https://doi.org/10.1051/e3sconf/202560302008

Production of mortar with calcined alum sludge as partial cement replacement

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Abstract. Alum sludge is a largely generated and disposed waste from water treatment plants. This study aimed to produce mortar using alum sludge calcined at different temperatures (600 – 900 ºC). After the optimal calcination temperature was selected, the calcined alum sludge was used to replace 5, 10, and 15 % of cement by mass in mortar. The performance of the mortars was evaluated based on the workability, compressive strength, flexural strength, porosity, and percentage of water absorption. Mortars with alum sludge calcined at 800 ºC had the highest strength as compared to the other temperatures. The mechanical strength of mortars reduced while the porosity and percentage of water absorbed increased with increasing calcined alum sludge content. Although replacing 5 % of cement with calcined alum sludge would reduce the mechanical strengths by 13 – 15 %, it was still acceptable as it had negligible influence on the porosity and water absorption value of the mortar. In short, the partial substitution of cement with calcined alum sludge should be limited within 5 % to maintain the performance of the mortar.

1 Introduction

Global urbanization has increased the demand for more infrastructure, requiring the cement industry to boost production to meet market needs. However, cement manufacturing contributes to 8 % of global CO_2 emissions [1], primarily from limestone calcination and electricity generation to heat the kiln [2]. Thus, finding affordable and sustainable alternative materials becomes imperative.

Alum sludge is a solid residue from water treatment plants where aluminium salts are used as coagulants [3]. Water operators in Malaysia generate 2.0 million tons of alum sludge per year, with global daily production estimated at over 10,000 tons [4,5]. It is typically disposed of in stockpiles, sewers, and landfills [6], posing pollution risks from aluminium and heavy metal toxicity, thus harming ecosystems and human health [7,8].

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Researchers have explored the uses of alum sludge in concrete and mortar. Most studies claimed that 800 ºC is the optimal calcination temperature to pre-treat alum sludge [3,4,9,11]. Calcination eliminates organic matter and enhances the pozzolanic activity of silica and alumina [3,11]. This promotes the formation of aluminium-bearing phases that contribute to strength such as calcium aluminate hydrate, ettringite, and stratlingite [9,12]. Studies suggested that replacing 10 – 15 % of cement with calcined alum sludge yields maximum concrete strength [4,9,10,12]. However, high-temperature calcination is energy-intensive and not economical. Some studies proposed lower optimal temperatures such as 600 ºC [13] and 700 ºC [14]. Thus, the ideal treatment for alum sludge is still debatable.

The objectives of this study are to determine the optimal calcination temperature for alum sludge and to evaluate the impact of varying amounts of calcined alum sludge as a partial cement substitute to produce sustainable and cheaper mortar.

2 Materials and methods

2.1 Materials

Raw alum sludge was collected from KL-Kepong Oleomas Sdn. Bhd, Selangor. It was ground and sieved through a 90 µm sieve. The alum sludge was then calcined in a furnace at 600, 700, 800, and 900 ºC for 3 h. Portland limestone cement (MS EN 197-1:2014 CEM II / B-L 32.5N) and sand with a maximum size of 2.36 mm were used in this research.

2.2 Mix proportions and sample preparation

Firstly, a pilot study was conducted to identify the optimal calcination temperature for alum sludge. Mortar specimens, with a water-to-binder-to-sand ratio of 0.55:1:3, had 5 % of cement replaced with different calcined alum sludge. The specimens were cured by water immersion for 7 days and their mechanical strengths were evaluated. After determining the optimal temperature, the specimens were produced with 5, 10, and 15 % of cement replaced with the selected calcined sludge (see Table 1) and were cured for 7, 14, and 28 days.

Table 1. Mix proportions of mortar.

