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Effect of Incorporating Pottery and Bottom Ash as Partial Replacement of Cement

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Effect of Incorporating Pottery and Bottom Ash as Partial Replacement of Cement

Abstract

This study addressed the environmental constraints in cement production. Ordinary Portland cement (OPC) was replaced with pottery powder (PP, produced by grinding locally available pottery) and bottom ash (BA) at 10%, 20% and 30% of cement mass. Moreover, 4% calcium chloride solution ($CaCl_2.2H_2O$) was used as mixing water. Material properties, such as standard consistency, setting time and compressive strength, were measured with different percentages of OPC replacement with PP and BA. Results indicated that the replacement with PP and BA increased the water demand to achieve the standard consistency. These results revealed that the strength evolution of 30% PP and BA is lower than that of the corresponding OPC mix, whereas the 10% and 20% replacements have a similar compressive strength to the control mix at 28 and 90 days, respectively. Slightly higher compressive strength was observed with the addition of 4% $CaCl_2$ than the OPC mix.

Keywords

Pottery powder; bottom ash; calcium chloride; Eco efficient mortar; durable mortar

1. Introduction

Cement is the most used building material worldwide. However, in environmental aspects, the cement industry is responsible for 5% of total CO_2 emissions. Environmentally friendly alternatives to cement are required to preserve the environment [1−9]. Many waste materials produced by this industry are neglected by humans. Some of these waste materials can be replaced by the weight of cement, and this technique reduces the environmental impact, construction costs, energy consumption, CO_2 emissions and the volume of waste materials. In addition, with the global attention on the political and social requirements for recycling industrial by-products and waste materials, artificial lightweight aggregates have been manufactured from various source materials, such as crushed waste clay brick (CB), pottery powder (PP), marble, glass powder and bottom ash (BA); these materials are naturally occurring products from the coal combustion process [10−19]. Using industrial by-products and waste materials is beneficial to sustainability goals, including recirculation of resources and restoration of landfill. Studies [10,16,18,20−22] have been conducted as positive actions in the concrete industry in response to the global sustainability requirements. They have regarded CB as a Pozzolanic material on the basis of the chemical analysis of clay that contains 58.4% silica and 28.7% alumina [10]. The amounts of silica and alumina in CB are 60.64% and 14.23%, respectively [16], and ground brick has a high content of SiO_2 (73.64%) and low content of CaO (1.29%) [23,24]. ASTM C618 states that for a potentially suitable Pozzolanic material, the combination of SiO_2, Al_2O_3 and Fe_2O_3 must not be less than 70% [1,21]. Thus, partial or complete use of BA and PP for producing concrete can be highly effective in preserving natural resources, such as sand, crushed rock and gravel, considering previous reports [8,24,25] emphasising that approximately 9 billion tons of natural aggregates are consumed annually by the concrete industry.

Previous studies [26−29] have indicated that the workability of concrete is kept constant when cement is replaced with 10%−20% of CB and reduced in bulk density [13,16]; however, its compressive strength has a significant improvement at 28 days compared with the control mix. They concluded that the fineness of clay from 360 m^2/kg to 420 m^2/kg insignificantly increases the strength. Clay effectively reacts with the activators NaOH and KOH solutions, and compressive strength increases with age [10,29]. However, the addition of high percentages of CB slightly decreases the splitting tensile strength, and the range of tensile strength is 2−4 MPa with replacements of 10%, 20% and 30% at 28 days [13]. The flexural strength is not adversely affected by the addition of CB [23], and the flexural strength is 10−12 MPa with replacements of 10%, 20% and 30% [13].

Ge et al. [13] reported that replacing cement with CB decreases the hydration heat because CB has high water absorption and reduces the autogenous shrinkage. Given good internal curing, limited research work has been conducted on mixing cement mortar with PP and BA. Hence, the present study aims to investigate the behaviour of PP and BA as Pozzolanic materials in cement mortar. From the durability viewpoint, the effect of calcium chloride solution ($CaCl_2$) is also reported. On this basis, the authors seek a sustainable alternative to partially replace Portland cement, as well as to reduce the disposal of this waste in landfills.

