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Fly Ash in Conjunction with NaOH: Impact on Sand Mold Properties and Aluminum Casting Quality

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Abstract

This research examines the combined influence of fly ash and sodium hydroxide (NaOH) on sand mold properties and aluminum casting quality. Experimental investigations were carried out by systematically varying fly ash content (0, 10, 14, 18, and 20 wt%) in molding sand formulations, both with and without the addition of 10 wt% NaOH. The analysis showed that as fly ash content increased, sand mold samples with NaOH gained compressive strength and hardness but lost permeability, whereas samples without NaOH experienced a decline in strength and hardness along with an increase in permeability. Microstructural characterization confirmed that fly ash particles fill interstitial voids between sand grains, with NaOH creating binding bridges that enhance structural cohesion. The appropriate composition of 18 wt% fly ash and 10 wt% NaOH yielded aluminum castings exhibiting excellent mechanical performance and minimal surface imperfections. This composition balances critical mold properties, including adequate permeability, sufficient compressive strength, and appropriate hardness while representing an environmentally beneficial approach through industrial byproduct utilization. The findings provide foundries with a scientifically validated sand casting methodology using fly ash and NaOH activation that simultaneously improves aluminum casting quality and reduces costs through enhanced mold properties and sustainable waste material utilization.

Keywords: Sand casting, Fly ash, NaOH, Aluminum, Casting defects

1 Introduction

Sand casting represents one of the most widely utilized metal forming processes in foundry operations due to its versatility, cost-effectiveness, and ability to produce complex geometries. The quality of sand castings depends significantly on the properties of the molding sand, which can be modified through various additives to enhance specific characteristics [1,2]. Traditional additives in sand casting include bentonite, wood ash, coal dust, dextrin, and silica flour, each selected based on the casting material, mold type, and desired final properties.

Fly ash, a byproduct of coal combustion in thermal power plants, has emerged as a promising additive for sand mold applications. Its fine, spherical particles offer multiple benefits in sand casting, including improved permeability, enhanced thermal resistance, reduced mold distortion, better collapsibility after casting, and minimized surface defects on castings [3]. Previous studies have demonstrated that fly ash incorporation at concentrations up to 15-20 wt% can maintain or enhance key mold properties while potentially reducing material costs by approximately 25% [4,5]. Researchers have also observed that fly ash particles, being smaller than sand grains, improve conductive heat transfer and create smoother casting surfaces by filling gaps between sand grains [6].

Sodium hydroxide (NaOH), a strong alkali, has been identified as an effective activator that increases the reactivity of various binders in foundry applications. It has been incorporated in patent formulations with other components such as starch and alkyl silicate to enhance overall binder performance through improved mold strength and structural stability [7,8].

While previous investigations have examined the effects of fly ash or NaOH independently on sand mold properties, limited research exists on their combined influence, particularly regarding aluminum casting applications. This study aims to address this knowledge gap by systematically investigating the synergistic effects of fly ash in conjunction with NaOH on sand mold properties and resultant aluminum casting quality. The research seeks to identify appropriate compositions that balance critical mold characteristics including permeability, compressive strength, and hardness, while enhancing the mechanical properties and surface quality of aluminum castings.

2. Methodology

2.1. Materials

The sand used was silica sand, which is commonly utilized in foundry applications. It possessed an average grain size of 50–60 mesh, corresponding to approximately 250–300 μm in particle diameter. The sand had a predominantly sub-angular shape, suitable for balancing flowability and compaction.

Fly ash was incorporated into the molding sand to evaluate its influence on the sand properties. The fly ash was supplied by Electricity Generating Authority of Thailand. The SEM micrographs in Fig. 1 reveal that the fly ash particles predominantly exhibit a fine, smooth, and spherical morphology. This characteristic geometry is advantageous in particulate systems, as the spherical shape enhances flowability and promotes efficient packing within the sand matrix. Such morphology enables the fly ash to effectively occupy interstitial voids between coarser sand grains, thereby improving the homogeneity, compaction, and overall stability of the mold structure. The use of high-magnification SEM (1–5 μm scale) was intentional and aimed at highlighting the morphological characteristics and distribution of fly ash particles within the sand matrix. Fly ash particles are significantly smaller and tend to occupy interstitial voids between the much larger sand grains.

NaOH flakes were dissolved in water to prepare a 10 wt% NaOH solution. The NaOH flakes were procured from Global House Co., Ltd., Thailand. The proportions of fly ash and NaOH were determined according to experimental procedure.