Replacement level (%)	Water (wt %)	Cement (wt %)	Alum sludge (wt %)	Sand (wt %)
0	12.09	21.98	0	65.93
5	12.09	20.88	1.10	65.93
10	12.09	19.78	2.20	65.93
15	12.09	18.68	3.30	65.93

2.3 Experimental procedures

2.3.1 Flow table test

The flow table test was conducted in accordance to BS EN 1015-3:1999. The diameter of the mortar spread was measured after the table was jolted 15 times at a rate of 1 rev/s.

2.3.2 Mechanical tests

The compressive strength test was conducted using mortar cubes (50 mm × 50 mm × 50 mm) according to BS EN 12390-3:2009. The flexural strength test was conducted with mortar prisms (40 mm × 40 mm × 160 mm) complying with BS EN 1015-11:2019. The mechanical strengths of the specimens were assessed after 7, 14, and 28 curing days.

2.3.3 Porosity test

The porosity test was conducted using the water displacement method. Cylindrical mortars (ø 45 mm × 40 mm) that had been cured for 28 days were weighed to determine their saturated surface dry masses (M_{sat}). The specimens were placed in the water buoyant apparatus to measure their masses in water (M_{wat}) and then dried in an oven for 24 h at 100 °C to obtain their oven-dried masses (M_{dry}). The porosity was calculated using Eq. 1.

$$\text{Porosity} = \frac{M_{sat}-M_{dry}}{M_{sat}-M_{wat}} \times 100\ \% \qquad (1)$$

2.3.4 Water absorption test

The water absorption test was performed according to BS 1881-122:2011. Cylindrical mortars (ø 45 mm × 40 mm) which had been cured for 28 days were dried in an oven for 24 h at 100 °C. The percentage of water absorption of mortar was calculated based on the mass difference before and after immersing the specimens in water for 30 mins.

3 Discussion

3.1 Effect of different calcination temperatures on alum sludge

Figure 1 shows the 7-day compressive and flexural strengths of mortar containing different calcined alum sludge. Among the four treatment temperatures, the specimens calcined at 800 ºC exhibited the highest compressive (13.191 ± 0.375 MPa) and flexural strengths (4.1118 ± 0.2405 MPa), closely matching those of the control specimens (15.266 ± 1.031 MPa and 4.335 ± 0.2942 MPa, respectively).

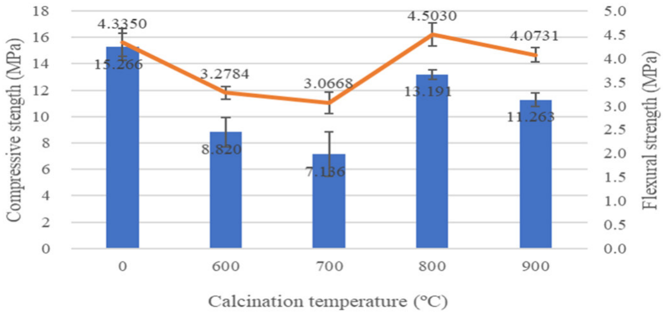

Fig. 1. Compressive and flexural strengths of mortar containing alum sludge calcined at different temperatures.

Heating alum sludge at 800 ºC enhanced its pozzolanic activity by preserving the amorphous silica phase and forming poorly crystalline η-alumina which possess cementitious activity [3,12]. These compounds reacted with hydrated lime to produce calcium aluminate hydrates and calcium silicate hydrates [12]. Specimens treated at 900 ºC showed slightly lower performance due to mineral crystallization from amorphous to crystalline phases, which are less pozzolanic [3,12,15]. Based on these findings, 800 ºC was selected as the optimal calcination temperature for alum sludge in subsequent research.

3.2 Effect of different amounts of calcined alum sludge as cement replacement

3.2.1 Workability

Figure 2 shows that increasing amounts of alum sludge decreased the workability of mortar. The workability of the mortar with 5 % alum sludge decreased from 11.0 cm to 10.5 cm while those with 10 and 15 % alum sludge were unworkable. The loss in workability was because of the high water absorption capacity of the alum sludge arising from the large specific surface area and high porosity of the sludge particles as well as the increased amount of silica in the mixture. The rough and irregular surface texture of the alum sludge particles also increased the friction force among the cement, sand, and alum sludge particles, hence causing a certain degree of flow resistance. This phenomenon was also observed by Liu et al. [9] and Vasudevan [16].

