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Original Research Article

Synthesis and Characterization of Indonesian Natural Zeolite as a Potential Support Material for n-Hexane Isomerization Catalyst

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Abstract

The demand for high-quality fuel with a high-octane number or Research Octane Number (RON) continues to increase due to strict emission standards and the ban on lead-based additives. This study aims to develop a catalyst material based on Indonesian natural zeolites from Lampung (ZAL), Bayah (ZAB), and Tasikmalaya (ZAT) through pre-treatment optimization to obtain comparable mesoporous material properties with Mobil Composition of Matter No. 41 (MCM-41). This catalyst is designed for the isomerization process of n-hexane into iso-hexane as a model compound for light naphtha. The research focuses on utilizing Indonesian natural zeolite in combination with desilication techniques using NaOH and cetyltrimethylammonium bromide (CTAB) as surface directing agents. The catalyst is characterized by using X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF), Surface Area Analysis (SAA), and Scanning Electron Microscopy (SEM) to identify the surface morphology of zeolite. XRD results show structural alteration in the low-to-high θ/2θ region with increasing NaOH concentration. XRF analysis reveals that the bulk Si and Al contents remain relatively stable (Si: 34.73-36.6 wt%; Al: 6.55-8.1 wt%), confirming that desilication occurs selectively at the crystal surface rather than altering the bulk composition. SAA data demonstrate substantial enhancement of textural properties, with the specific surface area increasing from 40.5 to 131.7 m²/g for ZAL, 36.5 to 134.9 m²/g for ZAT, and 46.9 to 101.0 m²/g for ZAB after 1.5 M NaOH treatment. SEM images reveal morphological changes from a defined crystalline texture to a more dispersed surface upon increasing NaOH concentration.

Keywords: Indonesian Natural Zeolite; MCM-41; NaOH; CTAB; Desilication

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1. Introduction

Global demand for high-quality fuel continues to rise alongside growth in the transportation and industrial sectors. One of the main parameters of high-quality fuel is a high-octane number (Research Octane Number, RON), which plays a crucial role in improving combustion efficiency while reducing greenhouse gas emissions. Furthermore, the implementation of increasingly stringent emission standards, such as the Euro standard, has driven the fuel industry to produce more environmentally friendly products without using lead-based additives. The ban on lead-based additives is based on their detrimental impact on the environment and human health. The main challenge faced is meeting the demand for high-quality fuel through the application of innovative and efficient technology [1].

The light naphtha isomerization process presents an important solution for improving fuel quality. This process converts straight-chain n-paraffin molecules into branched iso-paraffins, which have a higher octane number. Iso-paraffins provide better fuel performance and help reduce harmful exhaust emissions. This aligns with the global need for environmentally friendly fuels [2]. Catalysts play a key role in determining the

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success of the isomerization process. One widely used bifunctional catalyst is based on platinum (Pt) metal. Platinum is known for its ability to facilitate hydrogenation / dehydrogenation reactions, which are the initial steps in converting n-hexane to iso-hexane. Additionally, platinum increases selectivity towards iso-paraffin products and prevents deactivation due to carbon deposition, thereby extending the catalyst's lifespan. This makes platinum a primary component in modern catalysts [3,4].

Current isomerization technology often relies on chloride-based catalysts, such as chlorinated alumina, which have long been used due to their ability to efficiently convert linear hydrocarbons into branched ones [7]. However, chloride-based catalysts have significant drawbacks, including sensitivity to water and oxygen contamination, which require strict operational control, and they produce hazardous chemical waste such as chloride gases that can pollute the environment and accelerate equipment corrosion [8]. As an alternative, newer technologies use sulfated metal oxide-based catalysts, such as LPI-100, which are more stable and allow operation at lower temperatures, thereby reducing energy consumption. Nevertheless, this technology has high initial investment costs, especially for implementation in developing countries, and the regeneration of metal oxide catalysts also requires complex techniques, adding to the challenges of its application [8]. The UOP Penex™ process, which uses a platinum-chloride catalyst to enhance isomerization efficiency at low pressure, is designed to minimize by-product formation. However, chloride gas emissions from this process cause environmental effects such as air pollution and health risks for workers, further driving the need to develop more environmentally friendly catalytic technologies [7].

Catalyst performance is not only determined by the active metal but also by the support material. A wide range of inorganic materials are utilized, including single-component metal oxide, carbon-based structures, and complex mixed oxides. Among these, aluminosilicates represent one of the most versatile and industrially classes of material. Aluminosilicates, most notably natural zeolites and clay minerals are used. Natural zeolites assemble into a rigid, three-dimensional crystalline network. By contrast, clay minerals arrange into two-dimensional layered phyllosilicates composed of stacked tetrahedral and octahedral sheets. Their internal volume exists strictly within dynamic interlayer spaces between adjacent sheets, which expand or collapse depending on hydration state and solvent polarity, lacking the rigid geometric confinement needed for shape-selective transformations.

As detailed in Table 1, the structural constraints of natural zeolites translate directly into superior isomer yields, higher selectivity toward high-octane branched paraffins, and significantly lower cracking losses compared to clay-based systems. Therefore, natural zeolites are selected. Mordenite (MOR) zeolite is a natural zeolite that has long been a primary choice in catalytic applications due to its high thermal stability and acidic properties [5]. However, its small microporous structure poses a limitation in handling large molecules like those in light naphtha. To overcome this limitation, mesoporous materials such as MCM-41 were developed. With larger porosity, MCM-41 allows for efficient diffusion of large molecules, enhancing catalyst activity and selectivity. The combination of mordenite and MCM-41 produces a composite catalyst that combines the strong acidity of mordenite with the high porosity of MCM-41, making it a promising solution for the isomerization process [6].