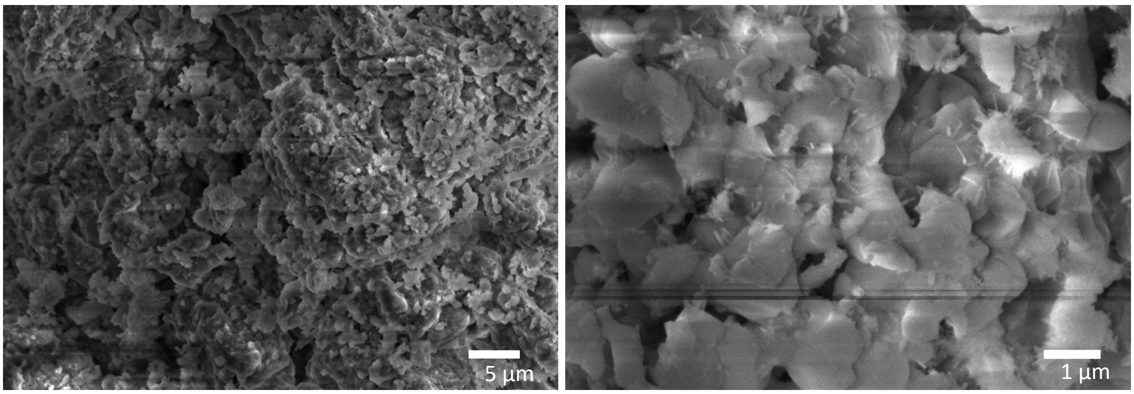


Fig. 1. SEM images of fly ash

2.2 Experimental procedure

The experimental procedure for this study followed a systematic approach to investigate the effects of fly ash and NaOH on sand mold properties and aluminum casting quality. All sand mold mixtures used bentonite as the primary binder. In the experimental groups containing NaOH, a 10 wt% NaOH solution was incorporated into the sand-bentonite-fly ash mixture to serve as an activator and enhance bonding performance. Fly ash was added at varying concentrations of 0, 10, 14, 18, and 20 wt%. To prepare the NaOH solution, NaOH flakes were dissolved in water to achieve a 10 wt% concentration. This solution was then added directly to the sand-bentonite-fly ash mixtures designated to receive NaOH.

Specimen tubes were prepared according to the methodology detailed by Khuengpukheiw et al. (2022) [1]. The sand mixtures were thoroughly blended to ensure homogeneous distribution of all components. The prepared mixtures were compacted into cylindrical specimen tubes for property testing. For each experimental condition, four replicate molding sand samples were prepared to ensure statistical validity.

Permeability was measured using a calibrated permeability meter (Georg Fischer [+GF+]), with results expressed in A.F.S. permeability numbers. Compressive strength was determined using a universal sand strength testing machine. Hardness was evaluated with a spring-loaded hardness tester, specifically designed for molding sand surfaces. In this investigation, the hardness of the sand mold sample was measured using a B-scale gauge. The microstructural characteristics of sand mold samples were examined using scanning electron microscopy (Hitachi, SU-8030) at an accelerating voltage of 20 kV, after breaking the molds to retrieve castings.

Recycled aluminum was melted and prepared for sand casting in accordance with standard foundry procedures. Aluminum was cast into prepared sand molds containing different proportions of fly ash and NaOH, producing sample bars with a diameter of 25 mm and a length of 150 mm. The aluminum casting was Al-Si-based, which is widely used in casting applications due to its good castability, corrosion resistance, and mechanical performance. After solidification and cooling, the molds were broken to retrieve the castings. Each casting was machined using a CNC milling machine (Micron VCE 750). Hardness testing was performed using a Galileo Durometria Rockwell hardness tester set to the Rockwell Hardness B-scale (HRB) in compliance with ASTM E18 standards. A 1/16-inch steel ball indenter was applied with a total load of 100 kgf for a dwell time of approximately 5 s to achieve consistent and reliable hardness measurements. The hardness of the aluminum castings was intentionally measured on the machined surface rather than the as-cast surface to ensure consistency and eliminate potential variability caused by surface roughness, oxide layers, or minor casting defects. The quality of the aluminum casting was examined by scanning electron microscope (Hitachi, SU-8030) operated at an accelerating voltage of 20 kV.

Tensile strength testing was conducted using a Shimadzu UH-50A universal testing machine in accordance with ASTM E8/E8M standards. Specimens with a gauge diameter of 6 mm and a gauge length of 30 mm were clamped using round-type wedge grips and aligned axially to ensure uniaxial loading. The test was performed at a constant crosshead speed of 1.5 mm/min. The system is integrated with data acquisition and analysis software to ensure precise measurement and interpretation of the results. For statistical reliability, the tensile tests were repeated four times following standardized testing procedures.

3 Results and discussion

3.1 Sand mold properties

Fig. 2 shows how permeability of sand molds varies with different percentages of fly ash (0-20 wt%), both with and without 10 wt% NaOH addition. For molds without NaOH (0 wt%), permeability starts at around 22 units and gradually increases as fly ash content increases, reaching approximately 35 units at 20 wt% fly ash. This represents an upward trend where permeability improves with increasing fly ash content. In contrast, sand molds with 10 wt% NaOH show a completely different behavior. These molds start with much higher permeability (around 50 units) at 0% fly ash, but then show a consistent decline as fly ash content increases. The permeability decreases significantly to about 30 units at 20 wt% fly ash. A crossover point is observed at approximately 16–18 wt% fly ash, indicating a transition in permeability behavior.

