A Waste Valorization Study on Pond Ash Based Geopolymer Mortar Incorporating Basalt Powder

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Abstract. This paper assesses the valorization of waste materials of pulverized pond ash (PPA) and basalt powder (BP) as a blend to form room temperature (RT) cured geopolymer mortar (GPM). Geopolymer (GP) binders were developed by using sodium-based alkaline activators and 5% BP was incorporated to partial replacement PPA in 0 to 20% increments. The ratio of liquid to solid was varied at 0.48 to 0.54 in order to determine its effect on strength development. M-sand was taken as the fine aggregate to ensure a uniform quality of the particles. Based on the results, the addition of BP enhanced binder reactivity in RT curing conditions and enhanced matrix densification and promoted the formation of more gels. The mixture with the liquid to-binder proportion of 0.50 and 15% BP replacement exhibited the better compressive strength (fc) among all the mixes. The findings reveal that both PPA and BP collaborate to deliver a sustainable and structurally sound GPM which can be applied in building environments with no heat curing.

1 Introduction

The need to find lower-carbon binders as an alternative has been motivated by the heavy consumption of cement as a very important construction binder that has led to a lot of CO_2 emission and a lot of energy used in the production of clinker [1]. Geopolymer binders (GB) as alkali-activated Ai-Si networks that have attracted much attention since they can utilize industrial by-products like ash fly ash, slag, pond ash, and metakaolin etc. to prepare strong cement-free binders with significantly lower embodied carbon [2]. A proper precursor to alkali activation is the pond ash (PA), which is a waste material stored in the ash pond of the coal-fired power stations and contains significant content of silica and alumina. PPA (pulverized pond ash) must be made fit for GB so that common methods include mechanical activation (pulverization), or adjustments of activator concentration and liquid-solid ratios. Raw pond ash is however often lowly reactive, non-homogeneous in particle size, and of variable composition with regard to origin and storage [3]. PPA based GP can obtain useful

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mechanical and durability properties under ambient or mild curing conditions with the appropriate pre-treatment and mix design. Even though GP may be made with pond fly ash that has been activated with a high level of $NaOH/Na_2SiO_3$, it has been shown to be sensitive to the amount of activator present and that some form of reactive additive is needed to enhance early strength. Compared to as-received PA, the decrease in the particle size (milling of PA) immensely enhanced alkali activation and fc, indicating that mechanical activation is an effective approach of rendering PA a precursor that is workable. PA can be valorized in alkali-activated systems when it is mixed with activator and/or reactive supplements (GGBFS, metakaolin); however, the variability in supply has a considerable effect on performance [4]. The combination of PA and GGBFS plus the optimization of NaOH molarity can strengthen and provide durability which has proven the synergy between Ca-rich supplemental materials. Through mix optimization, RT-cured GPM formulations may be produced using non-conventional ashes (including pond/bottom ash), and some blends may be RT curing [5]. The strength of PA was then acquired though there were major benefits to milling, activation, and/or mixing with finer reactive powders. These research [6] are always recommended to control the fineness of particles and the setting of activators. The contextualized fly-ash GP and, detected PA as an underutilized feedstock requiring additional processing steps to achieve geopolymerization; are focused on the advantages of robustness using proper techniques of their formulation. The experimental data prove that liquid-to-solid (L/S) ratio and activator content have a strong impact on the workability and final strengths of PPA geopolymers; the optimal L/S ratio often lies in a narrow range and depends on the particle fineness [7].

