Development and Characterization of Paper Sludge and Waste Foundry Sand-Based Alkali Activated Mortar

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Abstract. The alkali-activated materials (AAMs) have demonstrated a noteworthy impact on both CO_2 emission reduction with enhanced compressive strength (CS) and flexural strength (FS). In this work, the primary precursors hydrated lime (LM), paper sludge ash (PS), and fly ash (FA) were used for one-part AAM preparation. Waste foundry sand (WFS) was utilized as a substitute for the river sand. Impacts on the different characteristics of one-part AAM were evaluated under various mix designs.

The fluidity and rheology characteristics were assessed in the fresh state just after mixing, while the CS and FS tests were done at different ages after casting in the molds. The results revealed that FPL5 has maximum CS and FS in all the AAM mixes. The CS of FPL5 after 28 days is 31.6 MPa and FS is 5.94 MPa, which are 5.38% and 2.62 % less than the CS and FS of the control sample (SC) respectively. The rheological data indicate a positive correlation between the plastic viscosity and the WFS. Yield stress rises as paper sludge (PS) content grows but decreases as WFS content increases. This suggests that the integration of waste foundry sand can enhance the mechanical properties of AAM. Furthermore, the rheological analysis indicates changes in fluidity and viscosity based on the proportions of paper sludge and waste foundry sand. Overall, these findings contribute valuable insights into optimizing sustainable and high-performance one-part AAM formulations, offering potential solutions for reducing CO2 emissions and advancing the field of eco-friendly construction materials.

Keywords: One-part alkali-activated material, Paper sludge, Waste foundry sand, Rheology

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1 Introduction

Growing environmental consciousness has prompted substantial study calls to lessen the impact of cement production on the environment. When cement binds to other concrete ingredients, a concrete composite is created. Environment degradation is a result of the massive emissions of carbon dioxide (CO_2) that cement manufacture produces into the atmosphere [1, 2]. Cement is mostly responsible for the 0.5% annual rise in CO2 output, and regrettably, it accounts for 8% of global CO_2 emissions [3, 4]. In a similar vein, cement manufacturing costs are rising daily. Researchers began looking at other substitute materials and their potential use in composites because of this worry. An environmentally beneficial substitute is alkali-activated materials (AAMs), which are mostly made by the activation of precursors. These precursors are usually obtained from industrial or agricultural /wastes. For instance, slag, fly ash (FA), and rice husk ash[5]. The process of activating and binding the concrete uses alkali activators (AA) such as sodium silicate and sodium hydroxide instead of regular cement [6]. This method employs industrial residue while reducing the usage of cement, which contributes greatly to carbon emissions. Consequently, the entire carbon footprint associated with building is reduced [7]. AAM has also been shown to have greater compressive and flexural strengths as well as improved durability when compared to traditional composites [8-10].

In the past decade, several researchers have shown a strong interest in investigating the complete substitution of cement with AAM [11, 12]. Precursor material selection in polymerization manufacturing is based on the material's availability, initial cost, and intended use [13, 14]. The kind of AA determines whether AAM is a one-part or two-part complex. Introducing AA into a dry state is known as a one-part AAM [15, 16]. The AA are utilized in solution form in traditional AAM, sometimes referred to as traditional two-part AAM [17, 18]. However, treating very caustic and dangerous alkaline solutions has proven to be quite challenging [22]. Furthermore, the rheology of conventional geopolymers and AAM can be complicated and difficult to manage because they form a dense, filthy paste, particularly in combinations when sodium acts as the alkali source [17].

NaOH (SH) and Na_2SiO_3 (SS) have been extensively studied and used as activators in alkali-activated materials. Researchers have gained significant insights into their behavior, effectiveness, and impact on the properties of the resulting AAM [19]. This wealth of research contributes to the confidence in using these activators for specific applications. The motivation stems from the environmental impact of cement, which prompts a shift towards innovative solutions. Specifically, our research narrows its focus to one-part AAM, where sodium hydroxide and sodium silicate activators are added to dry-state binders. This strategic choice aligns with the broader objective of reducing cement dependence and mitigating carbon emissions associated with construction [20]. Our detailed objectives encompass the examination of various ratios of precursors, including hydraulic lime, fly ash, and paper sludge, to understand their effects on workability, rheology, compressive strength, and flexural strength. By discovering these specific parameters, the aim was to contribute valuable insights to the development of sustainable and high-performance construction materials.