Various previous studies have shown the great potential of combining mordenite zeolite with mesoporous materials like MCM-41 in improving the efficiency of the isomerization process. Wang *et al.* [5] reported that an optimized

Table 1. Catalyst performance between natural zeolites vs clay.

Parameter	Natural Zeolites	Clay
Catalyst Support	Natural Modernite	Al-Zr pillared Tagan Montmorillonite
Mineral Type	Tectosilicate	Phyllosilicate
Isomerisation Substrate	Hexane	Hexane
Active Metal	Pt (~0.5 wt%)	Pd (0.35 wt%)
Reaction Conditions	270°C	400 °C
Conversion	70.7%	58.9%
Selectivity	98.3%	91.3%
Main Advantage	Strong Brønsted acidity; shape selectivity;	Low Pd Loading
Main Disadvantage	-	Requires higher temperature

MCM-41/MOR catalyst through alkalization treatment achieved an n-hexane conversion of 59.8% and high selectivity towards the <C8 fraction, while Tang *et al.* [4] developed a Ni_2P-MCM-41/MOR-based catalyst capable of achieving an n-hexane conversion of 73.0% and iso-paraffin selectivity up to 84.0% at 250 °C and 3.0 MPa pressure. The addition of active metals such as Ni or Zn to the mesoporous structure has been proven to enhance catalyst activity and resistance to deactivation, as seen in the Pt-Zn/HY nanocatalyst which has superior stability and high selectivity in hydrocarbon reforming [9]. In Indonesia, the potential of abundant natural zeolites in regions, such as Bayah, Lampung, and Tasikmalaya, has been utilized for various catalytic applications. For example, Lampung zeolite successfully improved the quality of crude biodiesel with a conversion of 60.79% [10], while Bayah and Tasikmalaya zeolites achieved biodiesel conversions up to 67.90% through the transesterification of kapok seeds [11] and hydrocracking of used cooking oil with a yield of 43.5% using modified Klaten's zeolite [12].

The transformation of mordenite zeolite into MCM-41 involves complex chemical processes, one of which is desilication using a NaOH solution. Desilication aims to remove some silicon atoms from the zeolite structure, increase the Si/Al ratio, and create larger porosity. This process is carried out by immersing the zeolite in a basic solution containing CTAB (cetyltrimethylammonium bromide), which functions as a structure-directing agent in the formation of mesopores. CTAB aids the formation of the mesoporous structure during the desilication process, which breaks the tetrahedral SiO_4 bonds, producing soluble silicate monomers. The result is a mesoporous material with larger pores and higher surface area. This transformation allows the catalyst to handle larger molecules like n-hexane more efficiently, enhancing catalytic activity and improving selectivity towards the desired products [6,13].

Based on the results of previous research, the combination of modifying natural zeolite into MCM-41 through a desilication process using NaOH and platinum impregnation has great potential to produce a catalyst with high activity towards iso-paraffins and good stability during operation. This process not only provides a solution to the challenges of the isomerization process but also supports industrial sustainability by utilizing local Indonesian resources. Therefore, this research aims to develop a catalyst based on MCM-41 produced from the transformation of Indonesian natural zeolite using NaOH-CTAB desilication at three concentrations (0.5, 1.0, and 1.5 M) followed by Pt impregnation. The characterization results obtained therefore aim to identify which Indonesian natural zeolite and NaOH treatment condition are most suitable for further development as a Pt-supported isomerization catalyst. It is hoped that the results of this research can support the development of technology based on local resources, increase the added value of natural zeolites, and provide a significant contribution to economic and environmental sustainability.

2. Materials and Method

2.1. Materials

The natural zeolites used in this study were obtained from three Indonesian deposits, namely Lampung (ZAL), Bayah (ZAB), and Tasikmalaya (ZAT). Cetyltrimethylammonium bromide (CTAB, ≥ 98% purity, Merck) was used as a structure-directing agent, and anhydrous sodium hydroxide (NaOH, ≥ 99%, Merck) as the desilication agent. Hydrochloric acid 6 M (HCl, prepared from 37% Merck pro-analysis grade) was used for pH adjustment, ammonium nitrate (NH_4NO_3, ≥ 99%, Merck) for the ion-exchange step, and chloroplatinic acid hexahydrate ($H_2PtCl_6 \cdot 6H_2O$, ≥ 99.9%, Sigma-Aldrich) as the platinum precursor. Distilled water (aquadest) was used throughout the synthesis. High-purity gases used during characterization were helium, hydrogen, nitrogen, and synthetic compressed air (≥ 99.999%, supplied by Samator).

2.2. Apparatus

The main apparatus used during synthesis comprised a Teflon-lined stainless-steel hydrothermal autoclave (100 mL) for the hydrothermal treatment, a programmable muffle furnace (up to 1200 °C) for calcination, and a magnetic stirrer with integrated hot plate for solution preparation. Solid-handling instruments included an analytical balance, a digital pH meter for pH control during synthesis, and a vacuum filtration unit for solid separation. Common laboratory glassware (watch glass, beaker glasses, measuring cylinders, Mohr pipettes, and funnels) and a porcelain mortar were used for sample preparation, and a hydraulic pellet press was used for shaping characterization samples.

