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Alkali Activation of Coal Fly Ash: Characterization and Potential for Oil Remediation

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Abstract

Fly ash, a byproduct of coal combustion, has attracted increasing attention as a low-cost adsorbent for environmental remediation. This study aims to investigate the effect of alkali activation on the structural and surface characteristics of fly ash and to evaluate its potential for oil remediation. In this work, fly ash was activated using sodium hydroxide (NaOH) followed by thermal treatment at 250 °C. The structural and surface properties of the materials before and after activation were characterized using Fourier Transform Infrared spectroscopy (FTIR), X-ray Diffraction (XRD), and Brunauer–Emmett–Teller (BET) surface area analysis. FTIR analysis indicated changes in the surface functional groups of fly ash after alkali activation, while hydrocarbon-related bands observed after contact with used oil suggested the presence of oil-derived compounds on the adsorbent surface. XRD results showed that the activated fly ash retained a predominantly amorphous phase with slight changes in crystallinity. BET analysis revealed only a slight increase in specific surface area from 22.71 to 23.53 $m^2 g^{-1}$, accompanied by a small increase in average pore diameter from 5.49 to 5.77 nm, indicating limited modification of the mesoporous structure after alkali activation. These structural modifications suggest that alkali activation alters the surface characteristics of fly ash and may support its potential use in oil remediation. The findings indicate that alkali-activated fly ash has potential as an economical and sustainable adsorbent for environmental remediation applications, particularly for the treatment of oil-contaminated waste.

Keywords: alkaline activation, adsorbent, BET, FTIR, XRD

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Abu terbang, produk sampingan dari pembakaran batubara, telah menarik perhatian yang semakin meningkat sebagai adsorben berbiaya rendah untuk remediasi lingkungan. Studi ini bertujuan untuk menyelidiki pengaruh aktivasi alkali terhadap karakteristik struktural dan permukaan abu terbang serta mengevaluasi potensinya untuk remediasi oli bekas pakai. Dalam penelitian ini, abu terbang diaktifkan menggunakan natrium hidroksida (NaOH) diikuti dengan perlakuan termal pada suhu 250 °C. Sifat struktural dan permukaan material sebelum dan sesudah aktivasi dikarakterisasi menggunakan spektroskopi inframerah transformasi Fourier (FTIR), difraksi sinar-X (XRD), dan analisis luas permukaan Brunauer–Emmett–Teller (BET). Analisis FTIR menunjukkan perubahan pada gugus fungsional permukaan abu terbang setelah aktivasi alkali, sementara pita terkait hidrokarbon yang diamati setelah kontak dengan oli bekas pakai menunjukkan adanya senyawa turunan minyak pada permukaan adsorben. Hasil XRD menunjukkan bahwa abu terbang yang diaktifkan

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mempertahankan fase amorf yang dominan dengan sedikit perubahan kristalinitas. Analisis BET menunjukkan sedikit peningkatan luas permukaan spesifik dari 22,71 m^2 g^{-1} menjadi 23,53 m^2 g^{-1}, disertai dengan sedikit peningkatan diameter pori rata-rata dari 5,49 nm menjadi 5,77 nm, yang mengindikasikan bahwa modifikasi terbatas pada struktur mesopori setelah aktivasi alkali. Modifikasi struktural ini menunjukkan bahwa aktivasi alkali mengubah karakteristik permukaan abu terbang dan dapat mendukung potensi penggunaannya dalam remediasi oli bekas pakai. Temuan ini menunjukkan bahwa abu terbang yang diaktifkan alkali memiliki potensi sebagai adsorben yang ekonomis dan berkelanjutan untuk aplikasi remediasi lingkungan, khususnya untuk pengolahan limbah yang terkontaminasi oli.

Kata Kunci: adsorben, aktivasi alkali, BET, FTIR, XRD

INTRODUCTION

Coal-fired power plants are a primary source of electricity in Indonesia, playing a significant role in fulfilling the energy demands of the population. However, the combustion of coal in these plants generates substantial amounts of waste by-products, primarily bottom ash and fly ash. Typically, around 10% of the solid waste is bottom ash [1,2], while the remaining 85% consists of fly ash, which is the finer particulate residue carried by flue gases. As the use of coal increases, the accumulation of this solid waste also escalates, posing a serious environmental and health challenge [3,4]. If fly ash is not properly managed or utilized, it can become a significant pollutant, contributing to both land and air contamination [5-7]. Fly ash is classified as a hazardous waste, requiring regulatory oversight and permits to mitigate its environmental impact [8].

