Surface properties of pillared acid-activated bentonite as catalyst for selective production of linear alkylbenzene

Hossein Faghihian *, Mohammad Hadi Mohammadi

Department of Chemistry, University of Isfahan, Isfahan 81746-73441, Islamic Republic of Iran

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Acid-activated and pillared montmorillonite were prepared as novel catalysts for alkylation of benzene with 1-decene for production of linear alkylbenzene. The catalysts were characterized by X-ray diffraction, FT-IR spectroscopy, N₂ adsorption isotherms, temperature programmed desorption of NH₃, scanning electron microscopy and elemental and thermal analysis techniques. It was found that acid-activation of clays prior to pillaring increased the porosity, total specific surface area, total pore volume and surface acidity of the catalysts. Optimization of the reaction conditions was performed by varying catalyst concentration (0.25–1.75 wt%), reactants ratio (benzene to 1-decene of 8.75, 12 and 15) and temperature (115–145 °C) in a batch slurry reactor. Under optimized conditions more than 98% conversion of 1-decene, and complete selectivity for monoaalkylbenzenes were achieved.

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1. Introduction

Bentonite is dioctahedral clay of smectite group and is composed of stacked alumino-silicate layers. The silica tetrahedra (Si⁴⁺ coordination with O²⁻) and alumina octahedra (Al³⁺ coordination with O²⁻) are interconnected by the sharing of O²⁻ at polyhedral corners and edges in such a way that a sheet of alumina octahedral is sandwiched between two sheets of silica tetrahedral, thus making the composition of Si–Al–Si (TOT). Partial substitution of Al³⁺ in octahedral sites by Mg²⁺ and Fe³⁺, and to a lesser degree, a partial substitution of Si⁴⁺ in tetrahedral sites by Al³⁺ is observed in natural samples. Due to this substitution, T-O-T layers are negatively charged and interlayer space between T-O-T layers is occupied by exchangeable cations such as Na⁺, K⁺ and Ca²⁺ to neutralize the charge. During acid treatment, the interlayer cations are replaced by H⁺ ions followed by dissolution of aluminum octahedral and silicon tetrahedral sheets and subsequent dissolution of structural cations. The structural changes occurring in the clay depend on both the clay type and the acid treatment conditions. The surface acidity and textural properties (surface area and pore volume) which determine the catalytic behavior of the clay largely depend on the structural modifications resulting on acid treatment [1]. Therefore, it is imperative to monitor the structural and textural modification during the acid treatment.

* Corresponding author. Tel.: +98 3117932700; fax: +98 3117932700.
E-mail addresses: faghihian@iau-sh.ac.ir, h.faghih@sci.ui.ac.ir (H. Faghihian).

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1. Introduction

Pillaring of clay with inorganic polycations, followed by calcination produces thermal stable layered materials that can be used as solid acid catalyst for variety of organic reactions. The first common characteristic of pillared interlayered clay (PILC) is the distance (d₀₀₂) separating of contiguous layers after heating. Thus, PILC have permanent porosity and higher accessible specific surface area than the intact clay [2]. Application of Al, Ti, Zr, La and other cations as intercalating agents has been described in literatures [3–5]. Linear alkylbenzenes (LABs) used as starting material for manufacturing of linear alkylbenzenesulfonates are the main active material of the most detergents. The solid acid catalysts are developed to replace the traditional Friedel–Crafts catalysts which are obsolescent because of their hazardous nature [6]. Zeolites [7–9], clays [10,11], heteropolyacids [12] and silica–alumina [13] have been studied as solid acid catalysts.

In this research a novel catalyst was prepared by acid activation and pillaring of a bentonite sample, and then characterized and used for alkylation of benzene with 1-decene.

2. Experimental

2.1. Materials

H₂SO₄ (95–98%), NaOH, aluminum chloride (AlCl₃·6H₂O, 99%), benzene and 1-decene were purchased from Merck Company. All chemicals were research grade and used as received without further purification. Bentonite was purchased from Sigma–Aldrich.