2.3. Synthesis of MCM-41 Modified from Indonesian Natural Zeolite

Modified MCM-41 was synthesized using Indonesian natural zeolite as a silica-alumina source. The procedure involved dispersing 4.5 grams of each natural zeolites from Bayah (ZAB), Lampung (ZAL), & Tasikmayala (ZAT) in 25 mL of a NaOH solution (0.5-1.5 M) and stirring at room temperature for 30 minutes. Then, 60 grams of a CTAB solution were added (concentration of 16 wt%), and the mixture was stirred for another 30 minutes before undergoing hydrothermal

treatment in an autoclave at 100 °C (373 K) for 24 hours. Cool the mixture to room temperature afterwards. After cooling, the pH was adjusted to 8.5 using 6 M HCl, followed by a second hydrothermal at 100 °C (373 K) for 24 hours. Upon cooling, the solid product was collected by filtration and washed repeatedly with deionized water until the filtrate reached a neutal pH. Lastly, the product is calcined at 550 °C (823 K) for 5 hours to remove organic species.

2.4. Characterizations

All characterizations were performed at the Research and Technology Center, PT Pertamina (Persero), following established standard procedures and in-house methods. X-Ray Diffraction (XRD) analysis was carried out following an in-house method developed at PT Pertamina (Persero). The catalyst or support was first ground in a porcelain mortar, prepared on a flat sample holder, and then inserted into the diffractometer. Measurement was performed using Cu-Kα radiation (λ = 1.5406 Å) operated at 40 kV and 35 mA, with a 2θ range of 1–40° and a step size of 0.02°. The resulting diffractograms were used to identify the crystalline phases of natural zeolites and to monitor the structural alteration of the supports following alkaline treatment. X-Ray Fluorescence (XRF) analysis was performed in accordance with the ASTM E 1621-05 standard method. The catalyst was first ground into a fine powder, packed into a specialized aluminum cup, and compressed using a hydraulic pellet press. After labeling, the sample was placed in the XRF spectrometer and analyzed under operating conditions of 40 kV and 45 mA using a quantitative analysis program. The principal elements monitored were silicon (Si) and aluminum (Al), reported as weight percentages of the bulk composition.

Surface Area Analysis (SAA) was carried out following ASTM D3663, D4641, and D4222, using an Autosorb (Quantachrome) instrument. The procedure degassed a 0.2 g sample at 100 °C for 1 hour under slow vacuum, followed by 300 °C for 5 hours under fast vacuum. Subsequent analysis employed nitrogen adsorption–desorption isotherms to calculate the specific surface area (m^2/g), pore volume (cm^3/g), and pore diameter (Å).

Scanning Electron Microscopy coupled with Energy Dispersive X-ray spectroscopy (SEM) was used to examine the surface morphology. Samples were placed on conductive carbon tape mounted on aluminum stubs and coated with a thin layer of gold by sputter-coating to enhance conductivity. Imaging was carried out using a scanning electron microscope at an accelerating voltage of 15 kV.

3. Results and Discussion

3.1. X-ray Diffraction (XRD)

The XRD patterns (Figure 1) compare Natural Zeolite Bayah with zeolite Bayah treated using NaOH solutions at different concentrations (0.5 M, 1.0 M, and 1.5 M). The diffraction pattern of the natural zeolite exhibits multiple sharp and well-defined peaks, confirming its crystalline aluminosilicate structure, which is shown in Figure 1. The peaks are consistently positioned at approximately 22.4-22.5° θ/2θ. However, NaOH-treated ZAB samples exhibit discernible structural alterations when compared to the parent zeolite, with changes observed across all NaOH concentrations, particularly in the low θ/2θ region of the diffraction patterns specifically

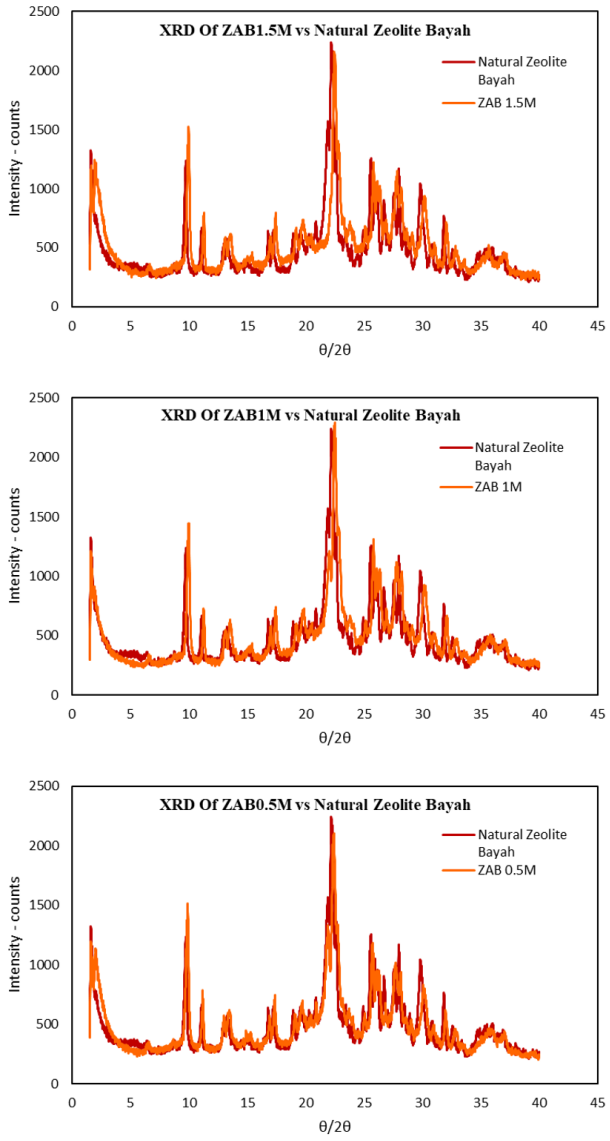


Figure 1. Comparison of XRD diffractogram of synthesis ZAB 0.5 M, 1 M, and 1.5 M with Natural Zeolite Bayah.

at approximately 9.9-10.0° θ/2θ. These observations indicate that ZAB possesses a stable framework.