Fly ash generated from coal combustion contains a mix of inorganic and organic materials [9], including heavy metals like arsenic, mercury, lead, and cadmium [10]. When improperly disposed of, these metals can leach into groundwater or be blown into the air, creating health hazards for nearby communities. Exposure to fly ash, particularly through inhalation or ingestion of contaminated water, can lead to respiratory illnesses, heavy metal poisoning, and other serious health conditions [11]. The environmental impacts of fly ash are equally concerning, as it can negatively affect soil and water quality, harming plant and animal life. Given the scale of coal usage, fly ash waste is generated in vast quantities, making it a growing threat to the environment and public health [12].

Despite its status as a waste product, fly ash has potential uses that can mitigate its negative environmental impact. Traditionally, fly ash has been used in construction, particularly in the production of concrete and cement, where its pozzolanic properties improve the durability and strength of building materials. However, its application in environmental remediation, particularly as an adsorbent for pollutants, has gained increasing attention in recent years [13]. Fly ash contains a high concentration of silica (SiO_2), alumina (Al_2O_3), and iron oxides (Fe_2O_3) [9], making it suitable for chemical modification and activation to enhance its surface properties for adsorption purposes [14]. The use of fly ash as an affordable adsorbent for removing organic compounds, with the goal of identifying new applications that enhance its beneficial uses while minimizing its environmental pollution effects [7,15].

The composition of fly ash varies depending on the type of coal burned, but in general, it consists of a combination of metal oxides and trace heavy metals. Silica and alumina make up a significant portion of fly ash, allowing it to be processed into materials with zeolite-like structures. These porous structures are highly effective as adsorbents for capturing pollutants from industrial effluents, including dyes, heavy metals, and organic contaminants [16]. The high silica content, approximately 46.4%, is particularly advantageous because silica contributes to the fly ash's ability to form a porous matrix, which is essential for adsorption applications [13].

In recent years, numerous studies have explored the potential of fly ash as an adsorbent for environmental remediation. For example, by [17] Ahmed *et al.* (2023) focused on synthesizing magnetic fly ash composites for the removal of methylene blue dye from wastewater. In this study, fly ash was treated with magnetic nanoparticles after chemical surface modification to enhance its adsorption capacity. The results demonstrated that the modified fly ash (MFA) effectively removed methylene blue from aqueous solutions, with the rate of removal influenced by factors such as pH, adsorbent dosage, and contact time. The Langmuir isotherm model provided the best fit for the adsorption data, indicating monolayer adsorption of methylene blue onto the surface of the MFA. These findings underscore the potential of fly ash as an effective and low-cost adsorbent for dye removal from industrial wastewater.

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Another application of fly ash in environmental remediation involves its use in the removal of hydrogen sulfide (H_2S) from natural gas. Aslam [18] investigated the preparation of a carbonaceous adsorbent from waste oil fly ash (OFA), which was treated with various chemical agents to enhance its surface characteristics for H_2S adsorption. The study found that surface treatment with hydroxides such as KOH and NaOH significantly improved the porosity and adsorption capacity of the fly ash, with KOH-treated fly ash exhibiting the highest adsorption capacity. This research highlights the versatility of fly ash as an adsorbent for gaseous pollutants and its potential as a replacement for more expensive commercial activated carbons in gas purification processes.

The adsorption process involves the accumulation of molecules or ions from a liquid or gas onto the surface of a solid material, known as the adsorbent. In the case of fly ash, its adsorption capacity is largely dependent on its surface area and the presence of functional groups that can interact with the target pollutants. Alkali activation is a common technique used to enhance the adsorption properties of fly ash. This process involves treating fly ash with alkali metal hydroxides, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), to increase its surface area and introduce functional groups that can interact with adsorbates [19].

Alkali activation improves the pore structure of fly ash and creates active sites for adsorption, making it more effective in capturing pollutants such as heavy metals, dyes, and organic compounds. For example, in the study by Ahmed et al. [17], alkali activation combined with magnetic nanoparticles resulted in a highly porous material capable of removing methylene blue from wastewater with high efficiency. Similarly, Aslam [18] demonstrated that alkali activation enhanced the surface properties of fly ash for hydrogen sulfide adsorption, leading to a substantial increase in adsorption capacity.

The use of NaOH-activated fly ash in wastewater treatment has also been explored in the context of recovering waste oils. Chang et al. [20] examined the regeneration of waste rolling oil (WRO) using an inorganic flocculation-adsorption process, where fly ash was used as the adsorbent. The study found that NaOH-activated fly ash, in combination with ferric hydroxide, was highly effective in removing impurities, organic acids, and lipids from waste oil. This highlights the broad applicability of alkali-activated fly ash in not only water purification but also in oil recovery and regeneration processes.