Basalt powder (BP), a fine-grained by-product of crushing basalt or the refining of volcanic rock, is composed of silica, alumina (in lesser concentrations), and large proportions of $CaO/MgO/FeO_3$ depending on the source of the material [8]. BP can be used as a micro-filler or reactive additive in alkali-activated binders, improved particle packing, more reactive silica/calcium, and vary pore structure. Nevertheless, workability or reactivity of geopolymers can be reduced when the replacement levels are high and the BP is less reactive than the original precursor [9,10]. BP additions to foamed GP increase the small-pore fractions and reduce the pore size, with further additions adversely affecting the desired properties; it is assumed that BP has a significant effect on porosity and consistency. BP is a promising additive that enhanced the property of fly-ash GP cement by 2.5 to 20 % in several mixes which defines a viable field of replacement, depending on system chemistry [11,12]. On the one hand, BP can be used as a useful filler or partial precursor in GP synthesis when it is combined with the appropriate activator and precursor to enhance fc strength. The GPM of BP and glass powder results indicated that BP composition-dependent effects on residual mechanical/microstructural heating reactions [13,14]. The size of BP particles and variability of source have a strong influence on performance; variability in reactive behavior can be increased by adding an alkali silica source or mixture of BP with Ca-rich precursors (slag) [15].

Despite a lot of study has been done on GP systems made from fly ash, metakaolin, and slag, there are still very few studies that explicitly look into the usage of pulverized pond ash (PPA) and basalt powder (BP) together in room temperature-cured GPM. Although the literature related to PA typically refers to the refinement of particle sizes, the alkaline activation parameters, or the incorporation with Ca-rich constituents, such as slag, most studies on the topic of BP are typically aimed at its incorporation into fly-ash or metakaolin-based binders. As a result, there is a dearth of experimental data regarding the effectiveness of BP as a partial substitute for PPA in mortar formulations that are cured at room temperature. Because room temperature cured GPM systems are more practicable for field applications where heat curing cannot be accomplished, this lack of targeted investigations creates a substantial knowledge gap. These gaps would be directly filled and useful advice for RT cured GPM mixtures would be provided by a focused experimental study that uses representative PPA and BP chemical data, investigates BP replacement from 0–20% by PPA mass, modifies the liquid/solid ratio within a RT curing, and relates these parameters to f_c development.

2 Materials and Methods

2.1 PPA

The pond ash used in this paper was collected by thermal power plant. In order to obtain a fine, reactive “Ai-Si" powder, the received PA was heated in an oven, and subsequently, it was milled in a lab ball mill. In order to achieve a constant fineness suitable to geopolymerization, milling was carried out at 180 rpm, 10-12 hours employing high density grinding media. Specific gravity of the treated PPA was approximately 2.17 and specific surface area was approximately 400 m^2/g.

2.2 BP

BP was obtained from an advert quarrying factory, where it is gathered as a finely produced byproduct of the stone-making process. Before being used, the powder was sieved to make sure every particle went through a 75-µm mesh. According to XRF and table 1, BP had a specific gravity of roughly 2.96 and was primarily composed of silica, alumina, and iron oxides with trace amounts of CaO and MgO.

Table 1. Chemical constituents and properties of PPA and BP

Elements	Oxides (%)	
	PPA	BP
SiO_2	52.11	44.66
Al_2O_3	29.45	13.90
Fe_2O_3	6.69	13.45
CaO	0.95	12.60
SO_3	1.26	0.007
MgO	1.37	7.62

2.3 M-Sand

In all mortar mixtures, the fine aggregate was M-sand supplied by a local supplier. The content was in compliance with the Zone II standards set in the IS 383: 2016. The physical characterisation and sieve analysis were performed according to the IS 2386 (Part I-III). The fineness modulus and specific gravity of the M-sand was 2.27 and 2.62 respectively.

2.4 Alkaline Activator Solution

NaOH was prepared by dissolving 97–98% pure NaOH pellet in distilled water. The sodium silicate solution contained about 28 - 30% SiO_2, 8 -10 % Na_2O, and the rest of the water. As per experimental design the l/b ratio ranged between 0.48 and 0.54.

