Innovative Use of Waste Foundry Sand in Alkali-Activated Mortar for Enhanced Strength and Rheology

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Abstract. Alkali-activated materials, renowned for their cost-effectiveness and environmentally friendly characteristics, are emerging as promising alternatives to conventional cement-based materials in the construction sector. This study formulates a tailored alkali-activated mortar (AAM) by integrating waste foundry sand (WFS), with a specific focus on optimizing its applicability for 3D printing purposes. AAM compositions were formulated with different percentages (0%, 15%, and 30%) of river sand replaced with WFS. Incorporating WFS improved the strength of AAM, with a 30% improvement observed at the 30% sand substitution level. The rheology of the AAM mix was examined at different water/binder (W/B) ratios, varying from 0.4 to 0.6, with increments of 0.25. The plastic viscosity showed a declining trend as the W/B ratio rose, whereas the yield stress initially rose with the W/B ratio until it reached a specific threshold, beyond which it declined. Moreover, the optimal rheological properties of AAM containing 0%, 15%, and 30% WFS were achieved at W/B ratios of 0.47, 0.50, and 0.55, respectively.

Keywords: Alkali Activated Mortar; Rheology; Plastic Viscosity; Yield Stress; 3D Printing.

1 Introduction

In contemporary construction practices, sustainability and environmental considerations have become paramount, driven by the urgent need to curtail carbon dioxide (CO_2) emissions and minimize the energy intensity associated with cement and concrete production. The cement manufacturing process, consuming approximately two tons of raw materials per ton of cement produced, contributes significantly to environmental degradation, emitting approximately one ton of greenhouse gases, predominantly CO_2 and nitrogen oxide gases. As the cement industry contributes to 8% of worldwide CO_2 emissions, it has become crucial to investigate environmentally friendly alternatives to conventional Portland cement [1]. One promising alternative for gaining traction is alkali-activated material (AAM), which offers compelling environmental benefits, including a 60% reduction in energy consumption and an 80% decrease in CO_2 emissions compared to OPC production. AAM is synthesized through the chemical interaction between aluminosilicate substances and alkaline activators, eliminating the need for conventional cement [2,3].

Sand, a critical component in AAM production, faces a scarcity crisis exacerbated by excessive extraction, which has adverse environmental consequences, including riverbed depletion and ecosystem disruption. Waste foundry sand (WFS) emerges as a sustainable alternative, owing to its abundance, low cost, and recyclability [4]. While offering advantages over natural sand, including heat resistance and high ductility, WFS poses challenges due to its classification as hazardous waste under European regulations, primarily attributed to the presence of organic pollutants and heavy metals. However, its integration into various applications, including concrete and subbases, presents an opportunity for sustainable waste management [5].

Understanding the rheological properties of AAM is paramount for assessing early characteristics crucial to construction applications, including compaction, spreading, molding, and pumping. Research conducted by Panda et al. [6] delved into the rheology of AAMs, revealing that high activator concentrations decreased yield stress while elevating plastic viscosity. Similar to OPC concrete, an increment in yield stress over time, attributed to particle interaction and binder activation, was observed. Investigations into fly ash based AAM blends unveiled intricate connections between rheological characteristics and mechanical properties. The flow behavior of AAM was found to depend on the alkaline solution used, emphasizing the pivotal role of alkaline activator concentration in shaping AAM rheology [7]. Ground granulated blast furnace slag (GGBFS) exerted minimal influence on early-age rheology but expedited the increase in yield stress later due to quicker setting. Despite its minimal initial rheological impact, GGBFS significantly improved compressive strength at early-ages [8]. These findings underscore the intricate interplay

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among activator, slag content, and rheological properties of the developed AAMs, crucial for their printability and performance in construction applications.

While previous studies have extensively investigated the rheology of AAMs, exploring factors such as alkaline activator concentration, and curing conditions, there is a significant gap in discerning the influence of W/B ratio and WFS replacement level on both the strength and rheology of AAM. The introduction of WFS into AAM and examination of its effect on rheological and strength properties across varying W/B ratios represent unique aspects of the current study, representing an area warranting further exploration.

2 Materials and Methods

2.1 OPC

This study utilized Type I OPC meeting ASTM C150-07-2007 standards, exhibiting specific gravity of 3.14 and fineness of 92.02% in compliance with ASTM C786-10 specifications.

2.2 River Ssand

Fine-graded river sand, with 2.6 specific gravity, 1.2% water absorption, and 2.61 fineness modulus, was employed in this study. The fineness modulus was determined using ASTM C136.