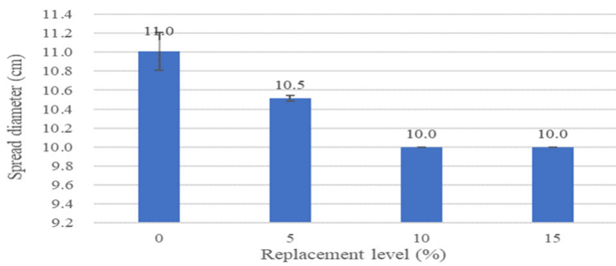

Fig. 2. Workability of fresh mortar.

3.2.2 Mechanical Strengths

Figure 3 and Figure 4 describe that increasing amounts of alum sludge weakened the compressive and flexural strengths of mortar at all three curing ages. The control specimens had the highest compressive (24.438 ± 2.363 MPa) and flexural strengths (5.1494 ± 0.2041 MPa). Specimens with 5 % alum sludge had the closest strengths to those control specimens. After 28 curing days, the compressive and flexural strengths achieved by specimens with 5 % alum sludge were 21.209 ± 2.363 MPa (13 % lower than reference) and 4.3754 ± 0.1459 MPa (15 % lower than reference), respectively. Meanwhile, specimens with 15 % alum sludge hardly developed any strength. Factors influencing the strengths include the decrease in workability due to the addition of alum sludge. This caused difficulty during casting and compaction as more open pores were in the matrix, hence interfering with the hydration and continuity of the matrix.

Besides, the dilution effect from cement being replaced may be more significant than the filler effect and pozzolanic activity of alum sludge, forming fewer hydration products necessary for strength development [9]. Physically, alum sludge particles are more porous and weaker than cement clinkers. Under compressive loading, the microcracks tended to propagate through the weaker alum sludge and form major cracks as opposed to the unreacted clickers and sand particles which are harder [9].

3.2.3 Water absorption and porosity

Figure 5 shows the percentage of water absorbed and the porosity of the specimens after curing for 28 days. The water absorption capacity of mortar is intricately linked to its porosity, with the water absorption pattern closely mirroring that of the porosity trend. As the proportion of alum sludge increased, so did the porosity and water absorptivity of the specimens. However, incorporating 5 % alum sludge in mortars remained acceptable, as its porosity and water absorption percentage were relatively akin to the reference specimen. This was because fresh mortar with 5 % alum sludge maintained a certain degree of flowability, facilitating better compaction and minimizing air voids.

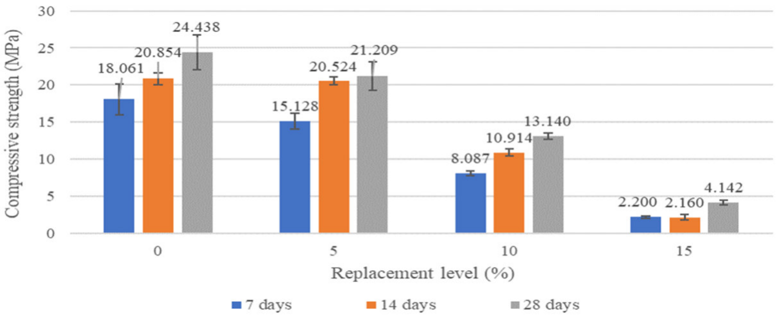

Fig. 3. Compressive strength of mortar at 7, 14, and 28 curing days.