Fig. 3 reveals opposite trends between samples with and without NaOH. Sand mold samples without NaOH exhibit an initial compressive strength of approximately 1.25 kg/cm², which progressively decreases with increasing fly ash content, declining to about 0.75 kg/cm² at 20 wt% fly ash. In contrast, sand mold samples containing 10 wt% NaOH exhibit a lower initial compressive strength of approximately 0.4 kg/cm², but demonstrate a consistent increase with rising fly ash content, reaching around 1.1 kg/cm² at 20 wt%. A crossover point is observed at approximately 14 wt% fly ash, where the compressive strengths of both NaOH-containing and NaOH-free samples converge.

As shown in Fig. 4, sand molds without NaOH exhibit higher initial hardness values, approximately 88 g/mm², which gradually decline with increasing fly ash content, reaching around 75 g/mm² at 20 wt%. In contrast, molds incorporating 10 wt% NaOH start with lower hardness values, about 72 g/mm², but demonstrate a steady increase as fly ash content rises, reaching approximately 85 g/mm² at 20 wt%. A crossover point is observed between 14–16 wt% fly ash, where both formulations yield comparable hardness values.

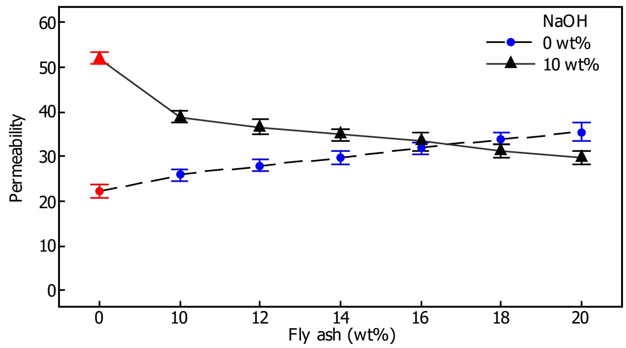


Fig. 2. Variations in sand mold permeability with different fly ash percentages, measured using AFS permeability number, for molds with and without NaOH

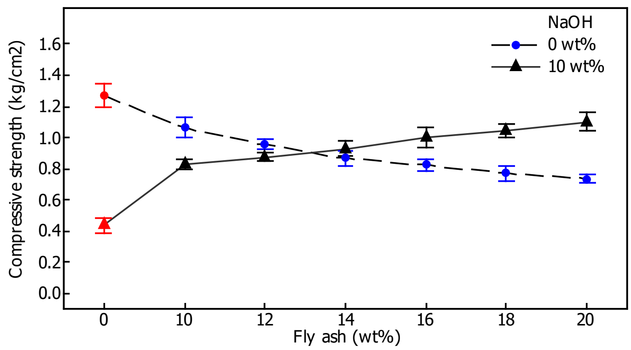


Fig. 3. Variations in sand mold compressive strength with different fly ash percentages, measured using a universal sand strength testing machine, for molds with and without NaOH

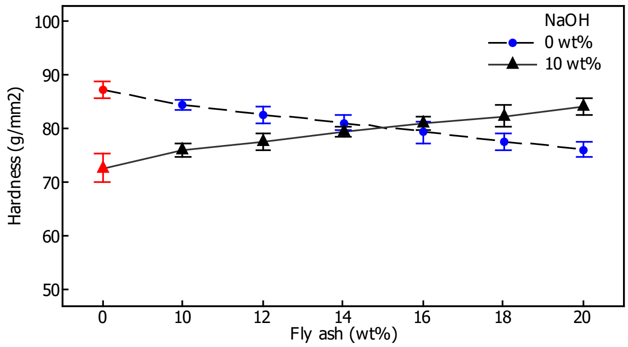


Fig. 4. Variations in sand mold hardness with different fly ash percentages, measured using a B-scale gauge, for molds with and without NaOH

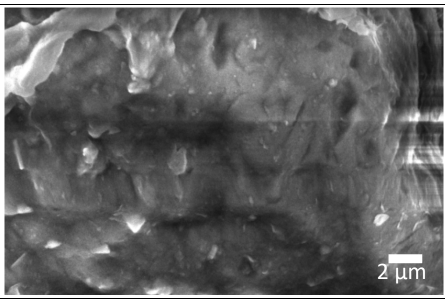
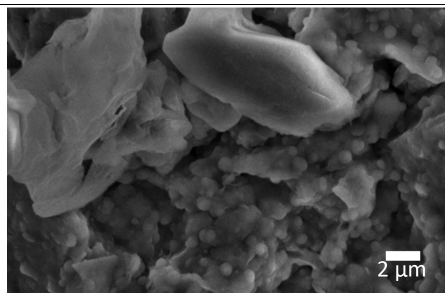
3.2 Microstructural analysis of sand mold

After breaking the sand mold to retrieve the castings, Fig. 5 presents SEM images of a matrix of sand mold samples with varying fly ash contents (0 wt%, 10 wt%, 14 wt%, 18 wt%, and 20 wt%) and NaOH levels (0 wt% and 10 wt%), providing valuable insights into the resulting microstructural changes. At the baseline (0 wt% fly ash and 0 wt% NaOH), the microstructure exhibits relatively large sand particles with pronounced intergranular spaces. The particles display angular morphology with limited interconnection, resulting in a porous structure with visible voids of approximately 5-20 µm.