It is known that fly ash is a promising and sustainable adsorbent for removing various pollutants [21,22]. In addition to its use in dye removal and gas purification, fly ash has been investigated for its ability to remove heavy metals from aqueous solutions. A study by Primerano & Milazzo [23] explored the use of oil fly ash for the removal of dyes from industrial wastewater after the recovery of valuable metals. The fly ash exhibited high adsorption efficiency, particularly for methylene blue, achieving dye removal rates of up to 99%. The study concluded that oil fly ash could serve as a low-cost alternative to commercial activated carbon for wastewater treatment, with the added benefit of metal recovery.

The use of fly ash in environmental remediation aligns with the principles of sustainable waste management by converting an industrial byproduct into a valuable resource. By enhancing the adsorption capacity of fly ash through chemical activation, its utility in various applications—ranging from dye and gas adsorption to heavy metal removal—can be significantly improved. Additionally, fly ash-based adsorbents offer a more economical and environmentally friendly alternative to conventional adsorbents, making them attractive options for large-scale industrial applications [24]. Adsorption is regarded as the most promising technique due to its affordability, high effectiveness, and ease of implementation [25]. Experimental data research by [26] shows that a new type of substrate can be used to remove Pb^{2+}, Cd^{2+} and Zn^{2+} cations from mixed solutions. The results show high efficiency and selective adsorption of Pb^{2+} and Zn^{2+} cations. This modified fly ash synthesized from fly ash using NaOH can provide a promising solution as a wastewater adsorbent with the advantages of high efficiency and low cost [27].

This study aims to investigate the effect of NaOH activation on the structural and surface characteristics of fly ash for its potential application in used-oil remediation. By modifying the surface properties of fly ash through alkali activation, this study explores its potential as a material for removing pollutants from used oil. The primary objective is to evaluate the impact of NaOH activation on the structural and chemical properties of fly ash and to assess its potential relevance for the removal of contaminants such as heavy metals and organic compounds. Through this research, we hope to contribute to the development of cost-effective and sustainable solutions for environmental pollution, while also promoting the reuse of industrial waste materials.

MATERIALS AND METHODS

Materials

Fly ash used in this study was obtained from a coal-fired power plant in Probolinggo, Indonesia. Before use, the fly ash was dried and sieved to obtain a uniform particle size. Sodium hydroxide (NaOH) pellets used as the activating agent were purchased from a commercial chemical supplier with analytical grade purity. Distilled water was used for the preparation of NaOH solution and for washing the activated samples.

Used lubricating oil was employed as the model oil contaminant for adsorption experiments. All chemicals were used as received without further purification. The fly ash samples were subjected to alkali activation using NaOH to modify their surface properties and enhance their adsorption performance.

Methods

Activation of fly ash

Fly ash was treated through an alkaline activation process to remove surface impurities and improve its surface properties. Raw fly ash was first dried in an oven at 105 °C to remove moisture. The dried fly ash was then activated using 3 M sodium hydroxide (NaOH) solution to dissolve impurities on the surface and modify the outer layer of the particles, thereby exposing previously blocked active sites. NaOH solution was added to the fly ash, corresponding to a 1:2 ratio (w/v, fly ash: NaOH), and the mixture was thoroughly homogenized to ensure uniform interaction between the solid and the activating agent.

The mixture was heated in an oven at 250 °C for 2 h under ambient air conditions. After heating, the samples were cooled to room temperature and washed several times with deionized water to remove residual alkali. The washing process was continued until the filtrate reached approximately neutral pH, which was monitored using universal pH indicator paper. The activated fly ash was subsequently dried in an oven at 105 °C for 12 h and stored for further analysis.

The obtained samples were characterized using FTIR to identify surface functional groups, XRD to determine crystalline phases, and BET analysis to evaluate the specific surface area and pore characteristics of the adsorbent.

Characterization of fly ash

IR spectra of raw and activated fly ash were recorded on a Nicolet iS10 Spectrometer (Thermo Scientific, USA) using the attenuated total reflectance (ATR) technique at the BRIN (Badan Riset dan Inovasi Nasional, Indonesia), in the wavenumber range 4000–400 cm^{-1}. X-ray diffraction (BRUKER) was operated using Co Kα radiation for understanding the role of alkali activation treatments on the crystallinity of raw and activated fly ash. N_2 adsorption–desorption was performed on a Quantachrome NOVA 4200e (New York, NY, USA) to characterize surface area and pore volume of the raw and activated fly ash.