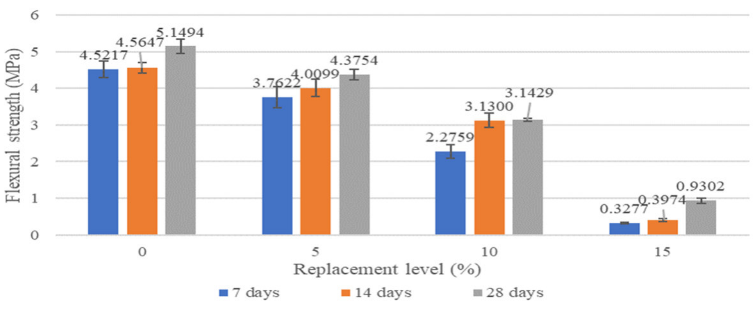

Fig. 4. Flexural strength of mortar at 7, 14, and 28 curing days.

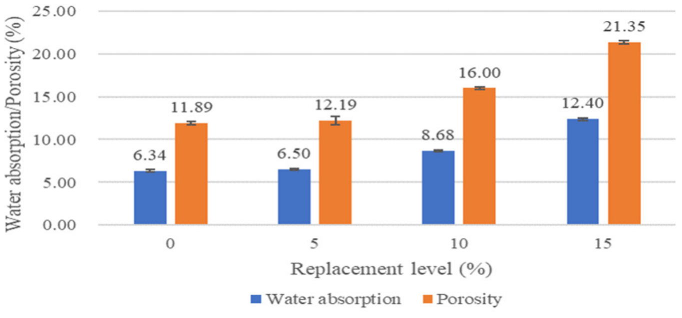

Fig. 5. Water absorption percentage and porosity of mortar at 28 curing days.

Meanwhile, the porosity and water absorptivity of the specimens rose significantly with increasing replacement levels. Adding 15 % alum sludge nearly doubled the porosity and water absorption. Previous studies have also noted a similar increase in porosity when waste sludge is added to concrete [17,18]. The preparation of fresh mortar became increasingly challenging with more alum sludge added, as the hydrophilic nature of alum sludge tended to absorb mixing water, resulting in unworkable mortar. Consequently, this increased pore size and volume in the hardened paste, impacting mortar strengths. The rise in porosity could also be attributed to a dilution effect, as fewer hydration products formed in the specimens, limiting the cement matrix's continuity.

Furthermore, as more alum sludge was added, higher porosity in the mortar meant a larger volume of water would be retained in these voids [12,17]. In addition to the irregular particle shape and large surface area causing high water absorption capacity of alum sludge ash [12], its high porosity makes it highly water permeable [19]. The distribution of these porous ash particles facilitated increased water absorption [19].

4 Conclusion

This study investigated the production of environmentally friendly mortar using alum sludge calcined at varying temperatures. The results indicated that calcination at 800 ºC yielded the highest strength mortar compared to other temperatures. As the research proceeded with using alum sludge calcined at 800 ºC, the workability of the fresh mortar decreased with the increase in replacement level as calcined alum sludge increased the water demand of the mortar. This replacement also contributed to decreased compressive and flexural strengths, attributed to reduced workability and increased pore volume in the hardened mortar. In addition, the porosity and water absorption value of the specimens increased as more cement was replaced by alum sludge. This was attributed to the high-water absorption capacity and high porosity of the calcined alum sludge. Higher alum sludge content, especially above 10 %, notably compromised mechanical strengths and durability. While specimens with 5 % alum sludge calcined at 800 ºC remained acceptable, exhibiting similar porosity and water absorptivity to control specimens, although they experienced a 13 % reduction in compressive strength and a 15% reduction in flexural strength. Thus, it is recommended to limit the use of calcined alum sludge as a cement replacement in mortar to 5 % or lower.

We sincerely thank the Ministry of Higher Education for the Fundamental Research Grant Scheme funding (FRGS/1/2022/TK01/UTAR/01/1). We are also grateful to KL-Kepong Oleomas Sdn. Bhd. for the alum sludge used in this research.

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