2. Experimental investigation

2.1. Materials

In this experiment, ordinary Portland cement (OPC) with a specific gravity of 3.15 and Blaine fineness of 350 m^2/kg (conforming to ASTM C150 Type I) [30] was used. Tables 1 and 2 present the chemical and physical properties of this cement. The fine aggregate was natural siliceous river sand with a saturated surface-dry specific gravity of 2.78 and absorption of 0.81%, and a fineness modulus of 2.64 was used. This material was purchased from Gaza Strip. Table 3 shows the grading. PP and BA were obtained from Gaza Strip factories. The pottery was ground in a laboratory-scale horizontal ball mill to obtain a powder. Grinding was performed until all samples passed through a No. 200 sieve (75 μm), as shown in Fig. 1 and Fig. 2 exhibits the methodology of pottery preparation. The chemical compositions of PP and BA were obtained using an X-ray diffraction, as shown in Table 1. Experiments and analysis involving SEM were considered from a previous

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Table 1
Chemical compositions of cementitious materials.

	OPC[a]	BA[a]	PP[a]
CaO, %	65	8.7	10.7
SiO_2, %	20.6	45.3	47.6
Al_2O_3, %	4.6	18.1	23.8
Fe_2O_3, %	2.7	19.84	7.42
MgO, %	2.4	0.969	1.5
SO_3, %	2.1	0.352	0.759
NaO_2, %	0.13	−	2.16
K_2O, %	0.49	2.48	1.68

[a] Note: OPC is ordinary Portland cement; BA is Bottom ash; and PP is pottery powder.

study [1]. Fig. 3 presents the image. In accordance with the manufacturer's recommendations of using 2%−4% of calcium chloride ($CaCl_2$) solution to obtain benefits and with the objectives of this investigation [31], this percentage was selected on the basis of previous work [32]. Thus, the $CaCl_2$ solution consisting of only one salt with 4% $CaCl_2$ was prepared, and the reagent grade $CaCl_2.2H_2O$ was used to prepare a solution with extra water (adjusted $CaCl_2.2H_2O$), as shown in Fig. 4. Tap water in Gaza was used.

2.2. Methodology and mixture proportions

A total of 23 mortar mixtures classified into two series was tested, as presented in Tables 4 and 5. The mixture proportions of all mortar specimens for the targeted requirements were designed in accordance with ASTM C109 [33]. In the first series, the variable parameters were studied. The replacement with PP was varied at 10%, 20% and 30% of cement mass, and the replacement with BA was varied at 5%, 10%, 15%, 20% and 30% of cement mass. All mixtures were divided into three main groups. The first group was composed of 18 binary blended mixtures incorporating PP as cement replacement at 10%, 20% and 30%. The second group was composed of 30 binary blended mixtures, incorporating BA as cement replacement at 5%, 10%, 15%, 20% and 30%. The third group was composed of 18 specimens, including three blended mixtures containing OPC, PP and BA, as illustrated in Table 5. In the second series, the effect of calcium chloride ($CaCl_2$) solution on the mixtures in the first series was studied. The $CaCl_2$ solution consisting of only one salt with 4% $CaCl_2$ was prepared. Mixture proportioning was performed for the M40 grade of mortar. Table 4 presents the details. The control mortar mixture used only OPC as binder. Mortar specimens were kept at ambient laboratory conditions [34] for 7, 28 and 90 days.

Table 2
Physical properties of cement.

Properties	Cement	ASTM Requirements
Density (Kg/m^3)	2960	ASTM C188-87
Fineness (cm^2/gm)	3500	ASTM C150-95 Min. 2800
Vicat set times (hr:min)	2:30	ASTM C150-95
Initial	5:00	≥45 min
Final		
Normal consistency (%)	25.5	–
Mortar Compressive	16.47	ASTM C150-95
Strength (MPa)	29.81	>12
at 3 days	44.03	>19
7 days		–
28 days		

2.3. Tests conducted

2.3.1. Fresh mortar test

Different ASTM standards were followed to identify the fresh properties of mortar for all mixtures, and the consistency and setting time were determined following ASTM C187 [35] and ASTM C191 [36], respectively.