RESULTS AND DISCUSSION

X-ray Diffraction Analysis (XRD)

Fly ash samples were analyzed using X-ray diffraction (XRD) to evaluate the effect of alkali activation on their crystalline phase composition. The XRD patterns of raw fly ash and activated fly ash are presented in **Figure 1a** and **Figure 1b**, respectively. The diffractogram of raw fly ash shows main peaks at 2θ = 24.26°, 31.03°, and 34.62°, while the activated sample exhibits similar peaks at 2θ = 24.27°, 31.07°, and 34.27°. The similarity of the diffraction patterns before and after activation indicates that treatment with 3 M NaOH, followed by heating at 250 °C, did not produce major changes in the crystalline phases of the material. The observed reflections are consistent with minerals commonly reported in coal fly ash, such as quartz, mullite, and iron oxide phases [28]. No substantial peak shift or prominent new diffraction peak was observed after activation, suggesting that the alkaline treatment did not significantly alter the bulk crystalline structure of fly ash under the applied conditions. However, because no Rietveld refinement or other quantitative phase analysis was performed, the relative contribution of non-crystalline components cannot be determined with confidence from the present XRD data alone.

Surface and porosity of raw fly ash and activated fly ash

The N_2 adsorption/desorption isotherms have been investigated for specific surface area and porosity to evaluate the effect of activation procedures. The N_2 adsorption–desorption isotherms of the fly ash and activated fly ash are shown in **Figure 2**. All samples showed type IV isotherms with a hysteresis loop following the International Union of Pure and Applied Chemistry's (IUPAC) classifications, indicating that

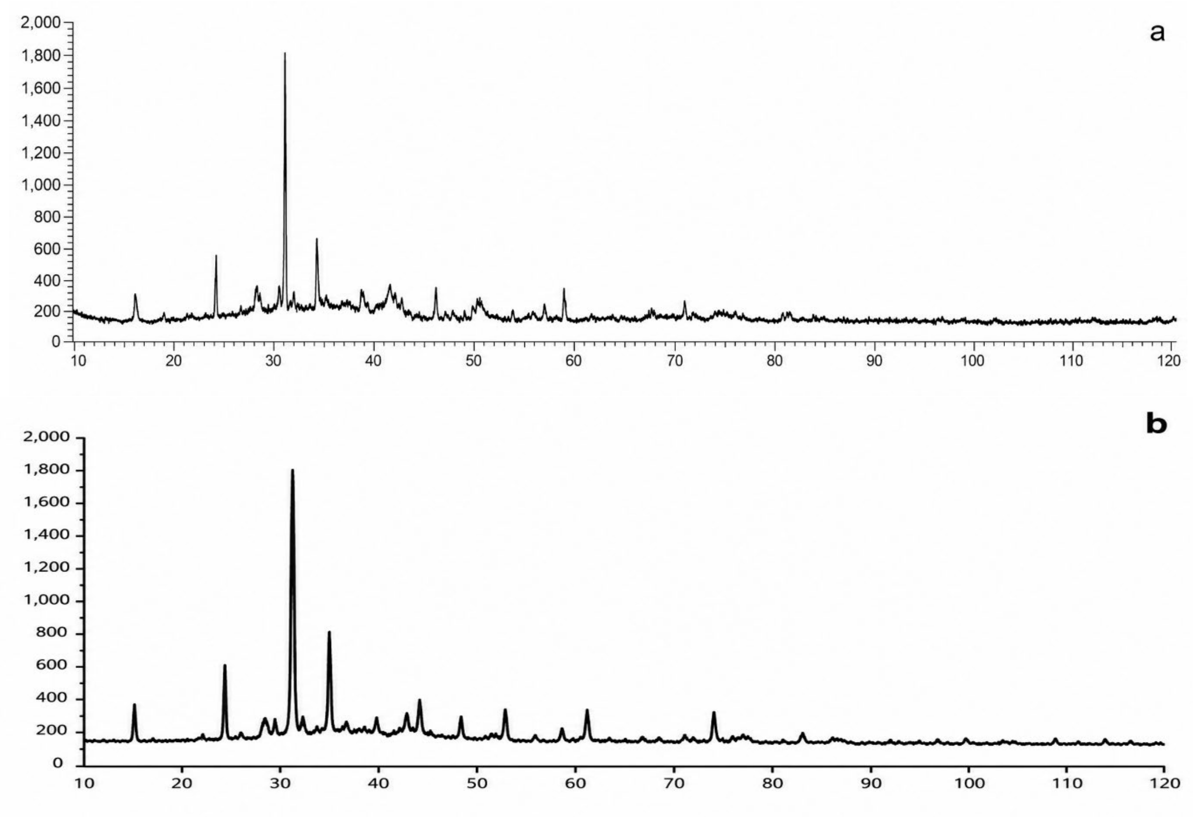

Figure 1. XRD patterns of raw fly ash (a) and NaOH-activated fly ash (b), showing similar diffraction features and the continued predominance of the amorphous phase after alkali treatment