Following the analysis of NaOH-treated zeolite Bayah, XRD of Natural Zeolite Lampung and zeolite Lampung treated using NaOH solutions at concentrations of 0.5 M, 1.0 M, and 1.5 M are also compared (Figure 2). Upon alkaline treatment, structural modifications are observed across all concentrations, with notable peak shifts observed throughout the θ/2θ range depending on NaOH concentration. At 0.5 M NaOH, the primary peak shifts toward the low θ/2θ region at θ/2θ = 9-10°, indicating selective dissolution of amorphous phases and possible reorganization of the zeolite surface layer. At 1.0 M, the primary peak shifts toward the higher θ/2θ region at 2θ = 28-29°, with maximum intensity reaching approximately 3,600 counts, representing a 49% enhancement relative to the untreated sample, attributed to progressive exposure of the crystalline framework as amorphous fractions are dissolved. At 1.5 M, the peak returns to θ/2θ = 22-23°, however peak intensity declines, falling below the untreated sample, indicating over-treatment where excessive alkaline exposure begins disrupting the crystalline framework itself. Lastly, untreated Natural Zeolite Tasikmalaya and Natural Zeolite Tasikmalaya treated using the same variable of NaOH are compared and the diffractogram results are comparable (Figure 3). The untreated ZAT exhibits multiple sharp peaks, confirming its crystalline aluminosilicate structure. Upon alkaline treatment, structural modifications are observed across the θ/2θ range, with the most

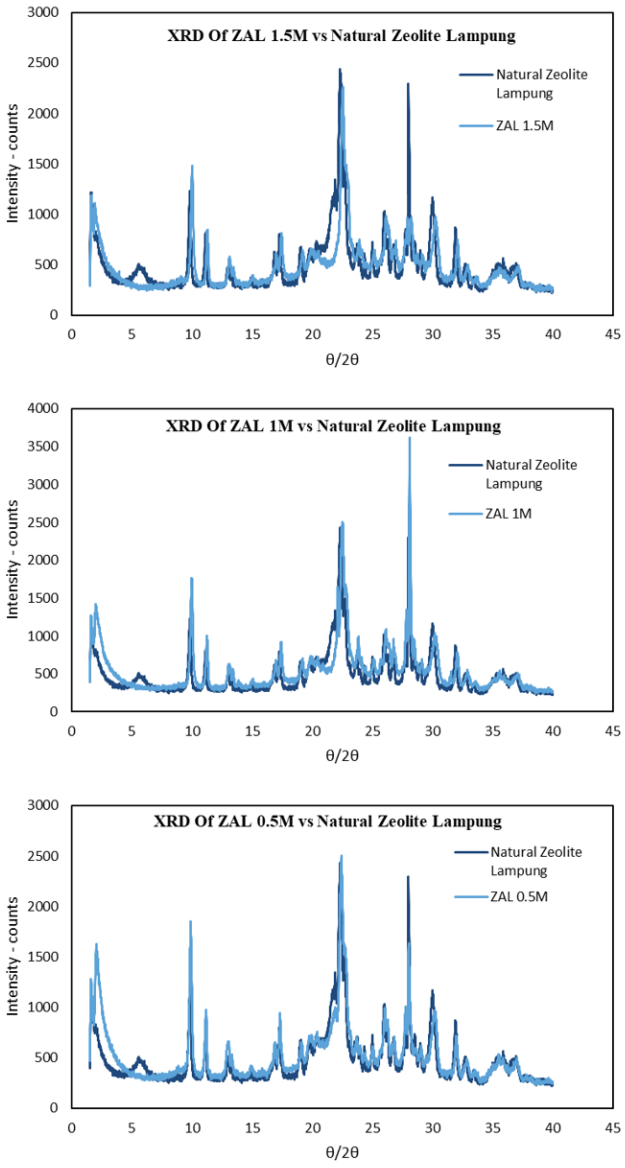


Figure 2. Comparison of XRD diffractogram of synthesis ZAL 0.5 M, 1 M, and 1.5 M with Natural Zeolite Lampung.