2.3.2. Hardened mortar test

The influence of replacement with PP, BA and $CaCl_2$ was investigated by producing mortar cubes (50 × 50 × 50 mm), as shown in Fig. 5. Three specimens were tested to determine the compressive strength at 7, 28 and 90 days. Furthermore, the microscopic analysis and durability indicators of cement mortar should be further investigated.

3. Results and discussion

3.1. Standard consistency

Fresh properties of the studied mortar were measured in accordance with ASTM C187 [35]. Table

Table 3
Grading size distribution of sand.

Sieve No.	Sieve Opening mm	Percentage of Passing (%)
#30	0.6	98
#40	0.4	70
#50	0.3	25
#100	0.15	0

Fig. 1. Pottery Powder passed through a No. 200 sieve (75 μm).

6 presents the results. The standard consistency of the control mix was equal to 23.5%. The uniform consistency of the trial matrixes was observed during the investigation. The increment amount of PP and BA increased the water demand given that the total powder content cement + PP or BA and w/cm remained constant for all mixtures. This finding may be related to the high early rate of hydration of pottery, BA and cement. The same conclusion was adopted by other studies [14,16,27,37]. This behaviour is related largely to the smooth surface texture of the PP and BA particles and the delay in the chemical reaction [16].

3.2. Setting time

PP and BA more slowly reacts with water than Portland cement; thus, its use is likely to increase the stiffening times of the mortar, as shown in Table 6 and Fig. 6. The extension in stiffening time is greater at high replacement levels with PP and BA at approximately 14.5% and 13%, respectively, and at normal temperatures (approximately 25 °C ± 2). Furthermore, the results indicated a possibility of shrinkage specially with the increasing percentage of replacement. Thus, all specimens were loaded at a controlled temperature of 70 °F (21 °C) and relative humidity of 55%.

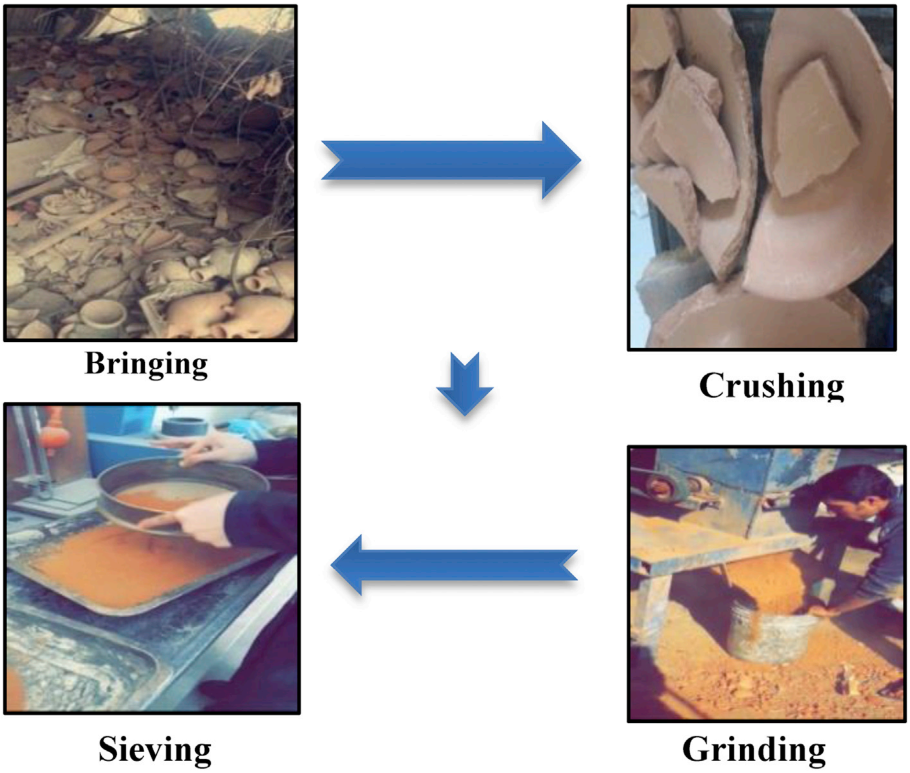


Fig. 2. Preparation of pottery pwoder.