2.3 Class F Fly Ash

Class F fly ash obtained from anthracite source was employed. It exhibited 2.3 specific gravity and demonstrated minimal inherent cementitious properties with a calcium content of less than 5%, as confirmed by X-ray fluorescence analysis (see Table 1).

2.4 WFS

Untreated WFS, with 2.3 specific gravity, 4% water absorption, and 2.16 fineness modulus, served as a river sand substitute, with its composition (obtained from the provider) detailed in Table 2.

2.5 Activators and Super Plasticizer (SP)

Alkali activators such as NaOH and Na_2SiO_3 were employed. A sulphonated naphthalene-based SP was added to enhance the flowability and reduce slump retention in the synthesized AAM.

Table 1. Mineral composition of fly ash

Compound	SiO_2	TiO_3	MnO	P_2O_5	SO_3	Al_2O_3	Fe_2O_3	CaO	Na_2O	MgO	LOI
Fly ash	51.3	1.34	0.12	0.91	0.2	25.25	12.8	0.81	0.74	1.5	0.54

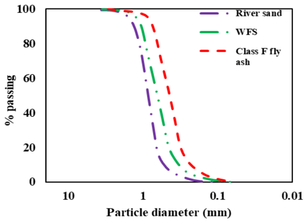

Fig. 1. PSD curve of river sand, WFS, and class f fly ash

Table 2. Elemental composition of WFS determined through energy dispersive spectroscopy

Characteristic of elements	O K	Si K	Br K	C K	Na K	Al K	Ca K	Fe K	Zr K	K K	Ti K
Weight %	47	18	9	7.2	6.5	4.8	4.6	2	1.45	0.72	0.42

2.6 Mix Proportioning and Specimen Preparation.

For mortar mix design, 70% fly ash and 30% cement constituted the total binder, maintaining a 1:1 ratio with fine aggregate particles. Activators comprised 10% of the binder, with NaOH pellets at 30% and Na_2SiO_3 powder at 70%. WFS effects were studied with 15% and 30% river sand replacement, while 0% WFS served as control (AAM-C). The W/B ratio was varied from 0.4-0.6 for each WFS replacement level and SP dosage (1-3%) was adjusted for the desired flow diameter (140-160 mm). Mixing involved dry blending of ingredients, followed by water and SP addition, mixed for uniform slurry, cast into 50 mm cubic molds, and electrically vibrated for 2 minutes [9]. Oven curing at 60°C accelerated strength development due to enhanced fly ash dissolution. Samples were retrieved from oven after 24 hours and stored at ambient temperature for subsequent testing. Table 3 summarizes the mixed proportions.

2.7 Compression and Rheometer Test

Compression and rheometer tests were carried out for AAM. For the compression test, samples were cured at 60°C for 1 day and tested at 7, 14 and 28 days following ASTM C109 guidelines (loading rate = 0.25 MPa/s). The rheology of the AAM mixture were analyzed using an ICAR rheometer equipped with a 4-blade vane. Stress growth and flow curve tests (refer to Fig. 2) were conducted to evaluate plastic viscosity and yield strength. Following the stress growth test, the mix were reworked and allowed to stabilize for 5 minutes to observe the thixotropic effect. By allowing the sample to settle, any settling-related effects, such as sedimentation or the separation of particles or components with different densities caused by gravity, were considered.

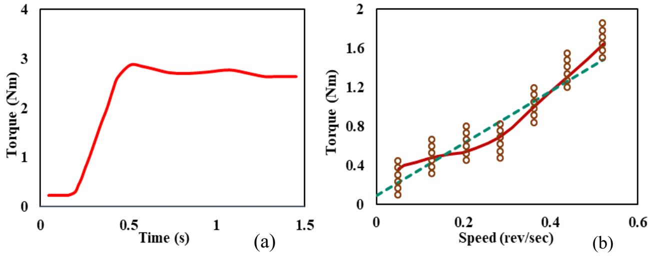

Fig. 2. Rheometer curves (a) stress growth test (b) flow curve test

Table 3. Mix proportions**.**

Mix constituents (Kg/m^3)	AAM-C	AAM 15	AAM 30
Cement	280	280	280
Fly ash	652	652	652
Sand	938	791	647
WFS	0	140	277
Na_2SiO_3	65	65	65
NaOH	28	28	28
W/B ratio	0.4-0.6	0.4-0.6	0.4-0.6
SP (% by wt. of total binder)	1-3	1-3	1-3