As fly ash content increases from 0 to 20 wt% without NaOH, a progressive filling of interstitial spaces becomes evident. At 10 wt% fly ash, the fine spherical fly ash particles (typically 1-5 µm in diameter) begin to occupy the voids between larger sand grains, creating a more heterogeneous but increasingly dense microstructure. At 14 wt% fly ash, further densification is observed, with the matrix showing improved particle packing. The microstructure at 18 wt% fly ash displays significantly reduced void space, though some interconnected porosity remains visible at the 2 µm scale indicated on the images. By 20 wt% fly ash, the microstructure appears substantially more compact than the baseline, with the fine fly ash particles effectively filling most interstitial spaces. However, the particles maintain distinct boundaries with limited evidence of fusion or strong interparticle bonding.

The most significant microstructural transformations occur when both fly ash and NaOH are present. At 10 wt% fly ash with 10 wt% NaOH, the SEM images reveal a markedly different morphology compared to the sample with fly ash alone. The microstructure reveals the formation of reaction products that create continuous phases between particles, with substantially reduced void space. The samples containing 14 wt% and 18 wt% fly ash exhibit particularly cohesive microstructures. At these concentrations, the combination creates a nearly continuous matrix where particle boundaries become less distinct. The images show formation of bridge-like structures between particles, consistent with NaOH's role as an alkali activator that increases binder reactivity as reported by Rangan et al. (2023) [8]. The samples containing 14 wt% and 18 wt% fly ash exhibit particularly cohesive microstructures, suggesting an appropriate range for these combinations. At 20 wt% fly ash, the microstructure appears almost completely consolidated, with minimal visible porosity at the 2 µm scale. The interstitial voids are nearly eliminated, which explains the observed decrease in permeability noted in the experimental results. The surface appears smoother with fewer angular features compared to lower fly ash concentrations.

It is noted that observing at this scale enables visual confirmation of how fly ash fills voids, identification of microstructural features such as binding bridges formed by NaOH, and evaluation of the mold's compaction and cohesion. While the overall sand structure exists on a larger scale, the critical microstructural interactions that govern mold strength and casting quality take place at the micron level, thereby justifying the use of SEM magnification.

Fly ash (wt%)	NaOH (wt%)	
	0	10
0		

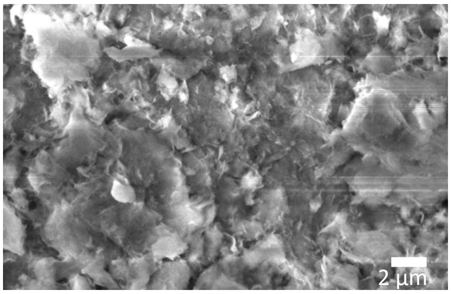
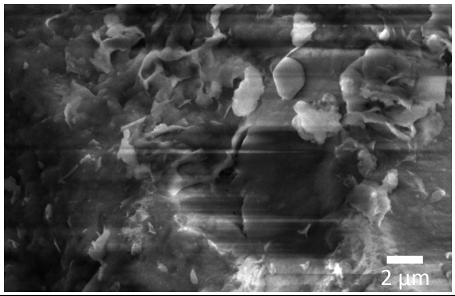
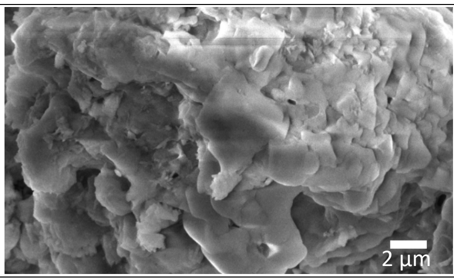
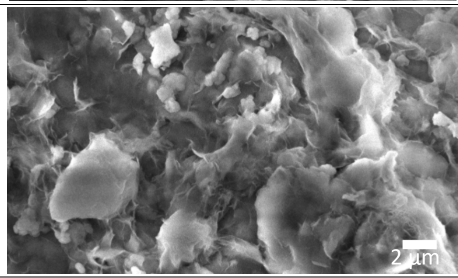
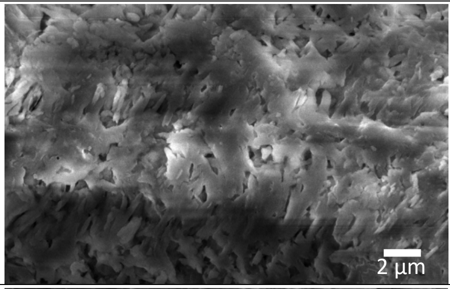
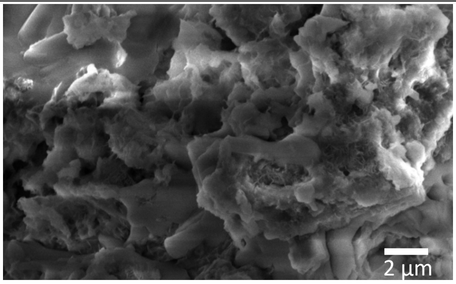
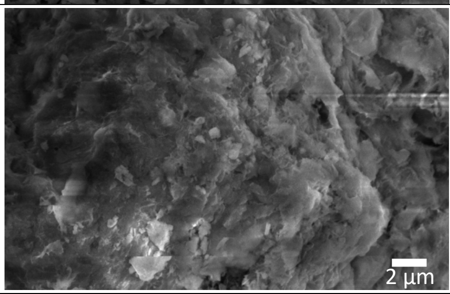
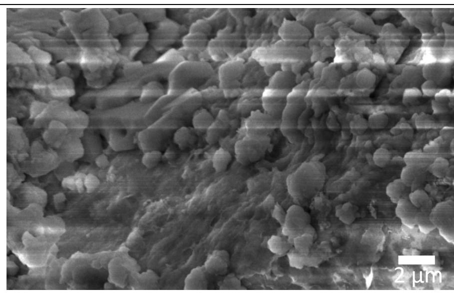
10		
14		
18		
20		