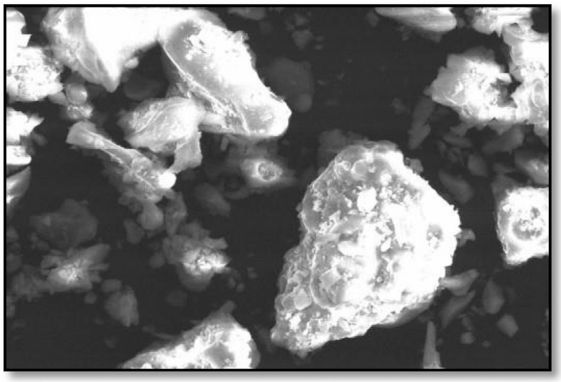


Fig. 3. SEM image of ground of BA [1].

Table 4
Mixture proportions of all mixes with 4% $CACL_2$ (kg/m^3).

Mixture ID	Cement	Sand	Water	$CaCl_2$	PP	BA
Control	740	2035	344.64	14.36	–	–
PP10	666	2035	344.64	14.36	74	–
PP20	592	2035	344.64	14.36	148	–
PP30	518	2035	344.64	14.36	222	–
BA10	666	2035	344.64	14.36	–	74
BA20	592	2035	344.64	14.36	–	148
BA30	518	2035	344.64	14.36	–	222

3.3. Compressive strength

The effect of various parameters, such as age and replacement with PP and BA and $CaCl_2$ solution, on compressive strength are discussed in this section.

At ambient temperature, compressive strength increased with age, as shown in Table 7. The compressive strength of all mixtures at 90 days was slightly higher than/equivalent to that at 28 days. When the cement was replaced with PP and BA, the compressive strength of the mortar was comparably equal to or marginally less than that of the reference mortar mixtures. The compressive strength of the cement mortar decreased with the increase in OPC replacement (up to 14%) with 30% PP in ambient curing conditions at 28 days, as shown in Fig. 7. A linear relationship was found between strength increments and PP and BA percentage replacement, as shown in Figs. 7 and 8. This linearity was observed for long curing times, probably due to the high contribution of PP and BA to strength.

An irregular strength increase was shown when the pottery materials were combined with different percentages, at a combination of 5%, 10% and 15% BA and 5%, 10% and 15% PP as an alternative to cement. Fig. 9 illustrates the compressive strength results of mixtures with control mix and combined pottery materials. The combined pottery materials provided nearly equivalent strength to control mixtures in all ages. A portion of the cracks is generated during the load due to the water absorbed from the PP and BA especially with the high percentage of pottery materials at earlier ages. In some cases, the strength increments increased at 90 days (also refer to Table 8). The compressive strength decreased with up to 18% replacement of OPC with 30% BA. With

Fig. 4. Calcium chloride powder and solution.

Table 5
Mixture proportions of all mixes without $CACL_2$ (kg/m^3).

Mixture ID	Cement	Sand	Water	PP	BA
Control Mix	740	2035	359	–	–
PP10	666	2035	359	74	–
PP20	592	2035	359	148	–
PP30	518	2035	359	222	–
BA5	703	2035	359	–	37
BA10	666	2035	359	–	74
BA15	629	2035	359	–	111
BA20	592	2035	359	–	148
BA30	518	2035	359	–	222
BA5%					
+PP5%	666	2035	359	37	37
+PP10%	629	2035	359	74	37
+PP15%	592	2035	359	111	37
BA10%					
+PP5%	629	2035	359	37	74
+PP10%	592	2035	359	74	74
+PP15%	555	2035	359	111	74
BA15%					
+PP5%	592	2035	359	37	111
+PP10%	555	2035	359	74	111
+PP15%	518	2035	359	111	111

the addition of 4% $CaCl_2$, the compressive strength was slightly improved, as shown in Figs. 10 and 11 and Table 7.