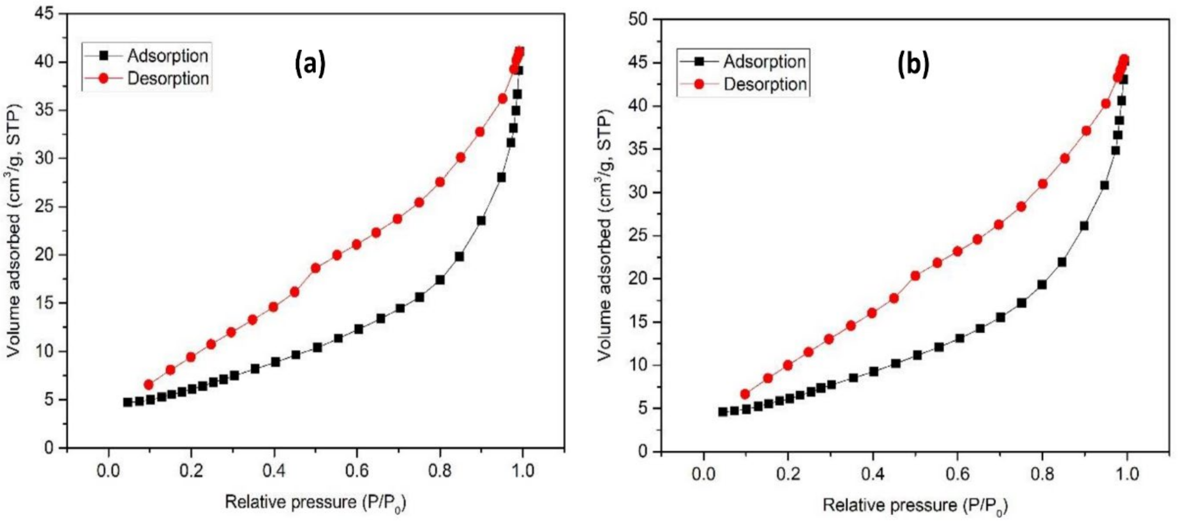

Figure 2. N_2 adsorption–desorption isotherms of raw fly ash (a) and activated fly ash (b), showing type IV isotherm behavior characteristic of mesoporous materials

The proposed adsorbent was a typical mesoporous material. The type IV isotherm can stay almost horizontal across the upper range of p/p_0, demonstrating the absence of macropores in the material [29]. A hysteresis loop type III according to IUPAC was found at P/P_0 = 0.1-1, which is often associated with capillary condensation. This phenomenon frequently appears by mesoporous materials and is caused by the condensation of N_2 [30].

The results of the Brunauer–Emmett–Teller (BET) analysis showed a slight increase in the specific surface area of activated fly ash to 23.53 $m^2\ g^{-1}$, compared with 22.71 $m^2\ g^{-1}$ for raw fly ash (**Table 1**). This suggests that the activation procedure may have removed some surface impurities and slightly altered the pore structure. The mean pore diameter of the raw fly ash and activated fly ash was 5.49 nm and 5.77 nm respectively, this value confirms that the material was classified as mesoporous materials (2 nm < pore diameter < 50 nm).

Table 1. Comparative surface parameter for fly ash and activated fly ash

Surface Parameters	Fly Ash	Activated Fly Ash
Surface area (SBET) m^2g^{-1}	22.71	23.53
Total pore volume (P/P_0 = 0.992990) (cm^3g^{-1})	0.0624	0.070
Mean pore diameter (nm)	5.488	5.77
Surface Parameters	Fly Ash	Activated Fly Ash

