the natural aggregates

Alternative green aggregates

Municipal waste (200 kg) was collected from more than one site in order to have a representative sample from the Gaza Strip waste. After separation, the organic waste weighed approximately 160 kg, which represents 80% of the total waste. It is worth noting that the organic waste was composed essentially from vegetables and some bone. Thereafter, the sample was placed in an open area at a temperature between 32 and 35 °C. After five days, the sample weighed approximately 80 kg and the following step entailed placing the sample in the oven at 105 °C for 24 h in order to remove the free water. The sample was reduced to 25 kg and the final step was burning the 25 kg of waste at 750 °C for 2 h to ensure the elimination of the organic component in the BA. The remaining ash after burning weighed 7.3 kg, which represents approximately 4.6% of the total amount of organic waste (see Fig. 2).

Figure 2. Image of remaining ash after burning at 750 °C

Figure 3 shows the mass loss of the organic waste after each step. At 105 °C, the free water departs from the sample and it represents more than 80% of the organic structure, which comes from the nature of the waste. The carbonation and elimination of the organic components occur at 750 °C.

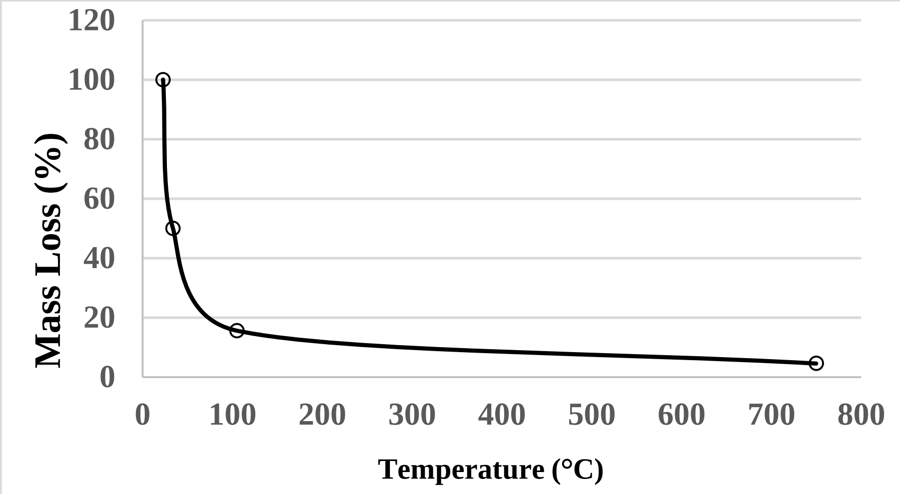

Figure 3. Mass loss after each treatment of the organic waste

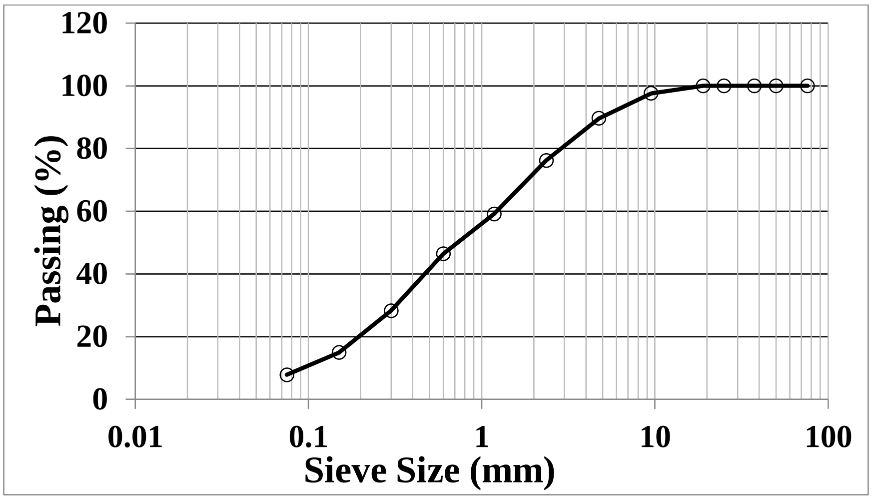

Figure 4. Particle size distribution of BA

Figure 4 depicts the cumulative particle size distribution of the BA according to the ASTM C136/C136M-14. The fine aggregate represents approximately 85% of the BA, originating from the nature of the domestic waste.