The compressive strength of pottery mortars with 4% $CaCl_2$ increased by approximately 2.3 and 0.7 times for 10% and 20% PP, respectively. When the cement was replaced with 30% PP, the compressive strength was comparably equal to that of the mixture without $CaCl_2$. The compressive strength of BA mixtures with 4% $CaCl_2$ was equal to that of the

Table 6
Fresh properties of tested mixtures.

Cement replacement, %	Water Content of Normal Consistency, %	Initial Time of Setting, min	Final Time of Setting, min
Standard	23.5	130	192
PP10	23.7	138	210
PP20	24.6	144	216
PP30	24.8	152	220
BA10	23.7	136	201
BA20	24.3	140	212
BA30	24.6	143	217

Fig. 6. Vicat test device.

Fig. 5. Moulds used to preparation mortar specimens.

Table 7
Compressive strength of mortar with 4% $CaCl_2$.

Mixture ID	Compressive Strength, MPa		
	7 days	28 days	90 days
Control	27.3	44.3	45.6
PP10	23.4	43.4	44.8
PP20	19.7	42.6	43
PP30	18.2	38.1	39.2
BA10	25.3	43.5	44
BA20	19.6	42.1	42.8
BA30	15.1	37.4	38.2

mixture without $CaCl_2$ at different ages. The same conclusion was drawn by other studies [16,37–40]. This behaviour attributed to the mechanism of clay swelling. When clay contacts with water, exchangeable cations in the clay interlayer space tend to hydrate, thereby forcing clay layers apart. Swelling can occur via two different regimes, namely, crystalline and osmotic swelling [5,7,28,41–44]. Moreover, the possibility of self-healing phenomena was detected by the identification of 20% BA and 20% PP hydration products in the previous cement cracks after

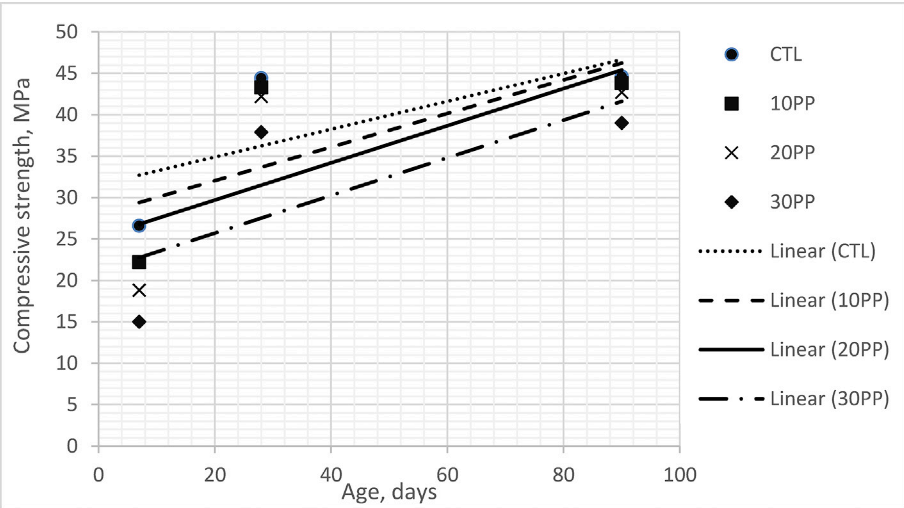


Fig. 7. Compressive strength of mortars with various replacement of PP.