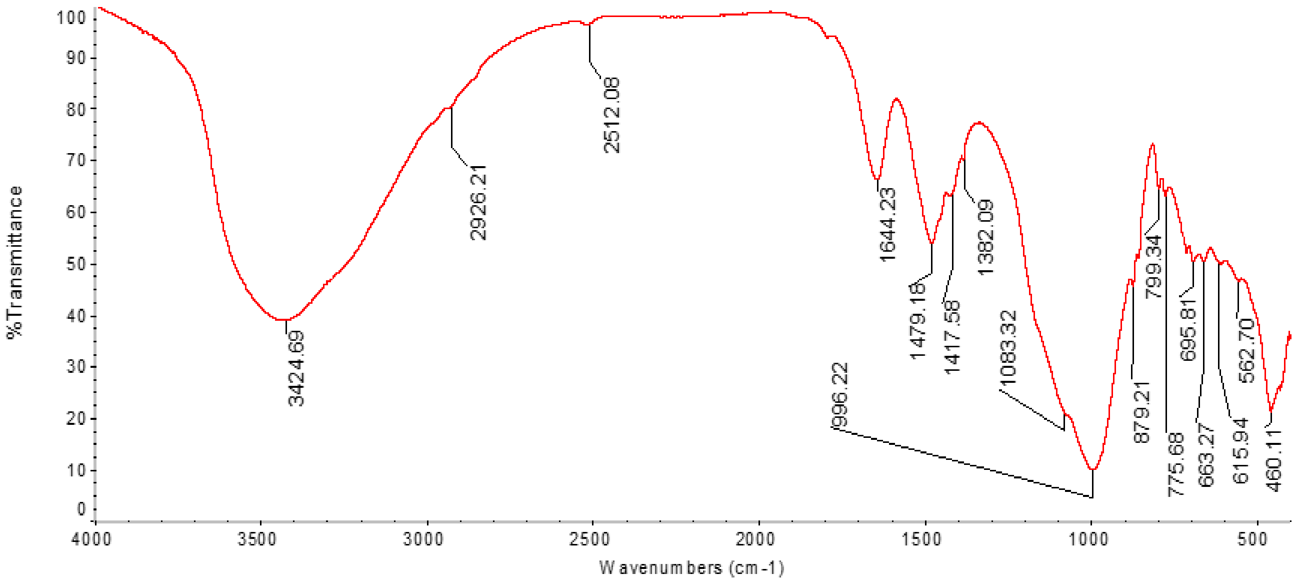

Figure 3. FTIR spectrum of raw fly ash showing characteristic bands associated with silicate functional groups

Table 2. Vibration type of raw fly ash.

No.	Wavenumber (cm^{-1})	Intensity	Vibration
1	460.00	22.75	Si-O
2	696.34	52.89	Si-O-Si
3	996.36	9.99	Si-O-Si
4	1482.36	51.62	CH
5	1647.67	65.45	H-O-H
6	3431.85	35.75	Si-OH

Infrared spectra of raw fly ash and activated fly ash

The FTIR spectra of raw and activated fly ash were analyzed to identify changes in surface functional groups after alkali treatment. The FTIR results of raw and activated fly ash are presented in **Figures 3** and **4**. Raw fly ash shows characteristic silicate-related bands, while the activated sample exhibits slight changes in the corresponding absorption features. The results of characterization using FTIR in **Figure 3** show that fly ash mostly contains silica compounds as indicated by 4 (four) absorption bands containing Si, namely Si-O, 2 (two) Si-O-Si, and Si-OH. After being activated with NaOH, it can be seen in **Figure 4** that the peak that disappears is the Si-O-Si absorption band at wave number 696.34 cm^{-1}. The process of activating fly ash with NaOH damages the outer layer of fly ash, releasing water so that the pore surface area becomes larger (see also **Table 2** and **3**).

Figure 5 shows the FTIR spectrum of activated fly ash after contact with used oil, which was analyzed to identify bands potentially associated with adsorbed oil components. The spectrum displays a range of absorption peaks corresponding to different functional groups, allowing researchers to identify the types of chemical bonds present in the sample (see **Table 4**). This can provide valuable insights into the interactions between the fly ash and the adsorbed oil, as well as any chemical modifications that may have occurred due to the adsorption process. The FTIR spectrum contains several prominent peaks that can be attributed to specific chemical bonds. These are the major peaks and their corresponding interpretations, as well as their relevance to the adsorption of used oil:

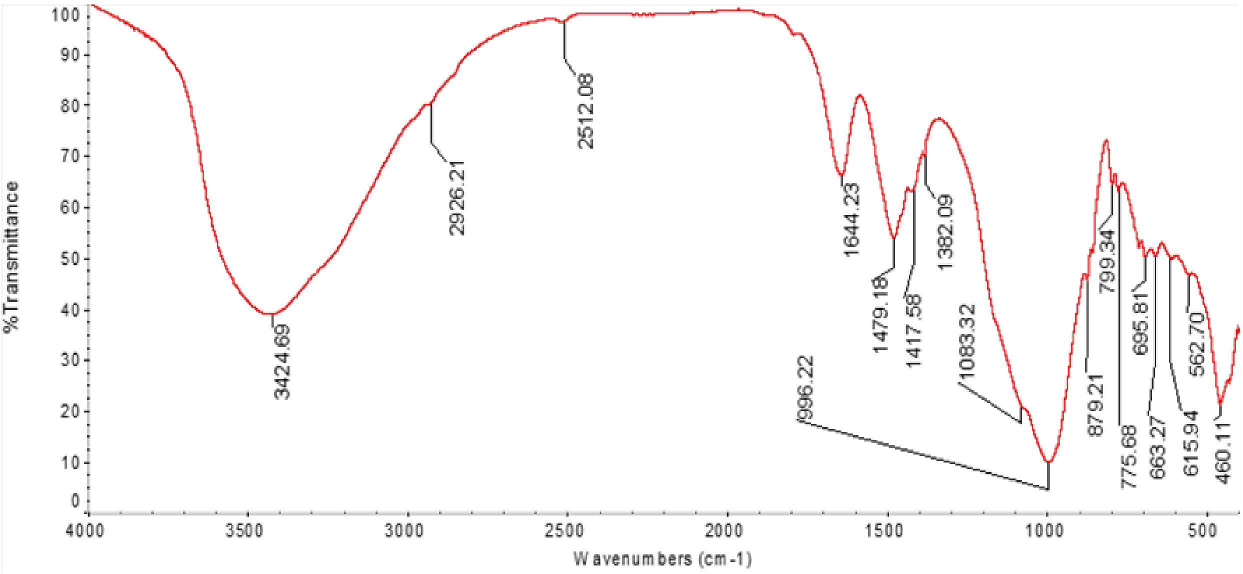

Figure 4. FTIR spectrum of NaOH-activated fly ash showing changes in surface functional-group absorption after alkali treatment