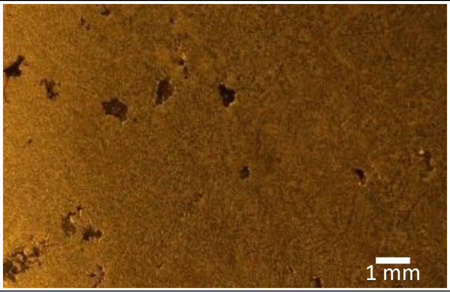
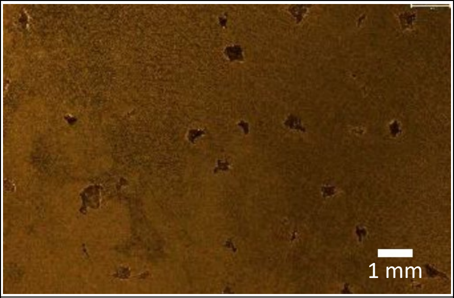
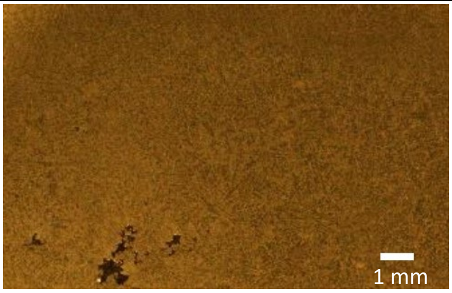
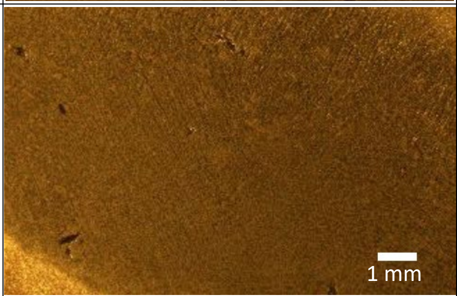
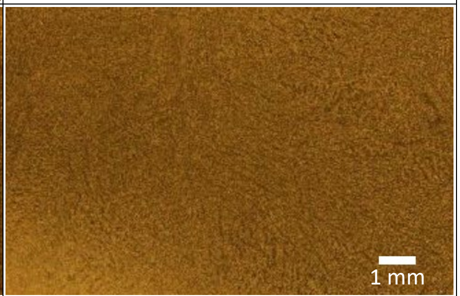
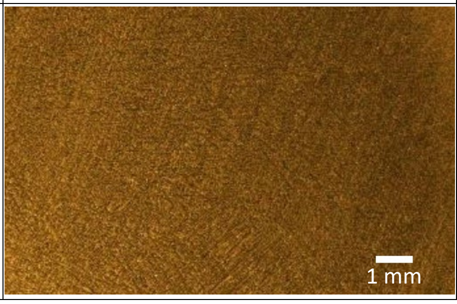
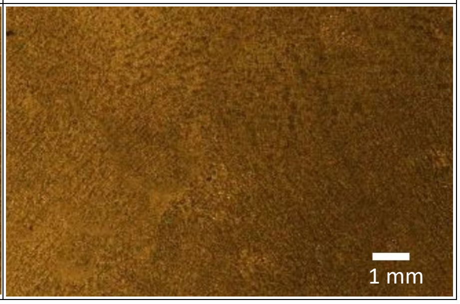
Fig. 5. SEM images of sand mold microstructures after mold breaking for casting retrieval

3.3 Quality evaluation of the aluminum castings

Fig. 6 provides significant insights into how fly ash content and NaOH addition influence aluminum casting quality, particularly regarding porosity and surface defects. The stereomicroscopy images display aluminum castings produced with varying fly ash concentrations both with and without 10 wt% NaOH addition. At 0 wt% fly ash without NaOH, the stereomicroscopic images reveal numerous visible pores and voids distributed across the casting surface, appearing as dark spots approximately 0.1-0.5 mm in diameter. These defects likely result from inadequate gas escape during solidification. As fly ash content increases to 10 wt%, there is a noticeable reduction in the number of visible pores, though they remain present. The defects appear smaller and less concentrated compared to the baseline sample. At higher fly ash concentrations (14-20 wt%), the progression towards improved surface quality continues, with progressively fewer and smaller voids visible. However, complete elimination of porosity is not achieved even at the highest fly ash concentration.