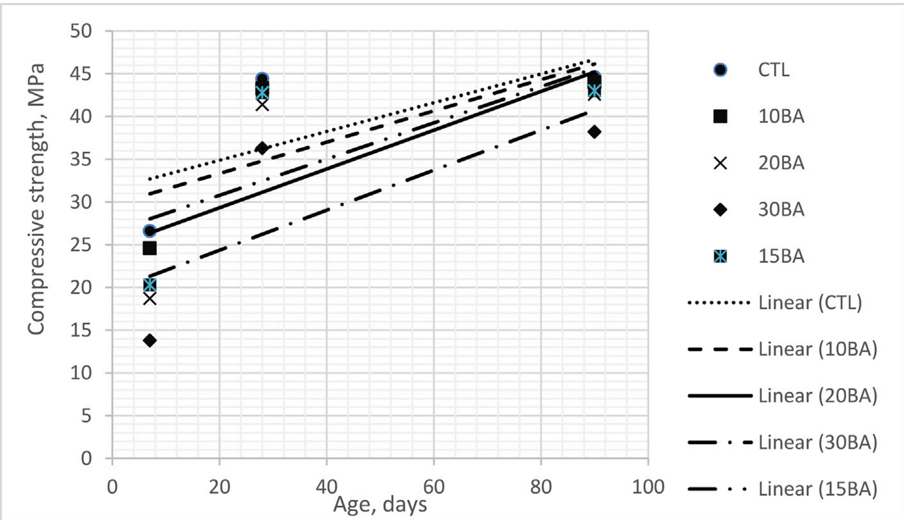
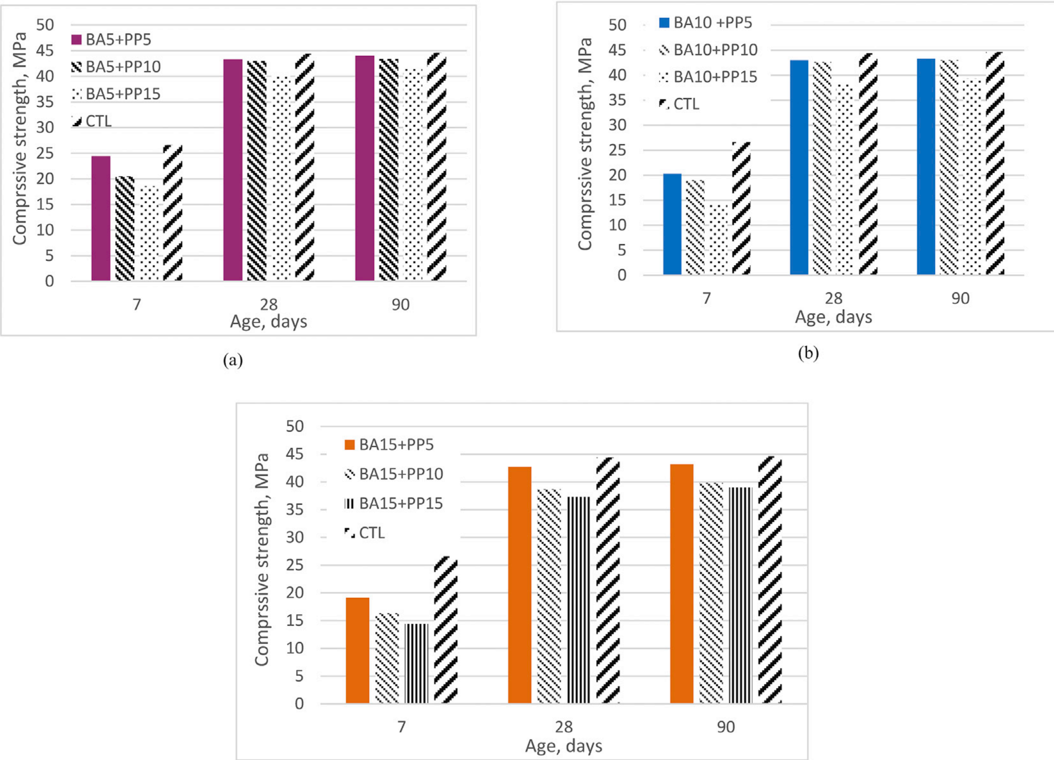


Fig. 8. Compressive strength of mortars with various replacement of BA.



(a) (b) (c)

Fig. 9. Compressive strength of mortars with various replacement of combined pottery materials (PP + BA).