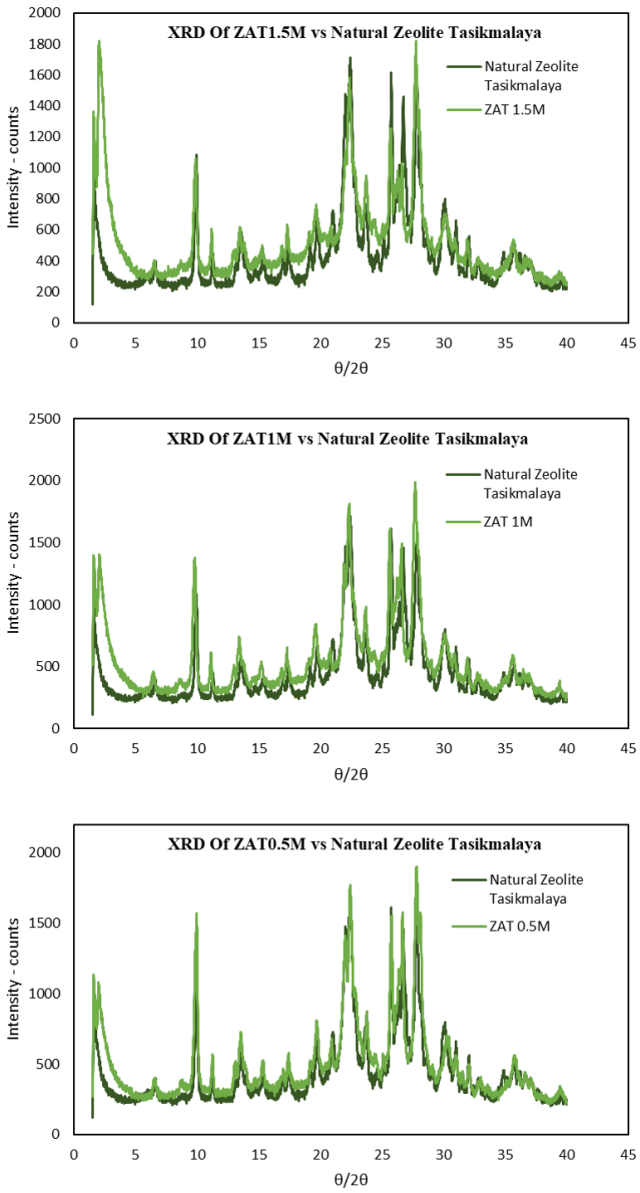


Figure 3. Comparison of XRD diffractogram of synthesis ZAT 0.5 M, 1 M, and 1.5 M with Natural Zeolite Tasikmalaya.

significant changes occurring in the mid-to-high θ/2θ region. Peak intensities show a moderate increase relative to the untreated sample, suggesting partial dissolution of amorphous phases that progressively expose the underlying crystalline framework. At 1.0 M, the enhancement becomes more pronounced, with peak intensity reaching its maximum among all treated samples. At 1.5 M, peak intensity slightly declines, though it remains above the untreated sample, suggesting that ZAT maintains reasonable framework integrity even at higher NaOH concentrations without exhibiting the over-treatment effect observed in ZAL.

These results indicate that 1.0 M NaOH represents the optimal modification condition for ZAT, consistent with the progressive increase in specific surface area observed in surface area analysis. The low-angle XRD patterns of NaOH-treated ZAL, ZAB, and ZAT show a broad reflection in the low 2θ region, suggesting incipient MCM-41-like mesoporosity. However, MCM-41 exhibits three reflections at 2θ = 2.4° (100), 4.1° (110), and 4.8° (200) [14]. The absence of the (110) and (200) reflections in the treated samples indicates that further optimization is needed to achieve fully ordered MCM-41-like mesoporosity.

3.2. X-ray Fluorescence (XRF)

The XRF data (Table 2) shows the elemental composition of the catalysts before and after NaOH treatment. The untreated parent zeolites exhibited Si and Al content reportedly comparable to the same geological sources used by Kurniawan *et al.* [15]. Also, the key observation is the remarkable stability of the silicon (Si) and aluminum (Al) content. Si content varies only within the range of 34.73-36.6 wt%, while Al content ranges between 6.55-8.1 wt%. Despite the significant changes in surface area and acidity observed in previous analyses, the Si and Al percentages remain largely constant across all samples and treatments. The XRF results show minor variations in Si and Al content across all three natural zeolites (ZAL, ZAT, ZAB) following NaOH treatment at 0.5-1.5 M, with no consistent directional trend observed with increasing alkali concentration. The absence of systematic Si-decrease and in several cases a slight increase relative to the untreated parent suggests that bulk framework desilication was limited under the conditions applied.

The increase in Si/Al ratio following CTAB treatment is attributed to desilication and surfactant-induced reassembly. NaOH dissolves a portion of Si atoms from the zeolite framework, generating soluble silicate species. CTAB subsequently acts as a structure-directing agent, facilitating the recondensation and redeposition of dissolved silica onto the zeolite surface rather than being lost to the filtrate. Similar behavior has been reported in the synthesis of hierarchical zeolites via desilication-reassembly mechanisms using NaOH and CTAB, where CTA^+ cations are attracted by negatively charged sites formed during desilication, promoting the redistribution of dissolved silica species within the zeolite structure [16].

3.3. Surface Area Analyzer (SAA)

NaOH treatment produced a concentration-dependent enhancement of the textural properties of all three natural zeolites (Table 3). BET surface

Table 2. XRF of ZAB, ZAB NaOH treatments, ZAL, ZAL NaOH treatments, ZAT, and ZAT NaOH treatments.

No	Samples	wt% Element		Si/Al Ratio
		Si	Al	
1	ZAL	35.17	7.28	4.83
2	ZAL NaOH 0.5 M	36.6	7.59	4.82
3	ZAL NaOH 1 M	35.81	7.29	4.91
4	ZAL NaOH 1.5 M	36.3	7.33	4.95
5	ZAT	34.89	6.55	5.33
6	ZAT NaOH 0.5 M	35.67	6.96	5.13
7	ZAT NaOH 1 M	35.39	6.75	5.24
8	ZAT NaOH 1.5 M	35.59	6.81	5.23
9	ZAB	34.73	7.54	4.60
10	ZAB NaOH 0.5 M	34.87	8.1	4.31
11	ZAB NaOH 1 M	35.33	7.63	4.63
12	ZAB NaOH 1.5 M	35.17	7.28	4.81

area increased progressively with NaOH concentration, rising from 40.5 to 131.7 m²/g for ZAL, 36.5 to 134.9 m²/g for ZAT, and 46.9 to 101.0 m²/g for ZAB at 1.5 M, corresponding to increases of approximately 225%, 270%, and 115%, respectively.