2.5 Mix Proportions

The GPM mixes incorporated PPA as a primary precursor of Ai-Si, and BP was replaced by PPA at the mass percentages of 0, 5, 10, 15 and 20. The ratio of the binder to the aggregate was 1:3 in all the mixes. Although the liquid-to-solid ratio was gradually varied (0.48, 0.50, 0.52, and 0.54) to determine fc changes during RT curing, the dosage of the alkaline activator remained the same during all trials. Take different quantities of GPM and mix with PPA and BP (see Table 2). P is an abbreviation of PPA, B is for BP, FA is for fine aggregate, SS is for sodium silicate and SH is for sodium hydroxide.

2.6 Mixing and Casting Procedure

In a mechanical mixer, the dry contents of PPA, BP, and M-sand were blended and allowed to mix over a period of three minutes to have a homogeneous distribution of solids. Then, the alkaline activator solution was slowly added and stirred after another four minutes. The fresh mortar was placed in two layers in 70 mm cube moulds and the mortar was crushed on a vibration table in order to release the trapped air. All the samples were then demolded and cured at room temperature until the desired testing ages (1,3,7 and 28 days) after 24 hours.

2.7 Test Methods

fc tests were done on cube specimens in accordance with the recommendation by IS 4031 (Part 6). In order to ensure reliability, three specimens were used as the mean of each test value. Before testing, dimensional and visual examination was conducted to eliminate the possibility of bad samples. Additional qualitative observations concerning fresh behavior, setting characteristics, and mix homogeneity were done during preparation.

Table 2. Mix proportion of GPM with different proportion of PPA and BP.

Mix Code	PPA (%)	BP (%)	FA (gm)	NaOH (gm)	Na_2SiO_3 (gm)	l/b ratio
PB0	100	0	600	27.42	68.58	0.48
PB5	95	5				
PB10	90	10				
PB15	85	15				
PB20	80	20				
PB0	100	0	600	28.57	71.43	0.50
PB5	95	5				
PB10	90	10				
PB15	85	15				
PB20	80	20				
PB0	100	0	600	29.71	74.29	0.52
PB5	95	5				
PB10	90	10				
PB15	85	15				
PB20	80	20				
PB0	100	0	600	30.85	77.15	0.54
PB5	95	5				
PB10	90	10				
PB15	85	15				
PB20	80	20				

3 Result and Discussion

3.1 f_c of GPM with different proportion of PPA and BP

3.1.1 L/B Ratio = 0.48

Fig. 1 shows that the fc increased gradually as BP was added in a l/b ratio of 0.48. The combination without basalt (PB0) had a moderate early f_c with 4.76 MPa at one day and 21.35 MPa at twenty-eight days. The matrix was created with the introduction of BP and PB15 had the highest f_c at all ages of curing with a high value of 26.72 MPa at 28 days and 8.23 MPa at 1 day. This enhancement indicates that with low l/b ratio, 15% BP enhances the geopolymerization performance and promotes densification. PB20 displayed a smaller decrease at any age beyond this age suggesting that there might have been excess filler material which limited binder reactivity.

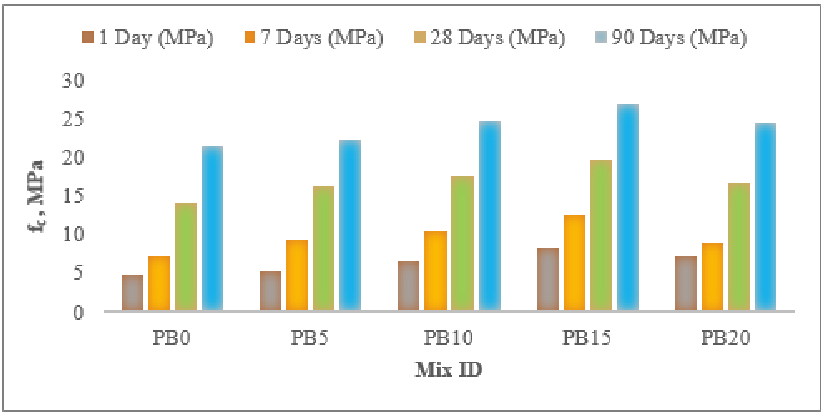

Fig. 1. Compressive strength results of GPM with PPA and BP (l/b- 0.48)