Table 8
Compressive strength with different percentages of PP and BA.

Mixture ID	Compressive Strength (MPa)		
	7 days	28 days	90 days
Control	26.6	44.4	44.6
PP10	22.2	43.3	43.8
PP20	18.8	42.2	42.7
PP30	15	37.9	39
BA5	25.8	43.6	43.8
BA10	24.6	43.3	44
BA15	20.3	42.8	43
BA20	18.7	41.4	42.6
BA30	13.8	36.3	38.2
BA5			
+PP5	24.4	43.3	44
+PP10	20.5	43	43.4
+PP15	18.6	40.1	41.4
BA10			
+PP5	20.3	43	43.3
+PP10	19	42.6	43
+PP15	14.3	38.3	39.3
BA15			
+PP5	19.1	42.7	43.2
+PP10	16.3	38.7	39.8
+PP15	14.4	37.3	39

recovery in air, as also observed in other studies [14,16,24].

4. Conclusions

On the basis of the test results, the following conclusions are drawn:

1. The increase in OPC replacement with PP or BA led to an increment in water required to obtain the standard consistency paste. The penetration time for PP and BA was investigated in this research. The results indicated that the heterogeneous powder rapidly absorbs liquid into the powder due to the high porosity among its particles.
2. The results showed that with an increase in PP and BA, the workability increased.
3. The compressive strength of mortar specimens with 10% replacement of PP or BA is similar to that of the control at ages 7, 28 and 90 days, whereas with 20% replacement, the obtained compressive strength is similar to that of the

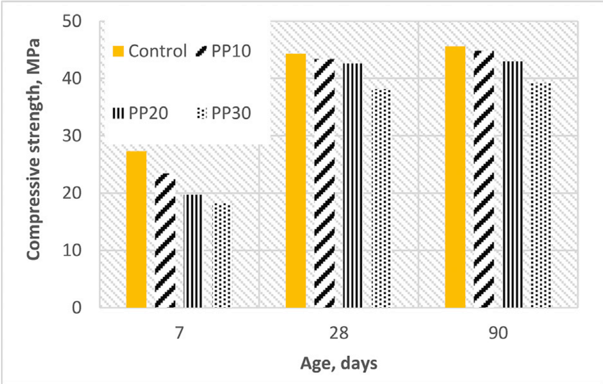


Fig. 10. Compressive strength of PP mortars with 4% $CaCl_2$ at different age.

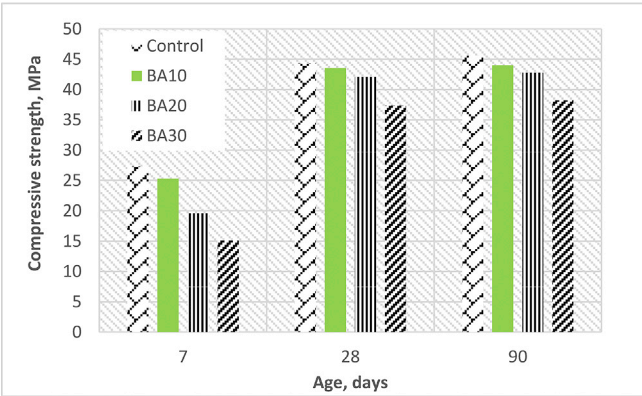


Fig. 11. Compressive strength of BA mortars with 4% $CaCl_2$ at different age.

control at ages 28 and 90 days only. The strength gain rate at an early age tended to increase, whereas the long-term gain rate slightly increased with high percentage replacement.

4. The compressive strengths of the third group of mortar were lower than those of the first and second groups. The best compressive strength result of the mortar specimens with different replacement ratios of PP and a constant ratio of BA (5%) is BA5 + PP10. The pottery materials were considered low-cost cementitious powder materials. This powder can be used in construction given that it fits the purpose and is affordable.
5. In the case of 4% $CaCl_2$, the compressive strength at 90 days was unaffected, nearly similar to that of the reference Portland cement mortar.

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