Table 5 hows the value of the density and the absorption (according to ASTM C642) of each material used within this study.

Table 5. The properties of the materials used

	Density (g/cm^3)	Absorption (%)
Cement	3.15	
Sand	2.67	0.03%
Natural aggregate	2.7	2.7%

Bottom ash	0.8	42.5%

MIX PROPORTIONS

Concrete

Cubic samples with the dimensions of 100*100*100 mm were cast according to the investigation variables. Mixes were prepared with BA as cement (10% and 20%), sand (15%, 30% and 50%), fine (FA), medium (MA) and coarse aggregate (CA) replacements with a cement to water ratio equal to 0.53.

Samples were tested at different ages, namely 7 and 28 days in order to evaluate the mechanical behavior. Mixing of the sample was conducted according to the ASTM C192/C192M-16a.

Tables 6-7 reveal the mix proportion used within this study, and the percentage of the replacement of each component. The amount of water to cement ratio was adjusted according to the mix's workability or to a fixed percentage. Two control mixes were used, the first with a water to cement ratio equal to 0.53 and the second according to the percentage of w/c of the mix with an aggregate replacement (w/c = 0.63, 0.74 and 0.84).

Mixing concrete

The two-stage method was used for mixing the concrete. This method was proposed by Tam *et al*. (2005) and was supported by subsequent studies (Tam and Tam, 2006; Tam *et al*, 2007; Tam and Tam, 2007; Elaqra, 2014, 2015, 2019; Elaqra *et al*., 2019a). This method involves mixing part of the water with the aggregate, adding all the cement, and the final step is mixing in the remaining water. The aim of this method is to facilitate the penetration of the cement paste into the poro-aggregate (aggregate with higher porosity resembling a crushed or lightweight texture). In this research, putting in the water first will help the adhesion of the cement particles onto the surface of the aggregate. When the remaining water is added, the penetration of the cement paste will occur, providing the aggregate with more strength. It should be noted that mixes with a high replacement had a higher water to cement ratio, which came from the higher water absorption of the BA.

Table 6. Concrete composition

	Cement (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)	BA (kg/m^3)	Water (kg/m^3)	w/c ratio
Control mix	330	660	1170	0	175	0.53
Cement (10%)	297	660	1170	33	175	0.53
Cement (20%)	264	660	1170	66	208	0.63
Sand (15%)	330	561	1170	99	208	0.63
Sand (30%)	330	462	1170	198	244.2	0.74
Sand (50%)	330	330	1170	330	277.2	0.84

Table 7. Concrete composition

	Cement (kg/m^3)	Sand (kg/m^3)	CA (kg/m^3)	MA (kg/m^3)	FA (kg/m^3)	BA (kg/m^3)	Water (kg/m^3))	w/c
Control	330	660	660	250	350	0	175	0.53
CA (10%)	330	660	594	250	350	66	175	0.53
MA (10%)	330	660	660	225	350	25	175	0.53
FA (10%)	330	660	660	250	315	35	175	0.53

TESTING PROCEDURE

Chemical analysis

The objective of this test is to determine the chemical composition of the BA using flame atomic absorption spectrophotometry according to the ASTM D4691-17. In contrast, the cement composition was determined by X-Ray Fluorescence (XRF) as affirmed by Elaqra and Rustom (2018).

Density

According to ASTM C642-13, the density was calculated using Eq. 1:

$$\rho=\frac{M}{V} \qquad (1)$$

MECHANICAL TESTING

Compressive strength tests

The concrete mixes were subjected to a compression test according to ASTM C39/C39M-18 at 7 and 28 days. At least three tests were conducted for each point on the figures, where the standard deviation was generally less than 3%.

Relative Activation Index (RAI)

Pu (2004) proposed Eq. 2 to study the reactivity of any replacement of cement or addition to cement:

$$\text{RAI} = 1 - \frac{Compressive\ Strength\ of\ Control\ mix * GP\ percentage}{Compressive\ Strength\ of\ GP\ mix * 100} \qquad (2)$$

RESULTS AND DISCUSSION

Chemical analysis and XRF

Table 8 presents the chemical composition of the cement and the BA powder. The BA powder is composed from the same oxide as the cement, which provides the rationale for cement replacement.