The addition of 10 wt% NaOH produces a marked improvement in casting quality even at 0 wt% fly ash. The baseline sample with NaOH shows significantly fewer voids compared to its NaOH-free counterpart. This improvement becomes more pronounced with increasing fly ash content. At 10 wt% fly ash, the casting exhibits dramatically reduced porosity, with only isolated voids visible at the 1 mm scale. At 14-18 wt% fly ash, the castings display nearly defect-free surfaces with minimal visible porosity. The 18 wt% fly ash sample appears to achieve appropriate quality, with virtually no visible defects at the 1 mm magnification level.

The stereomicroscopy images are captured at a consistent 1 mm scale, providing reliable comparative analysis across samples. This scale reveals that most defects in the untreated samples (produced using molds with varying fly ash content) range from 0.1-0.3 mm in diameter, while the treated samples (produced using molds with varying fly ash content with the addition of 10 wt% NaOH) show significantly smaller defects of approximately 0.05-0.1 mm. The progressive reduction in defect size and frequency correlates directly with the microstructural modifications observed in the sand molds. The fine, spherical fly ash particles effectively fill interstitial spaces between sand grains, creating a more homogeneous mold structure. This reduces the likelihood of metal penetration and gas entrapment during casting.

Fly ash (wt%)	NaOH (wt%) 0	NaOH (wt%) 10
0		
10		
14		
18		

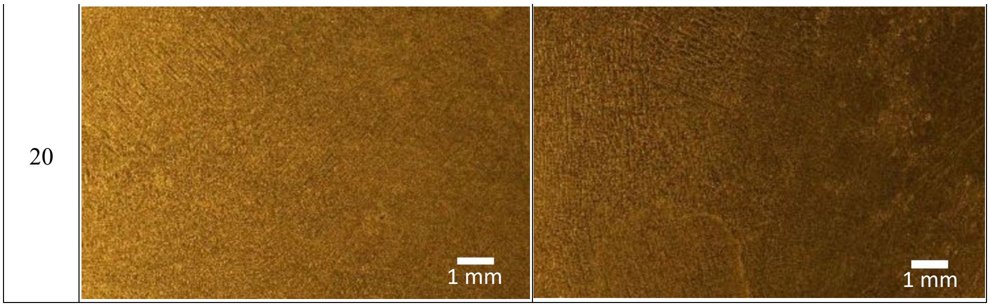


Fig. 6. Stereomicroscopy images of aluminum castings produced using sand molds with varying fly ash content (0, 10, 14, 18, and 20 wt%) and NaOH concentrations (0 and 10 wt%)

The observed defect reduction pattern aligns with previous research findings. Sadarang and Nayak reported potential increases in pinhole and blowhole formation when fly ash exceeds 15 wt%, but this negative effect appears to be mitigated in the current study through the addition of NaOH. Similarly, while Palaniappan identified 20 wt% fly ash as optimal for balancing surface finish and defect control (without NaOH), the current study demonstrates that the addition of NaOH shifts this optimal point to approximately 18 wt% fly ash, with evidence of potentially adverse effects beginning to appear at 20 wt%. This comprehensive analysis of Fig. 6 demonstrates that the combination of 18 wt% fly ash with 10 wt% NaOH produces aluminum castings with superior surface quality and minimal defects, representing an appropriate formulation for practical foundry applications.

3.4 Property evaluation of the aluminum castings

Fig. 7 shows how the hardness of aluminum castings varies with fly ash content (0-20 wt%) in sand molds, both with and without the addition of 10 wt% NaOH. For casting molds without NaOH (0 wt%), hardness starts at approximately 25 HRB at 0 wt% fly ash and shows a steady increase as fly ash content increases, reaching a peak of about 37 HRB at 18 wt% fly ash before slightly decreasing at 20 wt% fly ash. For casting molds with 10 wt% NaOH, hardness begins higher at around 28 HRB at 0 wt% fly ash and increases more gradually with increasing fly ash content, reaching approximately 33 HRB at 18 wt% fly ash before slightly decreasing at 20 wt% fly ash. It is also observed that maximum hardness for both conditions is attained at approximately 18 wt% fly ash, beyond which a slight decline in hardness is evident as the fly ash content continues to increase.

As shown in Fig. 8, tensile strength of aluminum castings increases with fly ash content, peaking at 18 wt% for both NaOH-treated and untreated molds. Without NaOH, the strength reaches approximately 142 MPa, while with 10 wt% NaOH, it attains around 128 MPa. Beyond 18 wt%, a slight decline in tensile strength is observed in both cases, indicating an appropriate fly ash concentration for mechanical performance.