The primary objective of this study is to examine the impact of various numerical ratios of precursors on the workability, rheology, and the FS and CS of the resulting AAM made with WFS. The primary binders such as hydraulic lime, FA, and paper sludge were used in different ratios in this research. The SH and SS alkali activators were used as 10% of the total binder content. Special attention was paid to the most crucial factors, such as the FA, PS, and LM ratios, AA/binder ratio, and curing temperature, and their effects on flowability, rheology, CS, and FS [7]. WFS has been replaced partially with sand with the ratio of superplasticizer remaining constant. Based on these findings, the ideal blended design has been produced. This approach is unique and distinct from traditional AAM formulations, offering a novel perspective on sustainable construction materials.

2 Experimental Methodology

2.1 Used resources.

The primary aluminosilicate resources employed in this work were FA, PS, and LM. The objective was to obtain an innovative one-part AAM utilizing locally accessible FA and PS powders. The chemical makeup of PS as measured by X-ray fluorescence (XRF) is shown in Table 1. Fig. 1 represents the sizes of WFS and PS.

The superplasticizer named Sika ViscoCrete was acquired from Pak Construction Chemicals located in Multan, Pakistan. The sand used in AAMs from river sand and Waste Foundry Sand, Natural Sand was procured from the Ghazi region of Pakistan, possessing a fineness modulus of 2.61 and WFS has a fineness modulus of 2.21. The particle size for waste foundry sand (WFS) and paper sludge (PS) is relevant to the study as particle size significantly influences the packing density, rheological behavior, and mechanical properties of concrete or mortar. Finer particles generally contribute to improved packing, potentially enhancing its workability and strength[21].

Table 1. Chemical formation of PS

Chemical Composition						
CaO	Al_2O_3	LOI	Na_2O	SiO_2	MgO	K_2O
58.3	9.06	11.54	0.08	16.44	2.73	0.23

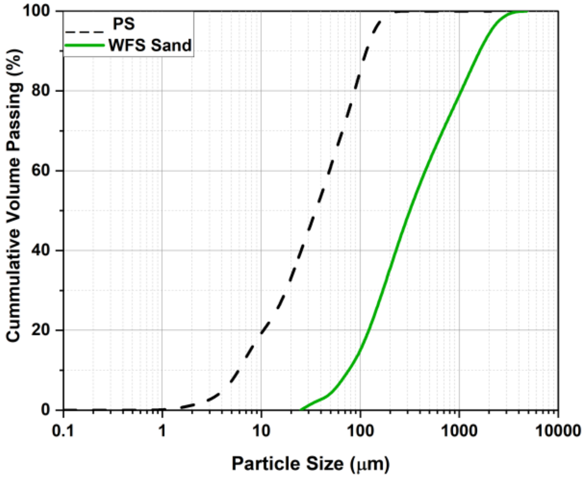

Fig. 1. Particle size of WFS and PS

2.2 Mixing Procedure.

Different mixed designs have been implemented in this research to get the desired results. In this research, the precursors are added in different proportions (see Table 2). To get the outcomes, firstly FA has been added as 90% of the binder and PS and LM have been added as 5% and 5%. While carrying out the research in a later phase the concentration of FA reduces, and PS & LM increases for better results. The ratio of WFS, sand, and activators remains constant. As PS soaks more water that W/B ratio is kept at 0.45. To maintain the workability superplasticizer content was kept constant at 2% of the binder. The rationale behind starting with a mixed design of 90% FA and gradually decreasing it while increasing PS and LM may be justified by the need to discover the effect of varying precursor proportions on the characteristics of the AAM mortar. This systematic variation allows for assessing the impact of changing binder compositions on workability, strength, and other performance indicators. The adjustment in mixed proportions might be aimed at optimizing the combination for enhanced properties, cost-effectiveness, or local availability of the materials.

Table 2. Mix Design

Materials	FPL1	FPL2	FPL3	FPL4	FPL5	SC
Fly Ash (%)	90	80	80	70	70	70
Paper Sludge (%)	5	15	10	15	10	0

Lime (%)		5	5	10	15	20	30
Activators 10% of Binder	**NaOH (%)**	30	30	30	30	30	30
	Na_2SiO_3(%)	70	70	70	70	70	70
W/B		0.45	0.45	0.45	0.45	0.45	0.40
WFS (%)		20	20	20	20	20	0
River Sand (%)		80	80	80	80	80	100
Super Plasticizer (%)		2	2	2	2	2	2

2.3 Specimen Preparation.

Yousefi Oderiji et al. (2019) inspired the AAM mortar mixing technique. In order to ensure consistency, the mixing of all dry binders and activators was performed in a Hobart mixer for a duration of 2 minutes. Liquid elements were thereafter added gradually for 1 minute. Two molds measuring (50x50x50) mm cubes and (40 x 40 x 160) mm prisms, respectively, were used (see Fig. 2). For two minutes, every mold was left on the electrified vibratory table.