Pore volume followed the same trend, increasing from 0.07 to 0.307 cm^3/g (ZAL), 0.068 to 0.292 cm^3/g (ZAT), and 0.070 to 0.234 cm^3/g (ZAB), while pore diameter expanded from a parent range of 6.4-7.0 nm to 8.7-10.7 nm after treatment. The treated pore diameters fall within the mesopore range and are comparable to the ±10 nm mesopore size reported [17] for NaOH-treated zeolite, supporting the development of mesoporosity in a similar size regime. The concurrent increase in surface area, pore volume, and pore diameter indicates the development of mesoporosity in all three natural zeolites following NaOH treatment.

The presence of CTAB on treated natural zeolite contributes to this enhancement. CTAB is a structure-directing agent which acts as a template that could deposit amorphous silica on the zeolite surface and create additional void spaces. These properties are therefore compared with unmodified MCM-41, which exhibits an S_{BET} of 1240 m²/g, V_p of 0.92 cm^3/g, and a pore diameter of 38.1 Å [18]. At the optimal NaOH concentration of 1.5 M, ZAL achieved the highest surface area among the three zeolites, followed by ZAT and ZAB. While these values represent substantial improvements over untreated zeolites, they remain significantly lower than that of MCM-41 in surface area and pore volume. By contrast, the pore diameter of treated NaOH natural zeolites is bigger than MCM-41. This result reflects that the NaOH treatment widens the pre-existing pores. A comparable enlargement of porosity through controlled alkaline desilication has been reported for ferrierite, where partial framework silicon removal generated additional mesoporosity without collapsing the parent crystal [19]. The development of such mesoporosity is particularly relevant for isomerization applications, since wider pores ease the diffusion of bulky branched intermediates; Gopal and Smirniotis [20] showed that the textural modification of platinum-loaded dealuminated zeolites strongly governs the isomer yield obtained during paraffin hydroisomerization.

3.4. Scanning Electron Microscopy (SEM)

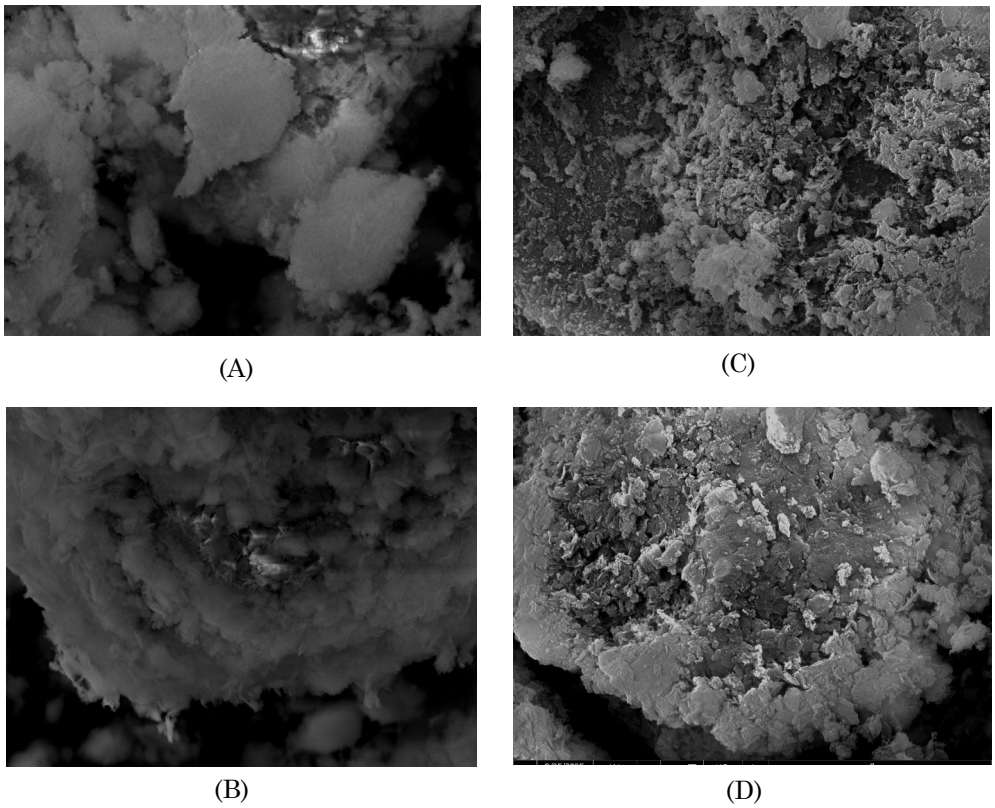
Investigation of the surface morphology via Scanning Electron Microscopy (SEM) revealed structural changes in the catalysts upon NaOH treatment. For the ZAT (Figure 4), morphology transitions from a defined structure to a collapsed and dispersed state. This degradation is attributed to the dissolution of the silica framework, a process whose intensity escalates with the concentration of the NaOH solution. The consistency of this behavior was also confirmed through analysis of the ZAB and ZAL samples, all of which exhibited analogous structural deterioration.