Table 3. Vibration type of activated fly ash.

No.	Wavenumber (cm^{-1})	Intensity	Vibration
1	460.11	21.25	Si-O
2	996.22	10.00	Si-O-Si
3	1479.18	54.01	CH
4	1644.23	66.27	H-O-H
5	3424.69	38.93	Si-OH

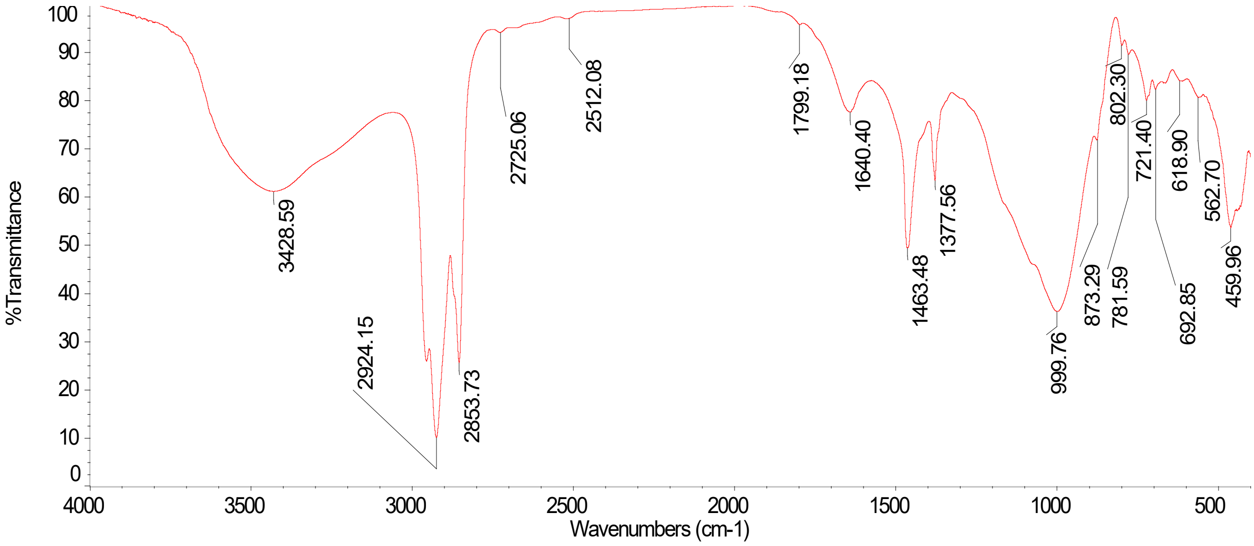

Figure 5. FTIR spectrum of activated fly ash after contact with used lubricating oil, showing hydrocarbon-related bands associated with oil-derived compounds on the adsorbent surface

Table 4. Vibration type of activated fly ash-oil.

No.	Wavenumber (cm^{-1})	Intensity	Vibration
1	453.96	53.46	Si-O
2	721.44	79.35	CH
3	993.76	36.16	Si-O-Si
4	1377.56	43.30	CH
5	1643.48	60.99	H-O-H
6	1660.40	47.51	C=O
7	2853.73	25.55	CH
8	2925.15	9.99	CH
9	3428.59	61.05	Si-OH

Hydroxyl (O-H) Stretch (3428.59 cm^{-1}). This peak is typically associated with O-H stretching vibrations, indicating the presence of hydroxyl groups. Hydroxyl groups are commonly found in alcohols, phenols, and carboxylic acids. In the context of activated fly ash, the presence of hydroxyl groups suggests surface hydroxylation, which may contribute to the material's adsorption capacity. The hydroxyl groups may interact with polar compounds in the used oil, facilitating the adsorption of polar species like oxidized oils and water content.

C-H Stretch (2924.15 cm^{-1} and 2853.73 cm^{-1}). The peaks around 2924.15 cm^{-1} and 2853.73 cm^{-1} correspond to the C-H stretching vibrations. These peaks are indicative of the presence of aliphatic hydrocarbons, which are common components of oils. The intensity of these peaks suggests that a significant number of hydrocarbons remain on the fly ash after the adsorption process, implying that the used oil contains non-polar hydrocarbon chains. This suggests the presence of hydrocarbon compounds associated with the used oil on the fly ash surface.