3.1.2 L/B Ratio = 0.50

Fig. 2 demonstrates that all blends exhibited higher 28-day f_c at an l/b ratio of 0.50 as than the 0.48 series. After 28 days, the zero point of the mix PB0 was 29.22 MPa, and BP contribution to the matrix response made it even more. As f_c steadily increased in the early curing stages (8.77 MPa at 1 day, 20.68 MPa at 7 days), PB15 again gave the highest f_c which was 36.01 MPa at 28 days. The volume of liquid was likely to enhance aluminosilicate ("Ai-Si") dissolution in both PPA and BP and the mobility of the activators. Whereas PB20 performance was slightly lower in comparison to that of PB15, it was better than PB0, indicating that there were some positive results of the addition of basalt.

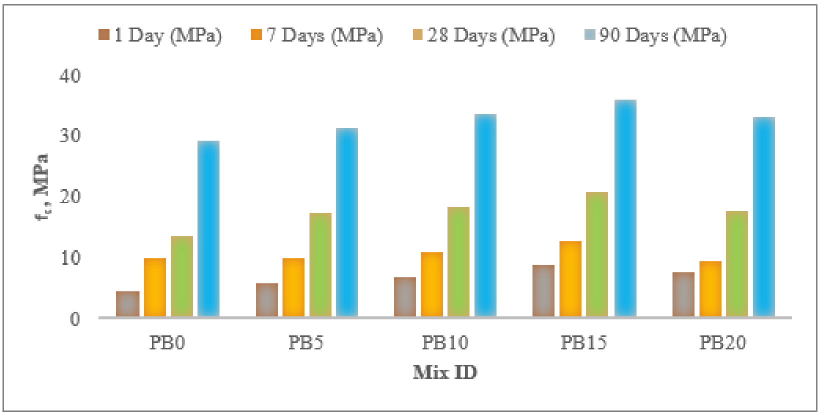

Fig.2. Compressive strength results of GPM with PPA and BP (l/b- 0.50)

3.1.3 L/B Ratio = 0.52

The similar tendencies are also reflected in Fig. 3, where l/b ratio is 0.52. PB15 had the best f_c of any age with 9.32 MPa at one day, 20.88 MPa at seven days and 43.83 MPa at twenty-eight days. Improved behaviour at this liquid level suggests that N–A–S–H gel synthesis becomes improved with improved availability of activators. The PB0 mix had a 28days reaction of 37.43 MPa, PB10 of 41.45 MPa, and PB20 of 40.89 MPa. It means that the plateau at 15% BP and above is strong, and the reactivity balance is optimal at this ratio, although all variants containing basalt worked well.

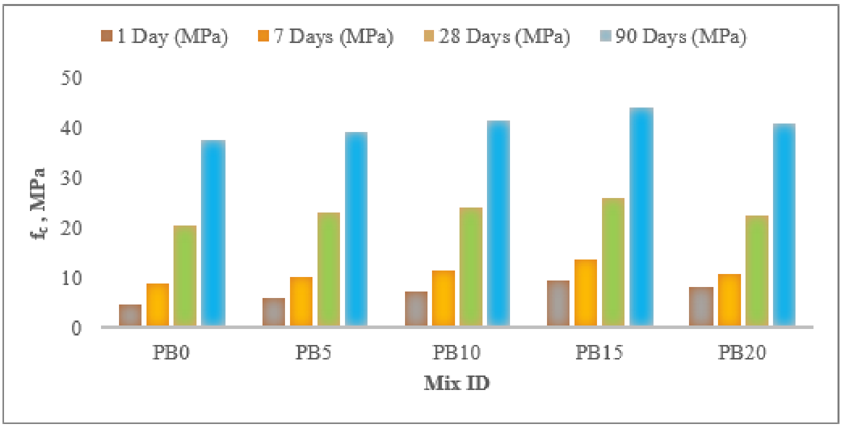

Fig.3. Compressive strength results of GPM with PPA and BP (l/b- 0.52)