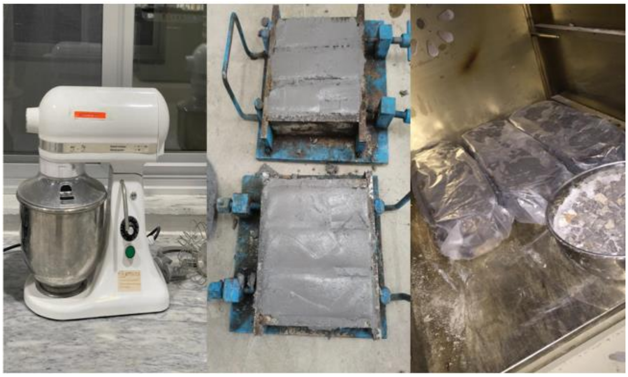

Fig. 2. Procedures of making AAM mortars.

2.4 Testing procedure.

Fluidity. Using the flow table (see Fig. 3), all samples are tested for workability using ASTM Standard C1437. The flow diameter determines the workability of fresh mortar.

CS and FS tests. Each of the samples was examined for CS (ASTM C109) and FS (ASTM C348) over 7, 14, and 28 days to evaluate the attributes of hardening (see Fig 4). Samples were cured initially for 24 hours at 80 degrees Celsius. Later they were allowed to cure naturally until the testing day [22]. The use of an oven curing temperature at 80°C for 24 hours, followed by natural curing, could be explained by the need for accelerated curing to simulate early-age strength development. The higher curing temperature accelerates chemical reactions in alkali-activated materials, promoting early strength gain. However, it is crucial to acknowledge that this departure from the standard 60°C curing might influence the results. Testing was conducted to determine the FS and CS at loading rates of 50 N/s.

Rheology. Using an ICAR rheometer [23] with an assembly of 4-blade vane, the rheological characteristics of the created mixtures were evaluated (see Fig. 5). A stress growth test was utilized to assess static yield stress, and the flow curve was utilized to assess Bingham's parameters. The AAM was mixed and then put into the rheometer to be tested. The testing methodology was adhered to in accordance with other studies [24].

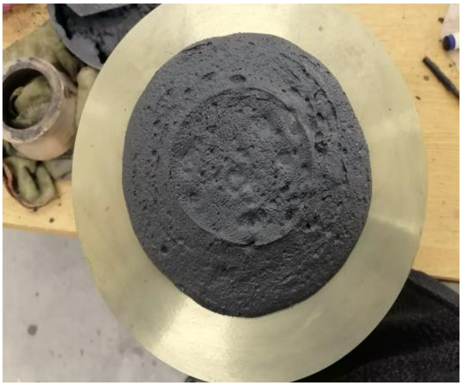

Fig. 3. Flow Table Test

Fig. 4. Compression Testing Machine

Fig. 5. Inner Vane Dimension and Rheometer [25]

3 Results and Discussions

3.1 Fluidity.

The impact of different mixed designs on AAM can be observed in the figure. From the figure we observed that by increasing the content of paper sludge ash the fluidity decreases this may be due to When contrasting with the other elements in the mixture, paper sludge could be able to absorb more water[26]. This may lead to a rise in water consumption, which would make the fluidity decrease. Cellulose fibers, which may be included in paper sludge, can obstruct the mix's ability to flow. Fibers could function as a barrier, limiting the flow of particles and raising viscosity. The highest decrease in workability is seen in FPL4 which is 11.79% less than the Control Sample (see Fig 6). Due to the ability of PS, to absorb water, which is generated by remaining cellulose fibers, fluidity decreases with increasing concentration of paper sludge ash (PS). These fibers may fight with one another for moisture, raising the need for water and decreasing casting fluidity.