Table 8. Chemical composition of cement and BA

	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	P_2O_5	Na_2O	C1
CEMII	66.69	18.84	6.3	3.72	2.66	0.61	0.5	0.70	0	0
BA	56.2	1.9	0.78	7.4	0	12.2	23.8	0	10	24.9

Density

Table 9 presents the results of the density according to the variation of the mixes and the age. The variation of the density is related to the initial amount of each ingredient in the mix. As the replacement is carried out with a lighter aggregate, the mix has a lower density. In contrast, as the aggregates become larger (such as CA), the possibility of the cement paste penetrating into the porosity becomes easier. This affects the mechanical behavior of the BA aggregate when it replaces larger aggregates in comparison to smaller ones. The use of the two-stage mixing method is the reason for this and as a result, the larger aggregates have better mechanical properties than the smaller aggregates.

Table 9. Density of the mixtures

Mix	w/c	7 days g/cm^3	28 days g/cm^3
Control	0.53	2.5	2.54
Control	0.63	2.45	2.5
Control	0.74	2.41	2.445
Control	0.84	2.35	2.395
10% Cement	0.53	2.47	2.515
20% Cement	0.63	2.405	2.475
15% Sand	0.63	2.41	2.465
30% Sand	0.74	2.345	2.365
50% Sand	0.84	2.2	2.3
10% FA	0.53	2.485	2.5
10% MA	0.53	2.52	2.54
10% CA	0.53	2.482	2.52

HARDENED PROPERTIES

Mechanical properties

Cement replacement

Figure 5 shows the compressive strength as a function of age and BA as the cement replacement (10% and 20%). As the figure shows, the more there is of the replacement, the less the compression strength. Moreover, the 20% BA mix requires more water in order to have the same workability as the control mix. The effect of the excessive amount of water in comparison to the control and the 10% BA mix is added to the effect of the cement replacement by a material less reactive and binding. This plays a determining role in the 20% decrease of the compressive strength.

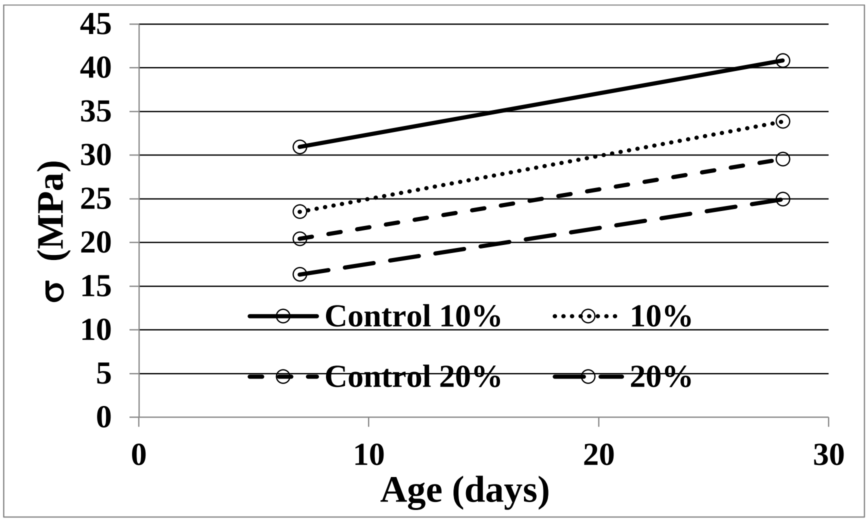

Figure 5. The compressive strength of concrete as a function of age and BA as cement replacement

The calculation of the normalized compressive strength provides a more comprehensive understanding of the effect of the value changes. Figure 6 shows the result of the 10% BA mix calculated in comparison to the control, the 20% BA mix is calculated in reference to its control (20% control), and the 20% BA mix based on its control is calculated in reference to the 10% BA mix control.

As stated in section 1926.752(a) of the US Department of Labor, Occupational Safety and Health Administration, "an appropriate ASTM standard test method of field-cured samples, either 75 percent of the intended minimum compressive design strength or sufficient strength to support the loads imposed during steel erection is needed.

At 28 days, the normalized compressive strength demonstrated that all mixes satisfied the requirement of strength, which exceeds 75% of the control. In contrast, all the mixes had a higher normalized stress, which comes from the activation of the BA as a binder.