The untreated ZAT showed large smooth crystal surfaces. With increasing NaOH concentration, surfaces progressively eroded, beginning at edges and grain boundaries at 0.5 M, developing a visible dissolution front at 1 M, and fully fragmenting at 1.5 M. The parent ZAL (Figure 5) exhibited irregular granular aggregates with cracks. Upon NaOH treatment, the irregular granular aggregate became increasingly dispersed with increasing NaOH concentration, indicating progressive dissolution

Table 3. BET of ZAB, ZAB NaOH treatments, ZAL, ZAL NaOH treatments, ZAT, and ZAT NaOH treatments.

Zeolite	S_{BET} (m²/g)	V_p (cm^3/g)	PD (Å)
ZAL	40.513	0.07	69.141
ZAL NaOH 0.5 M	101.292	0.2281	87.178
ZAL NaOH 1 M	120.27	0.2621	90.073
ZAL NaOH 1.5 M	131.735	0.307	93.228
ZAT	36.471	0.068	70.352
ZAT NaOH 0.5 M	64.499	0.113	74.2357
ZAT NaOH 1 M	80.943	0.1709	84.462
ZAT NaOH 1.5 M	134.911	0.2921	86.615
ZAB	46.928	0.07	64.255
ZAB NaOH 0.5 M	49.38	0.1321	92.678
ZAB NaOH 1 M	67.92	0.1393	99.71
ZAB NaOH 1.5 M	100.981	0.234	107

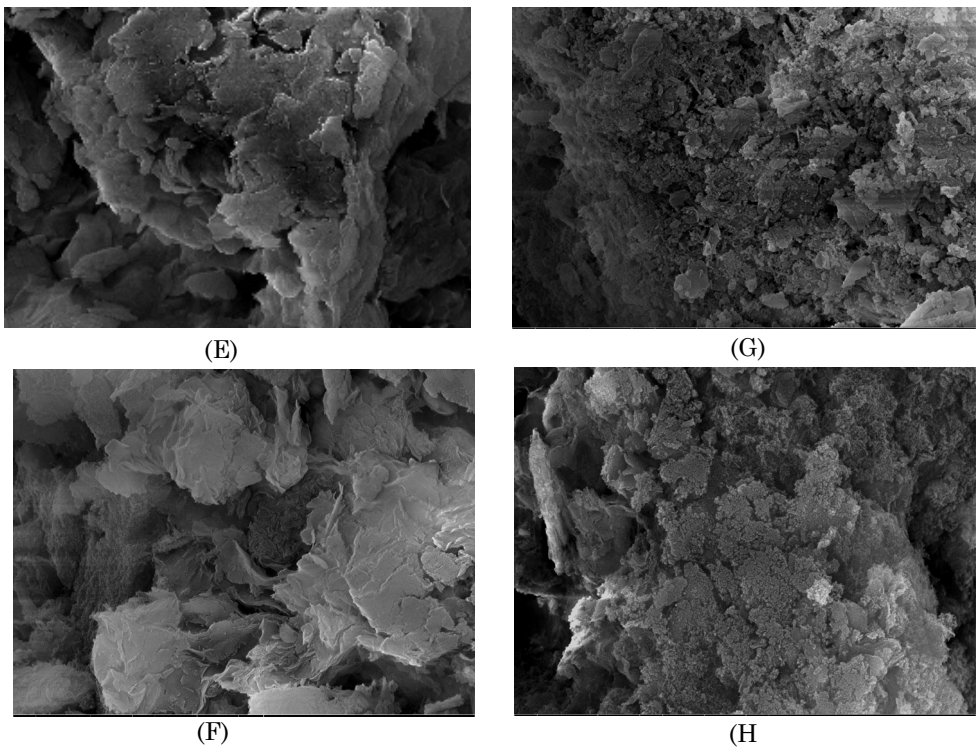
of the surface framework. Parent ZAB is already loosely aggregated, plate-like. At 0.5 M, thin angular platelets are liberated. At 1.0 M, surfaces are pitted/cratered with globular deposits at particle edges, and advanced etching is observed by 1.5 M. SEM images reveal that NaOH treatment disrupts the surface morphology of all three natural zeolites, transitioning from crystalline surfaces in the parent zeolites to increasingly dispersed granular aggregates at higher NaOH concentrations.



(A) (C)

(B) (D)

Figure 4. (A) ZAT 50000×, (B) ZAT 0.5 M NaOH 50000×, (C) ZAT 1 M NaOH 50000×, and (D) ZAT 1.5 M NaOH 50000×.



(E) (G)

(F) (H

Figure 5. (E) ZAL 50000×, (F) ZAL 0.5 M NaOH 50000×, (G) ZAL 1 M NaOH 50000×, and (H) ZAL 1.5 M NaOH 50000×.

This progressive morphological disruption of the zeolite framework is consistent with the external morphology of the synthesized MCM-41 in Figure 6, which similarly exhibits loosely agglomerated rounded particles. Such restructuring of a solid acid support is a recognized consequence of alkaline treatment, in which the controlled dissolution of framework silica reorganizes the external surface while preserving catalytically useful acid sites [21]. The combined development of mesoporosity and surface roughening observed here mirrors the behaviour reported for hierarchical ZSM-5 zeolites applied to light naphtha isomerization, where the interplay between mesoporosity and acidity was identified as the key factor controlling activity and selectivity towards branched products [22].