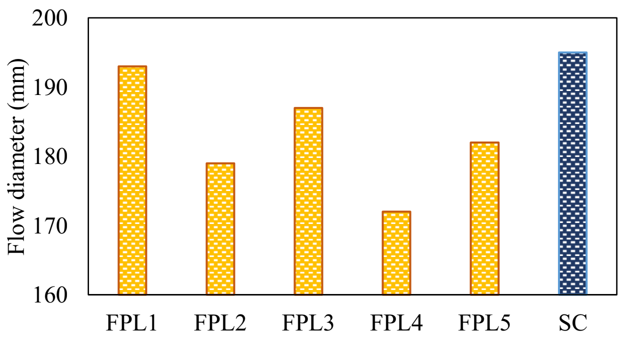

Fig. 6. Comparative analysis of Fluidity using SC and FPL.

3.2 CS and FS.

The results for the CS of different fiber percentages in AAM assessed 7, 14, and 28 days, are displayed in Figure 7. Several parameters, for instance, pore structure, brittleness, and microcrack propagation, affect the hardened characteristics of AAM particles [27]. The results indicate that by decreasing the concentration of FA and increasing the concentration of PS and LM the compressive strength increases. The sample FPL5 has the maximum CS in all of the specimens except SC but the strength is approximately equal to it. The CS for FPL5 after 28 days is 5.94 MPa and for SC it is 6.1 MPa. So, we observed a very minimal difference in strength. This is due to Fly ash is a frequently utilized aluminosilicate precursor rich in reactive components (silica and alumina) that contribute to geo polymerization. Reduced fly ash content may result in less of these reactive ingredients being available, which might have an impact on the production of the geo polymeric binder and, ultimately, compressive strength. The same is the case with Flexural Strength. The samples are tested at various ages (7, 14, and 28 days) after casting. (see Fig 8). FPL5 has greater FS in all the specimens and is approximately equal to the control sample (SC). The FS is about 2.62% less than SC which is a very minimal difference.

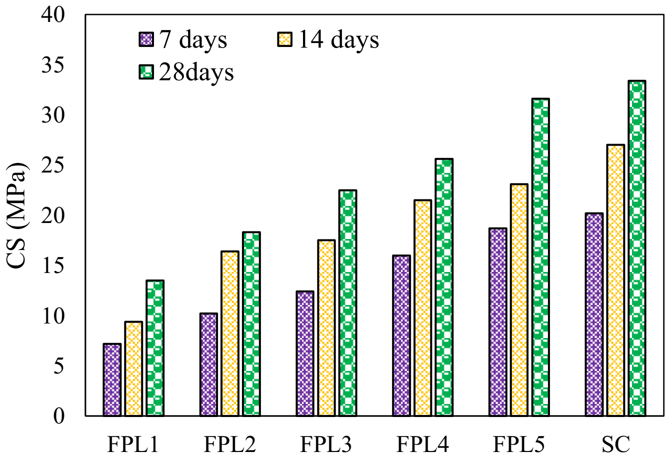

Fig. 7. CS at various ages.

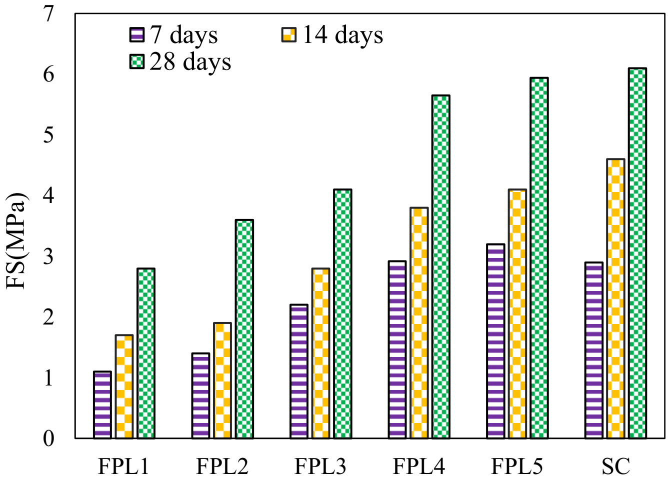

Fig. 8. FS at various ages.

3.3 Rheology

The rheological data indicate a positive correlation between the plastic viscosity and the inclusion of WFS. Nevertheless, the yield YS rises as the amount of PS grows, but it decreases as the amount of waste film solids (WFS) increases. The graph in Figure 9 demonstrates that the yield stress rises as the concentration of PS grows, compared to lime. However, as the percentage of LM begins to rise, the yield stress reduces, as demonstrated for FPL 5.