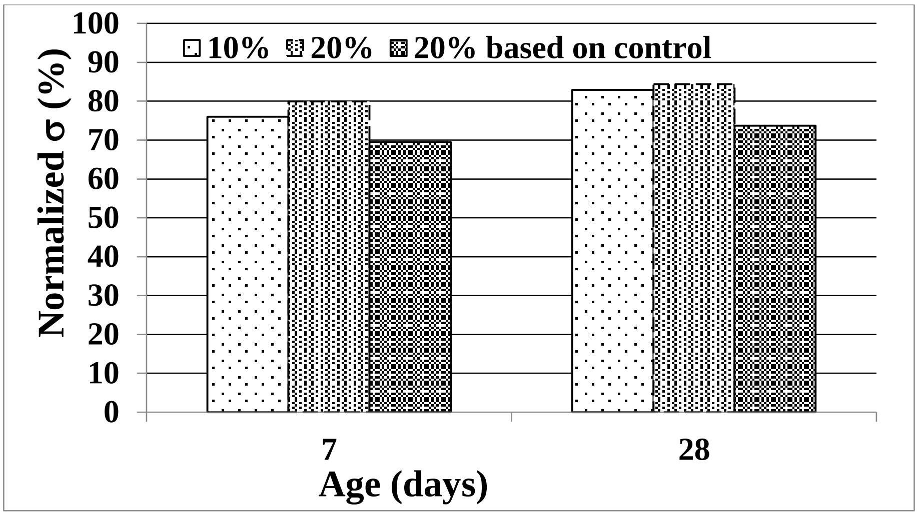

Figure 6. Relative compressive strength of concrete as a function of age and BA cement replacement

Figure 7 presents the calculation of the relative index activation as a function of age and replacement. Only the 20% BA mix based on the control of 20% BA was the mix with the positive index, which indicates that a higher w/c ratio activates the BA. The RAI becomes higher at 28 days, which indicates a pozzolanic reaction.

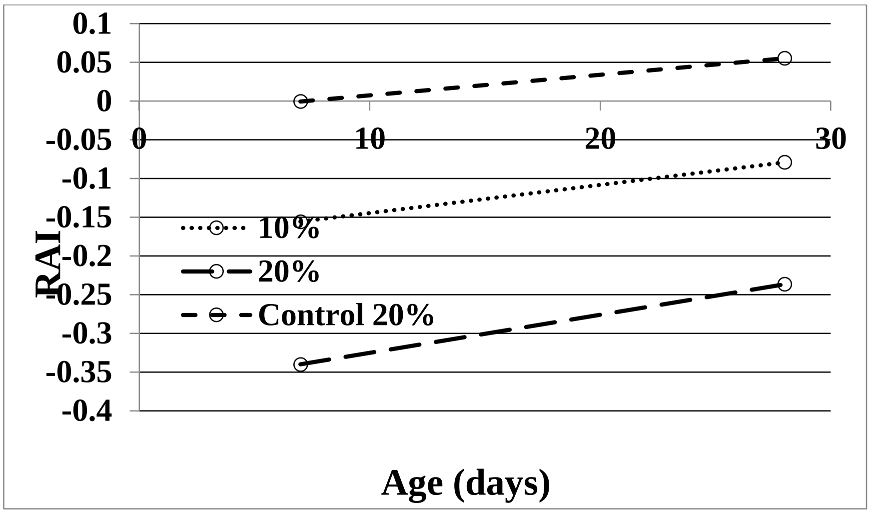

Figure 7. RAI as a function of age and BA as cement replacement

Sand replacement

Figure 8 shows the results of the compressive strength as a function of age and BA as the sand replacement. With an increased replacement, the compressive strength decreases, which is due to the necessity of additional water (which is required to have the same workability) and the replacement of a natural aggregate by a weaker one.