Carbonyl (C=O) Stretch (1640.40 cm^{-1}). The peak at 1640.40 cm^{-1} is attributed to the carbonyl (C=O) stretching vibrations. The presence of carbonyl groups is significant because it indicates oxidation processes in the oil. When oils are used in industrial processes, they undergo oxidative degradation, leading to the formation of carbonyl-containing compounds like ketones, aldehydes, and carboxylic acids. The presence of this band may be associated with oxygen-containing compounds from the used oil; however, this assignment should be interpreted cautiously in the absence of a control FTIR spectrum of the oil.

C=C Stretch (1443.48 cm^{-1} and 1377.56 cm^{-1}). The peaks around 1443.48 cm^{-1} and 1377.56 cm^{-1} are often associated with C=C stretching vibrations in aromatic compounds. Aromatic hydrocarbons are also commonly found in oils and can be products of thermal degradation. These bands may indicate the presence of hydrocarbon-related compounds associated with the *used oil after contact with the fly ash.*

Si-O Stretch (999.76 cm^{-1}, 873.29 cm^{-1}, 781.59 cm^{-1}, and others). Several peaks in the region below 1000 cm^{-1}, particularly at 999.76 cm^{-1}, 873.29 cm^{-1}, and 781.59 cm^{-1}, are indicative of Si-O stretching vibrations. These are characteristics of the silicate structure of the fly ash, which is derived from its original mineralogical composition. Fly ash is primarily composed of silicon dioxide (SiO_2) and other aluminosilicates, which form a porous structure ideal for adsorption. These peaks confirm the presence of the silicate backbone of the fly ash and indicate that the adsorption of used oil has not altered its basic mineral structure.

Sulfate (SO_4^{2-}) Vibration (1459.96 cm^{-1}). Another notable peak in the spectrum occurs at 1459.96 cm^{-1}, which can be associated with sulfate (SO_4^{2-}) groups. Sulfates in fly ash typically arise from the combustion process in coal-fired power plants, where sulfur in the coal is oxidized to sulfate. The presence of this peak suggests that the fly ash retains some of its original sulfate content, which might play a role in the adsorption of certain polar species from the oil.

The FTIR spectrum provides preliminary information on the bands observed (**Table 4**) after contact between activated fly ash and used oil. Several bands associated with both the fly ash matrix and oil-derived compounds are observed; however, the adsorption mechanism cannot be conclusively determined from FTIR data alone:

Adsorption of Hydrocarbons: The presence of prominent C-H stretching vibrations confirms that the fly ash has adsorbed hydrocarbons from the used oil. These hydrocarbons are likely aliphatic in nature, which is consistent with the composition of many oils used in industrial applications.

Oxidation Products: The appearance of carbonyl peaks suggests that the used oil has undergone some degree of oxidation, leading to the formation of polar oxidation products like ketones and aldehydes. The adsorption of these products by fly ash indicates that the material can be used not only to remove hydrocarbons but also to capture oxidized oil components, which are often more challenging to treat.

Retention of Silicate Structure: Despite the adsorption of oil, the FTIR spectrum shows that the basic silicate structure of the fly ash remains intact. This suggests that the adsorption process primarily occurs on the surface of the fly ash, without significant alteration of its mineral composition. This is important for the reuse of fly ash as an adsorbent in multiple cycles of oil treatment.

The FTIR spectrum of activated fly ash after contact with used oil shows bands associated with hydroxyl and hydrocarbon-containing compounds, suggesting the presence of oil-derived species on the fly ash surface. The spectrum also indicates that the basic silicate structure of fly ash remains observable after contact with used oil. This analysis provides valuable insights into the chemical interactions occurring during the adsorption process and highlights the potential of activated fly ash for environmental applications in oil waste management.

CONCLUSION

This study shows that alkali activation modifies the structural and surface characteristics of fly ash and suggests its potential for oil remediation applications. FTIR characterization revealed the removal of Si-O-Si absorption peaks and the presence of organic peaks from used oil on activated fly ash, indicating successful modification. XRD analysis confirmed that the activated fly ash retained a predominantly amorphous structure with enhanced crystallinity. BET analysis showed an increase in specific surface area from 22.71 m^2/g in raw fly ash to 23.53 m^2/g in activated fly ash, with an average pore diameter of 5.77 nm, classifying it as mesoporous. These structural changes, facilitated by NaOH activation, suggest that alkali-activated fly ash may be considered a potential low-cost material for environmental remediation applications. Further research should include quantitative adsorption studies, including adsorption capacity, kinetics, and isotherm analysis, as well as optimization of activation conditions.

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