3.5. Implications for Isomerization Catalyst Development

From a process standpoint, detailed kinetic descriptions of light naphtha isomerization over

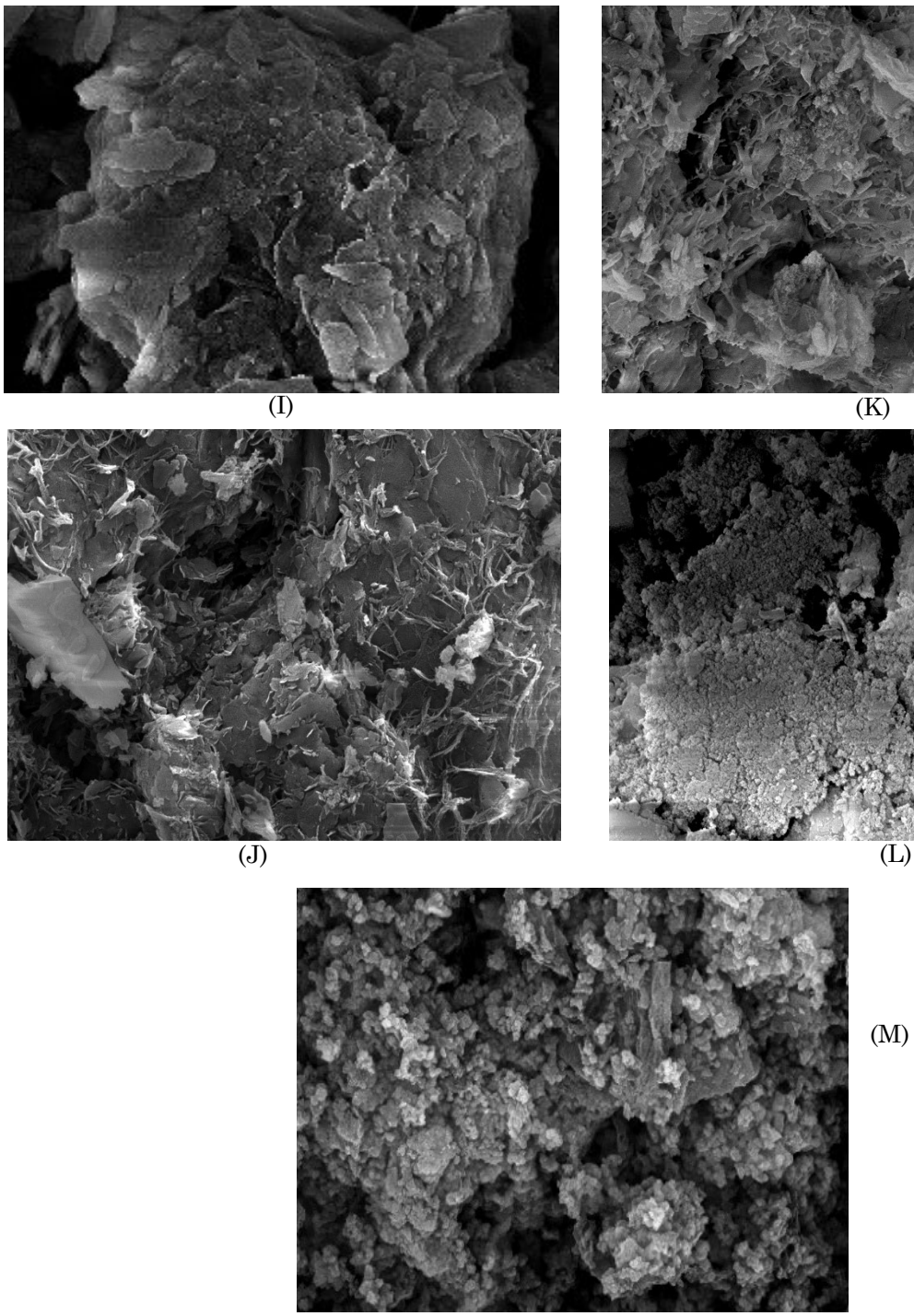


Figure 6. (I) ZAB 50000×, (J) ZAB 0.5 M NaOH 50000×, (K) ZAB 1 M NaOH 50000×, (L) ZAB 1.5 M NaOH 50000×, and (M) MCM-41 50000x.

Pt/zeolite catalysts emphasise that accessible acid sites and adequate pore transport jointly determine isomer yield [27], both of which are favoured by the mesoporosity generated in this study. The desilication-reassembly behaviour observed for the three Indonesian zeolites is consistent with the controlled mesopore formation reported for mordenite subjected to alkaline leaching [28], and with strategies that derive ordered MCM-41-type materials from inexpensive silica-bearing sources [29]. Collectively, these comparisons reinforce that the optimised NaOH treatment provides a credible, resource-efficient pathway toward a Pt-supported isomerization catalyst based on Indonesian natural zeolite.

4. Conclusions

Based on the comprehensive characterization data, the following conclusions can be drawn regarding the effect of NaOH treatment on the ZAB, ZAL, and ZAT catalysts. The alkaline treatment followed by CTAB-templated hydrothermal synthesis successfully induces desilication, as confirmed by consistent improvement in textural properties for all catalysts. The surface area (S_{BET}), pore volume (V_p), and pore diameter (PD) all increased significantly with higher NaOH concentration. The XRF data confirmed that the desilication process was selective, as the bulk Si/Al composition remained largely unchanged, proving that the enhancements are due to physical restructuring rather than chemical alteration. SAA characterization showed significant enhancement in surface area, pore volume, and pore diameter with increasing NaOH concentration, with ZAL at 1.0 M NaOH yielding optimal textural properties. SEM analysis revealed morphological disruption with increasing NaOH concentration.

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CRedit Author Statement

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During the preparation of this work the author(s) used ChatGPT in order to improve the readability and language of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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