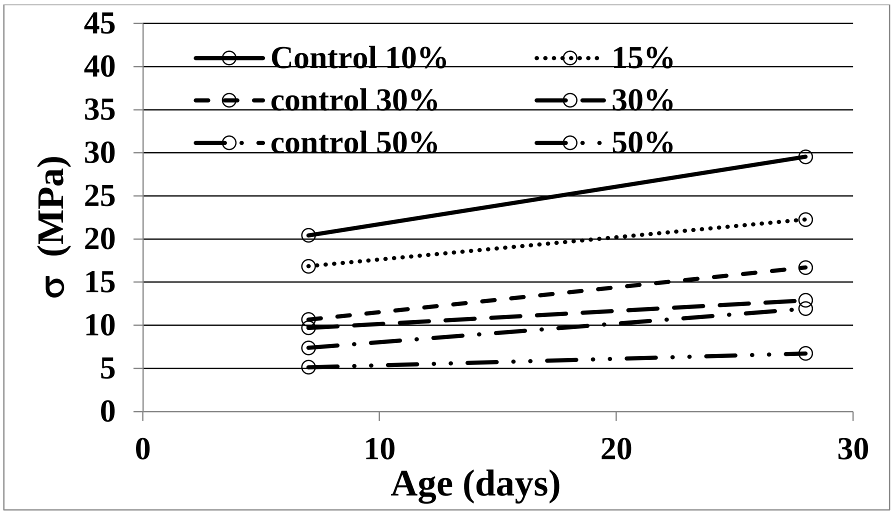

Figure 8. Compressive strength of concrete as a function of age and BA as the sand replacement

Figure 9 shows the results as a function of age and replacement. At 28 days, the 15% and 30% BA mixes are higher than 75% of the control, thus, they can be used. The optimum is located at 30% of the replacement in relation to its control. At 28 days, the normalized stress becomes smaller than at 7 days; this indicates a problem with the durability of this replacement. As a result, the replacement of the sand by the BA of the same size is not an effective solution.

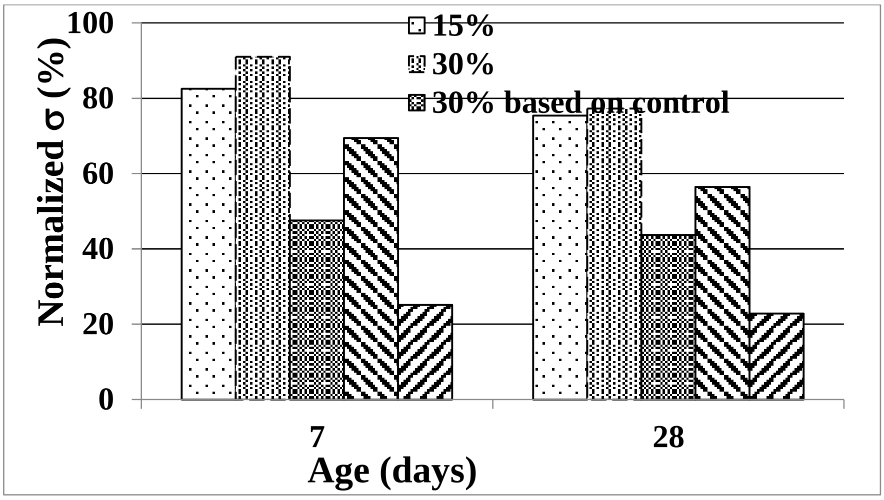

Figure 9. Relative compressive strength of concrete as a function of age and BA as the sand replacement

Fine, medium, and coarse aggregates' replacement

Figure 10 presents the results of the compressive strength as a function of age and replacement, where three replacements were conducted: BA replaced the fine aggregate (10% FA); medium aggregate (10% MA); and coarse aggregate (10% CA). At 7 days, the 10% MA mix had a higher compressive strength than the control; nonetheless, at 28 days, its compressive strength became smaller but extremely close to the control. At 7 days, the fine and coarse aggregates' replacement had the same value; and then at 28 days, the CA developed a higher compressive strength than the FA. In order to obtain an in-depth understanding of these results, the normalized stress would be extremely helpful.