3 Results and Discussion

The intricate composition of AAM leads to complex rheological behavior governed by interactions between its various components [10]. Fig. 3 (a-c) illustrates the impact of the W/B ratio on yield strength and plastic viscosity, with each data point representing the average of three tested samples. Rising the W/B ratio from 0.4 to 0.6 caused a gradual decrease in plastic viscosity across all WFS replacement levels, followed by a steeper decline. Yield stress, in contrast, initially increased with the W/B ratio until reaching a peak at 0.475, 0.50, and 0.55 for AAM-C, AAM-15, and AAM-30, respectively. Beyond these W/B ratios, a sudden drop in yield stress was observed for all compositions. This behavior can be attributed to the occurrence of peak polymerization reactions at specific W/B ratios for each mix. The high values of rheological parameters at lower W/B ratios are likely due to early-stage processes like flocculation, particle interactions, and reaction product formation [11].

Furthermore, the lightweight nature and higher water absorption capacity of WFS contribute to increasing plastic viscosity as its content rises (Fig. 3 a-c). Notably, all WFS-containing samples displayed lower yield stress compared to AAM-C. This is primarily caused by the light density of WFS compared to that of normal sand, directly affecting the mixture's flow characteristics. Similar trends were observed by Hassan et al. for diatomaceous earth (DE) additions, with increasing DE content leading to higher plastic viscosity and lower yield stress [12].

Fig. 3 d displays the average strength values obtained from three tested samples of AAM cubes at 7, 14, and 28 days. Samples containing WFS exhibited higher compressive strength than AAM-C, with a maximum 30% increase achieved when 30% of sand was replaced with WFS. This strength enhancement is due to the creation of a denser, less porous gel structure during the geopolymerization process, leading to stronger inter-particle bonds and improved mechanical properties. The observed positive correlation between WFS and compressive strength is corroborated by previous studies by Reza et al., Bavita, and Pardeep [9,13] The effect of WFS on the strength of OPC mixes—as studied by Bavita Barvaj et al.—appears to be the opposite of its effect on AAMs [13].

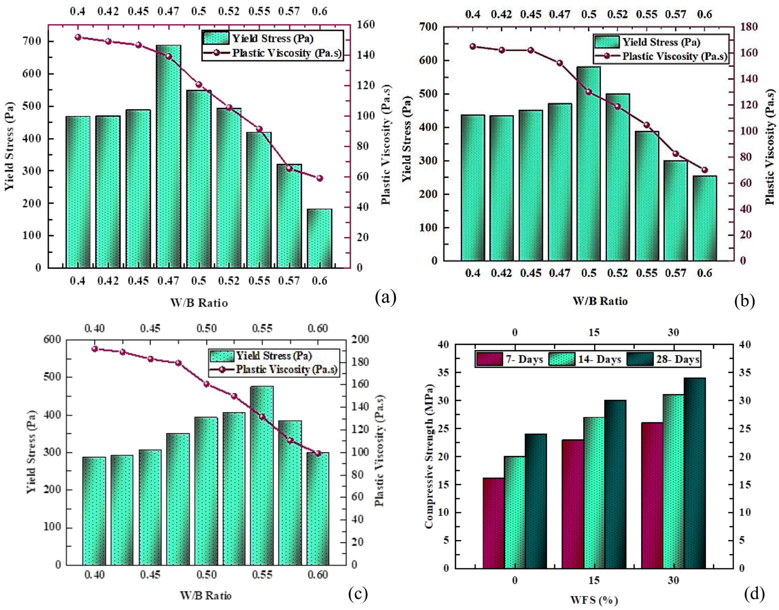

Fig. 3. Rheological properties for (a) AAM-C (b) AAM-15% (c) AAM-30%; (d) compressive strength

4 Conclusions

This study determines the influence of WFS on strength and rheology of AAM. The key findings are as follows:

- WFS incorporation caused a significant rise in AAM compressive strength. Replacing 30% of river sand with WFS yielded a 30% improvement in strength.
- WFS content demonstrated an inverse relationship with yield stress and a direct relationship with plastic viscosity. The W/B ratio had a non-monotonic effect on rheological properties. Plastic viscosity decreased with increasing W/B ratio, while yield stress exhibited an initial increase followed by a decrease beyond a specific W/B ratio. This behavior suggests a balance between workability and stability within an optimal W/B range.
- The combination of WFS content and W/B ratio significantly influenced rheological properties. Optimal rheological properties were achieved in AAM formulations containing 0%, 15%, and 30% WFS at W/B ratios of 0.47, 0.50, and 0.55, respectively.

Overall, this study demonstrates the effectiveness of WFS in improving the mechanical and rheological properties of AAM. The identified optimal formulations offer promising approaches for utilizing WFS in sustainable construction applications.

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