3.1.4 L/B Ratio = 0.54

As Fig. 4 illustrates, f_c increase was steady at the highest l/b ratio but not exceeding the values recorded at L/B 0.50 and 0.52. In mixes that contained BP, PB0 was slowly rising steadily to 28.26 MPa at 28 days. Again PB15 gave the best results with 29.43 MPa at the end of 28 days. The additional liquid was likely to raise the pore volume and consequently could not form a solid matrix despite appropriate setting and curing. The strengths however in total were lower than that of the mixtures that had the best L/B ratios, although basalt was added to enhance the mechanical responsiveness.

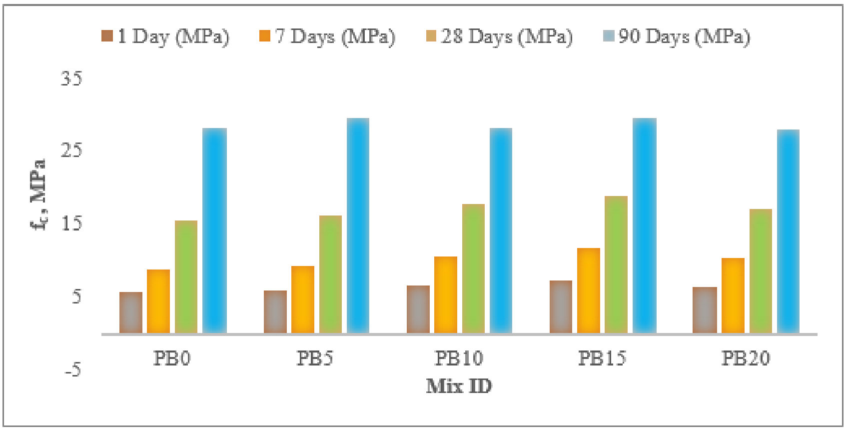

Fig.4. Compressive strength results of GPM with PPA and BP (l/b- 0.54)

3.1.5 Overall Observation

The PB15 blend always gave the highest fc at all the l/b ratios, which showed that the reactivity, packing density, and gel formation of PPA based geopolymer mortar are effectively enhance upon replacing approximately 15 % of BP. L/B ratio of 0.50 and 0.52 gave the best conditions and produced dense and well-structured matrices. Similar trend was noted by [25]. High content of inert could reduce the percentage of active ("Ai-Si") fraction required to form gels, based on the f_c decrease at 20 % BP.

4 Conclusion

Several significant conclusions can be made in light of the experimental results:

1. PA showed promise as a low-calcium (Ai-Si) source, and when mixed with appropriate amounts of BP, its reactivity was further increased. A feasible binder system that might achieve notable f_c under RT curing was offered by the PPA.
2. For all l/b ratios, BP had an impact on the matrix structure and fc development. At all curing ages, the 15% BP replacement consistently generated improved fc among the assessed proportions.
3. The optimization of (Ai-Si) was significantly influenced by the l/b ratio. Improved activator availability at ratios of 0.50 and 0.52 allowed for greater PPA and BP dissolution and encouraged the development of a denser reaction network. While the lowest ratio of 0.48 hindered activator mobility, excess liquid at 0.54 increased pore volume and limited f_c growth.
4. At l/b ratios of 0.50 and 0.52, the PB15 mix had the highest 28-day f_c, demonstrating that moderate basalt incorporation improves both early and long-term mechanical performance in RT mortars.
5. The findings demonstrate that RT-cured PPA–BP GPM is a viable and sustainable substitute for heat-cured systems, providing enhanced mechanical characteristics without requiring more energy. The results also show that low-carbon binder

development and waste valorization can be facilitated by mixing industrial by-products like PPA and BP.

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