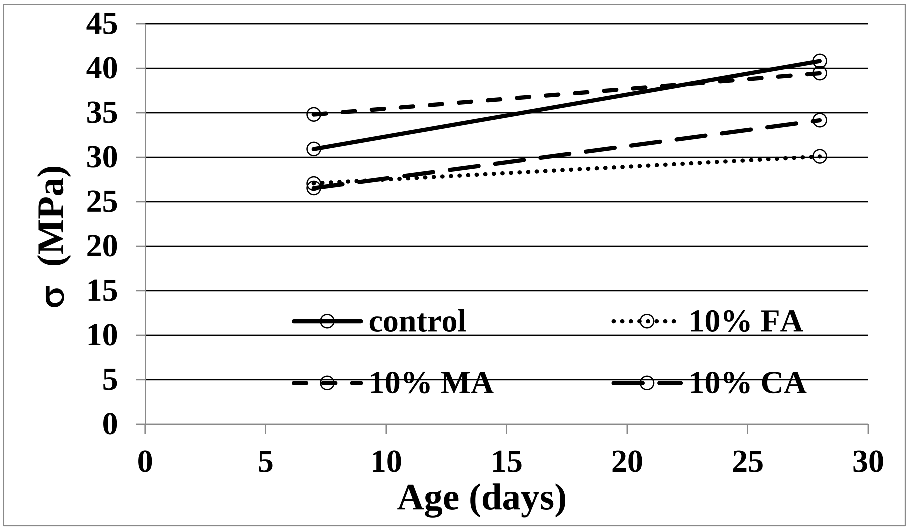

Figure 10. Compressive strength of concrete as a function of age and BA as an aggregate replacement

According to the calculation of the normalized stress, Fig. 11 demonstrates that at 28 days, the normalized values become smaller than at 7 days. Only the CA mix has an extremely small variation. Despite this decrease, it is still higher than 75% of the control stress.

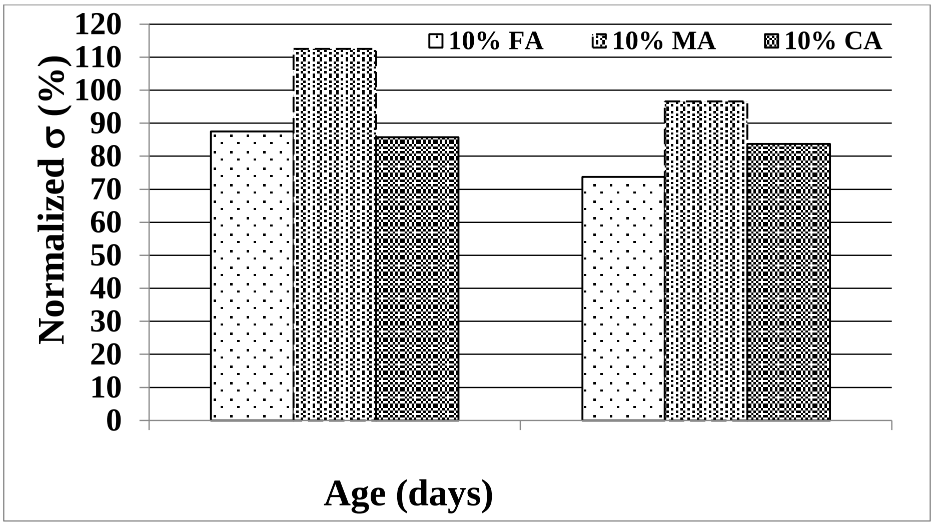

Figure 11. Relative compressive strength of concrete as a function of age and BA as an aggregate replacement

CONCLUSION

From the aforementioned investigations, the following conclusions were obtained:

1. Free water represents approximately 85% of organic domestic waste; this is due to the nature of the waste which is generally composed of vegetables.
2. After incineration, the BA represents less than 5% of the total mass of the waste.
3. The BA's chemical composition is extremely close to that of cement.
4. The optimum compressive strength of the cement replacement was 10%.
5. The BA powder had a pozzolanic reaction which was proved by the fact that: the normalized compressive strength at 28 days was higher than at 7 days; the RAI for the pozzolanic reaction was positive according to the calculation.
6. The optimum compressive strength for the sand replacement was 30% and higher than 75% of the control.

7. The medium aggregate BA replacement had the maximum compressive strength; it was higher than the control at 7 days and higher than 95% at 28 days.
8. The sand, fine and medium aggregates had a normalized compressive strength at 28 days, lower than at 7 days. This was due to the higher water absorption of the aggregate, which had a weaker interfacial transition zone between the cement paste and the aggregate.

Data availability statement

All data, models and code generated or used during the study appear in the submitted article.

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