As FPL4 has the same maximum concentration of PS and LM the yield stress is maximum there and is approximately equal to a control sample. The rheological findings provide valuable insights for adjusting mix designs to enhance workability, stability, and overall handling of alkali-activated materials during construction. Balancing the concentrations of WFS, PS, and LM is key to achieving optimal rheological properties and ensuring successful application in real-world construction scenarios.

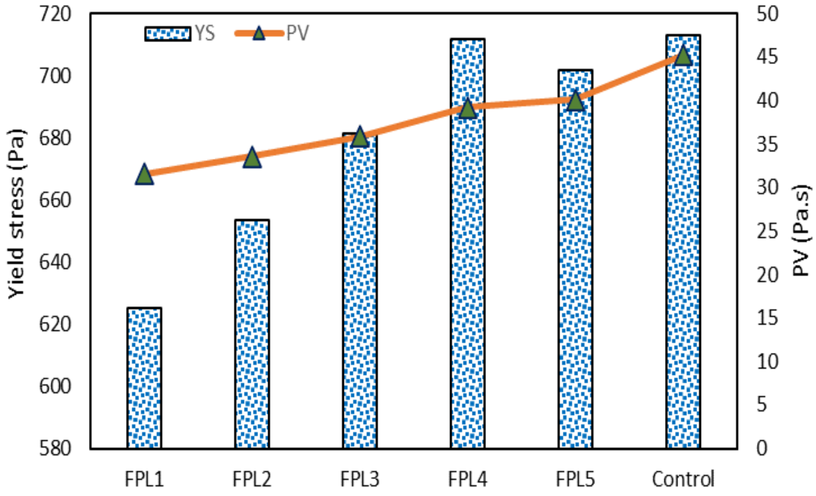

Fig. 9. Rheometer Parameters

4 Conclusions

This research aims to investigate the impact of different mix designs on flexural strength, compressive strength, and rheological factors of one-part AAM. The precursors used in this research are paper sludge ash, FA, and hydrated lime with alkali activators like SS/SH. Different mix designs are assessed during this study so that the best mix design may be chosen for upcoming research. Also, the workability of mortar has been checked in this research.

- The fluidity of alkali-activated mortar has been checked with respect to the control sample. Although, the effect of PS has been observed in this research. The fluidity of FPL4 which has a 70% concentration of FA and equal concentration of PS and LM i.e. 15% decreases with respect to SC. The decrease is about 11.79 % relative to SC. The value of fluidity for FPL4 is 172mm and for SC it is 195mm.
- The CS was checked at 7, 14, and 28 days after casting, and concluded that the sample FPL5 had more CS than all the specimens and slightly less than SC. The decrease in CS is about 5.3% to the control sample (SC). The CS for FPL5 after 7, 14, and 28 days is 18.7MPa, 23.1MPa, and 31.6MPa, and for the SC is 20.2 MPa, 27 MPa, and 33.4 MPa. As lime is calcium-enriched which is suitable to exhibit the geo polymerization process in AAM when the quantity of LM reduces in the mix the strength decreases but when testing different mix designs a suitable design will be formed with the usage of PS and WFS.
- Flexural strength was checked after 7,14 and 28-days just like the compressive strength. The increase in FS is observed in FPL5 which has a 70% concentration of Fly ash 20% concentration as LM and 10% `concentration as PS relative to the other

samples as FPL1, FPL2, FPL3, and FPL4 but there is a slight decrease with respect to SC. The decrease is about 2.62 % to SC. The FS for FPL5 after 7, 14, and 2- days is 3.2 MPa, 4.1 MPa, and 5.94 MPa, and for the control sample is 2.9 MPa, 4.6 MPa and 6.1 MPa.

- Rheology results indicate that the plastic viscosity increases with the increase in waste foundry sand (WFS). However, yield stress increases with the increase in paper sludge (PS) but reduces with the increase in WFS.

The optimal mix designs identified in this study, such as FPL5 for CS and FS, offer practical implications for constructing alkali-activated mortar with improved mechanical properties. Balancing PS, FA, Lime, and WFS in mixed designs can enhance workability and tailor rheological properties to suit specific construction needs. Furthermore, the aim is to implement further mix designs with these precursors and check their mechanical properties, microstructural properties, and durability studies by acid and sulfate attack. These insights are crucial for guiding future research and application of green cementitious materials in construction practices, promoting sustainability and performance.

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