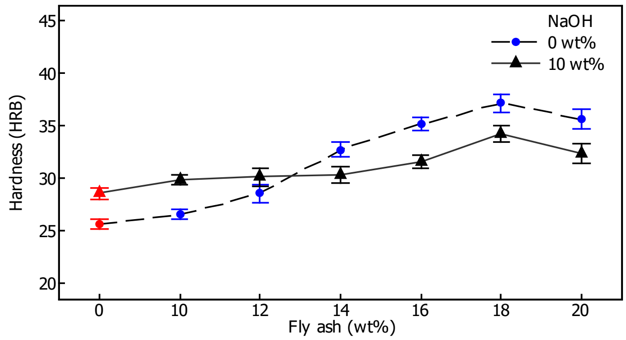


Fig. 7. Variation in hardness of aluminum casting samples as a function of fly ash content, evaluated with and without NaOH addition

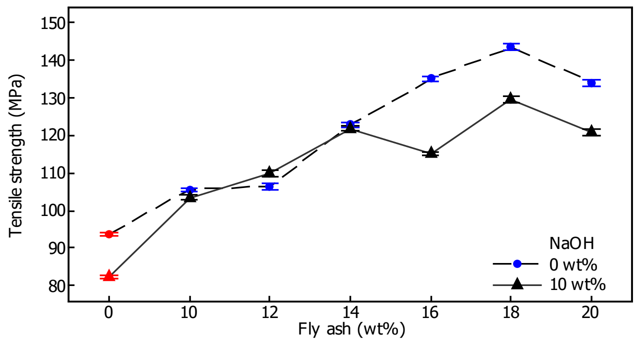


Fig. 8. Variation in tensile strength of aluminum casting samples as a function of fly ash content, evaluated with and without NaOH addition

4. Simulation results

Fig. 9(a) shows opposing trends between samples with and without NaOH. Without NaOH, permeability starts low and gradually increases as fly ash content increases, reaching approximately 35 units at 20 wt% fly ash. This suggests that fly ash particles improve gas flow pathways in the mold. In contrast, with 10 wt% NaOH, permeability begins much higher, but decreases considerably as fly ash content increases, dropping to about 30 units at 20 wt% fly ash. The plot clearly shows a crossover point at approximately 16-18 wt% fly ash where permeability values become similar for both conditions.

The response surface for compressive strength illustrated in Fig. 9(b) reveals inverse relationships between the two conditions. Sand molds without NaOH start with higher compressive strength which steadily decreases with increasing fly ash content to about 0.75 kg/cm² at 20 wt% fly ash. In contrast, molds with 10 wt% NaOH begin with lower compressive strength but show a consistent increase as fly ash content rises, reaching approximately 1.1 kg/cm² at 20 wt% fly ash. The plot indicates a crossover point at approximately 14 wt% fly ash where both formulations yield similar strength values.

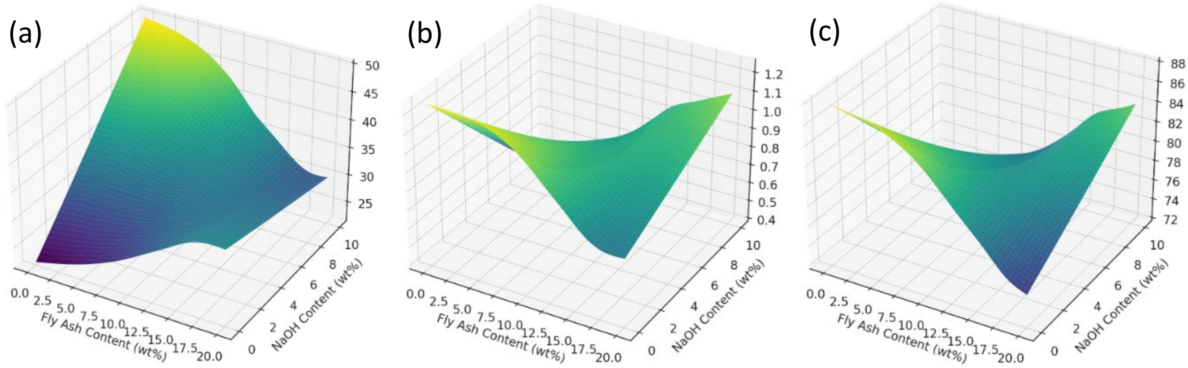


Fig. 9. Response surface plots illustrating the effects of varying fly ash content on (a) permeability, (b) compressive strength, and (c) hardness of sand molds, evaluated under conditions with and without NaOH addition

The hardness response surface exhibits similar inverse relationships as shown in Fig. 9(c). Without NaOH, sand molds begin with higher hardness values that gradually decrease with increasing fly ash content to around 75 g/mm² at 20 wt% fly ash. With 10 wt% NaOH, molds start with lower hardness but show a steady increase as fly ash content rises, reaching approximately 84 g/mm² at 20 wt% fly ash. A crossover point appears between 14-16 wt% fly ash where both formulations yield comparable hardness values.

Fig. 10(a) shows that for castings produced in molds without NaOH, hardness starts at approximately 25 HRB and increases steadily with fly ash content, reaching a maximum of about 37 HRB at 18 wt% fly ash before slightly decreasing at 20 wt%. For castings produced in molds with 10 wt% NaOH, hardness begins higher at around 28 HRB and increases more gradually, reaching approximately 33 HRB at 18 wt% fly ash before slightly declining at 20 wt%. The plot clearly shows that maximum hardness for both conditions occurs at approximately 18 wt% fly ash, beyond which there's a slight decline.

Fig. 10(b) exhibits that for castings produced in molds without NaOH, tensile strength starts at about 90 MPa and increases steadily with fly ash content, reaching a maximum of approximately 140 MPa at 18 wt% fly ash before slightly decreasing to 130 MPa at 20 wt%. For castings produced in molds with 10 wt% NaOH, tensile strength begins lower at around 82 MPa and increases more steadily, reaching approximately 130 MPa at 18 wt% fly ash before slightly decreasing to 120 MPa at 20 wt%. Similar to the hardness trend, both conditions exhibit peak tensile strength at around 18 wt% fly ash, followed by a decline at higher fly ash content.

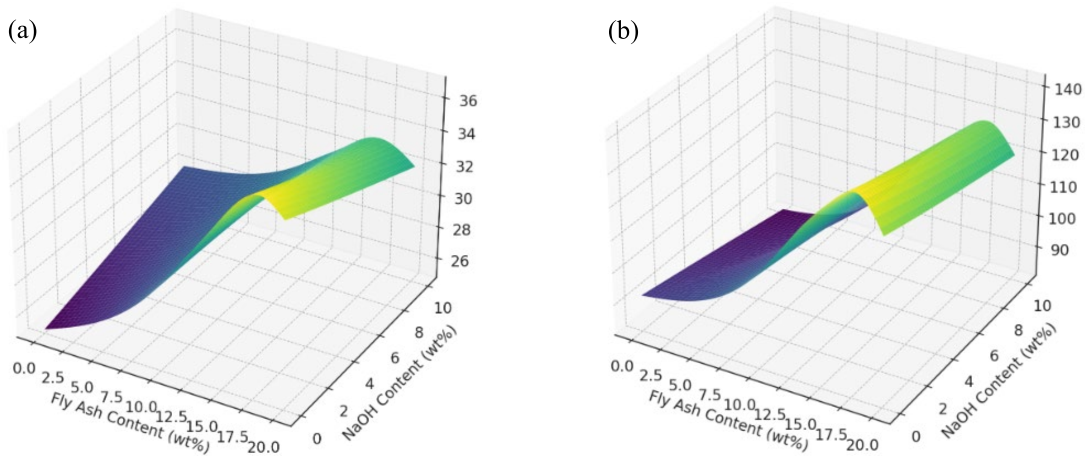


Fig. 10. Response surface plots illustrating the effects of varying fly ash content on (a) hardness and (b) tensile strength of aluminum castings, evaluated under conditions with and without NaOH addition

Based on the response surface analysis, a balanced integration of key mold properties is critical for high-quality aluminum castings. The findings suggest that a mold composition with 18 wt% fly ash and 10 wt% NaOH achieves an appropriate balance of properties including moderate permeability to facilitate gas venting during aluminum pouring, high compressive strength to withstand mold handling and metal pressure, and elevated hardness to ensure mold rigidity and enhance surface finish quality. The study also shows how microstructural changes in the sand mold directly affect casting quality. At 18 wt% fly ash with 10 wt% NaOH, the microstructure displays a particularly cohesive arrangement, where the fine, spherical fly ash particles effectively fill interstitial spaces between sand grains. This creates a more homogeneous and densely packed structure that contributes to improved casting quality. The NaOH acts as an alkali activator, promoting chemical bonding between particles and enhancing mold strength. This results in the formation of bridge-like structures that enhance the overall cohesiveness of the mold mixture. This explains why properties like compressive strength and hardness increase with fly ash content when NaOH is present, despite showing the opposite trend without NaOH. These findings are highly relevant to foundry applications, showing that the strategic use of fly ash combined with NaOH can be leveraged to optimize sand mold properties, thereby enhancing the quality of aluminum castings through improved mechanical performance and fewer defects. This study not only enhances mechanical performance and reduces casting defects but also presents an environmentally responsible solution by utilizing fly ash—a byproduct of coal combustion—as a valuable foundry material. The methodology established in this study offers foundries a scientifically-validated pathway to improve casting quality while potentially reducing production costs and environmental impact.

5. Conclusions

The study confirms that incorporating fly ash into sand molds enhances the mechanical properties of aluminum castings, with an optimal performance observed at 18 wt% fly ash. At this concentration, both tensile strength and hardness reached their peak, particularly in molds without NaOH. Although NaOH slightly reduced tensile strength, it significantly improved surface quality and mold cohesion, suggesting a trade-off between mechanical strength and defect reduction. These findings highlight 18 wt% fly ash with or without the addition of NaOH, as the most effective composition for balancing strength and casting quality. This outcome is consistent with and extends prior studies by Sadarang and Nayak (2021) [3], Palaniappan (2017) [9], and Karunakaran et al. (2014) [5], confirming that fly ash can be used effectively up to 18–20 wt% to enhance mold and casting properties. However, exceeding this range may introduce permeability and strength trade-offs due to over-compaction and pore blockage.

Future work will involve the use of complementary imaging techniques, such as confocal microscopy and 3D microscopy, to obtain a more comprehensive visualization of grain-level interactions and further enhance the understanding of microstructural behavior within the mold system.

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Conflict of Interest

The authors declare that there are no conflicts of interest or personal relationships that could have influenced the research presented in this paper.

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