2. Experimental
2.2. Synthesis of catalysts

Sodium bentonite (particle size ≤ 2 μm, cation exchange capacity (CEC) of 74.73 mequiv./100g) was used as starting material. Two different acid activated samples were prepared by treating bentonite with 2 M and 4 M H₂SO₄ according to the procedure described by Falahat et al. [14]. Thirty grams of bentonite was stirred with 175 mL of H₂SO₄ at 80 °C for 2 h in a round-bottom flask. The slurry was cooled in room temperature, centrifuged and washed with distilled water. The samples were designated as H–C and H₂–C respectively. Acid-treated samples were pillared according to the method reported by Chae et al. [15]. Aluminum hydroxyl-oligomeric solution (OH/Al molar ratio of 2) was prepared by adding adequate volumes of 0.2 M NaOH to 0.2 M AlCl₃ solution under vigorous stirring for 24 h. Appropriate amount of pillaring solutions, required for the Al/clay (mmol Al/g clay) ratio of 25 was then slowly added to 1.0 L of distilled water containing 10 g of the sample. The mixture was vigorously shaken, centrifuged and washed repeatedly with de-ionized water until free of Cl⁻ ions (as tested by AgNO₃). The final product was dried at 110 °C prior to calcination at 300 °C. Two alumina-pillared samples were prepared by intercalating the Keggin ion [(Al₃O₄(OH)₄(H₂O)₁₂)]⁺ in the framework of acid-activated materials (H–C and H₂–C) and were designated as H–Al–PILC and H₂–Al–PILC respectively.

2.3. Characterization of the samples

Chemical composition of the samples was determined by XRF method using a Bruker S4 PIONEER equipment. The CEC of the samples was measured with 0.01 M copper ethylenetetramine complex solution [16]. XRD patterns were obtained by a Bruker D8 ADVANCE, P4 PIONEER diffractometer, using Cu Kα radiation. FT-IR study was carried out using JASCO, FT-IR-6300 having a standard mid-IR DTGS detector. Pore volume and pore size distribution of the catalysts were determined by N₂ sorption using a Belsorp max 113, Japan, Inc. system. The surface area of the sample was calculated from the Brunauer–Emmett–Teller (BET) equation. The specific micropore volumes (Vₘ) of the samples were obtained from the t-plot method [17]. The micropore size distribution of the samples was calculated using the Horvath–Kawazoe (H–K) equation [18] and the Barret, Johner and Halenda (BJH) method was used to determine the distributions of the mesopores [19]. The surface acidity of the samples was evaluated by temperature programmed desorption (TPD) of ammonia in a Micromeritics TPD/TRP 2900 equipped with a thermal conductivity detector (TCD). Approximately 0.25 g of the sample was activated under helium flow at 300 °C for 1 h, and then ammonia was passed over sample at 100 °C for 30 min. The sample was purged with helium at the same temperature for 1 h to remove the adsorbed ammonia. The TPD profiles were obtained from 100 to 550 °C with heating rate of 10 °C min⁻¹. Thermal curves of the samples were taken by a Mettler, TG50 Thermal Analyzer. Scanning electron microscopy (SEM) was employed to examine the morphology of the samples by using a Philips XL SERIES, XL30 equipment.

2.4. Catalytic test

The catalytic activity of the synthesized samples was examined in a batch slurry reactor at different temperatures of 115, 130 and 145 °C. Benzene to 1-decene ratios of 8.75, 12 and 15 with 1 wt% of catalysts were examined. The alkylation products were analysed by GC techniques using a FISONS GC 8000 series gas chromatograph with a DB-17 capillary column coupled to a flame ionization detector (FID).

3. Results and discussion

3.1. Characterization studies

The studied bentonite consisted mainly of Al³⁺, Fe²⁺ and Mg²⁺ as framework cations and Na⁺, K⁺ and Ca²⁺ as exchangeable interlayer cations (Table 1). The aluminum content of the sample decreased after acid activation and increased after pillaring. Tetrahedral silica of the clay structure is stable and is not dissolved with lower acid concentration, but it is affected at higher acid concentration. The octahedral layer is affected even at lower acid concentration [20]. Therefore, the increase in silica content of the mild acid treatment is attributed to the leaching of octahedral and exchangeable cations [21].

The XRD patterns of the samples are shown in Fig. 1. Seven diffraction lines around 2θ of 7°, 20°, 22°, 27°, 35°, 54° and 62° are observed in the XRD pattern of the parent bentonite. The lines at 2θ = 22° and 27° belongs to cristobalite and quartz impurities. In the XRD patterns of acid-treated samples (H–C and H₂–C), the intensity of the characteristic lines decreased significantly. In fact, partial dissolution of the samples reduced their crystallinity. After intercalating with aluminum the d(001) (basal spacing of the parent clay as found in Table 2) reflection peak shifted toward the lower degrees which indicated enlargement of the basal spacing.

The CEC of untreated bentonite was 74.73 mequiv./100g. It was lowered to 68.21 and 67.47 mequiv./100g respectively in H–C and H₂–C samples which is attributed to the removal of octahedral cations and the protonation of the SiO groups [22]. Similarly, the CEC values of H–Al–PILC and H₂–Al–PILC decreased to 23.02 and 20.15 mequiv./100 g respectively, indicating that the exchangeable cations and the protons were replaced by pillars incorporated into the clay (Table 2).

Thermal behavior of the samples was examined by DTG analysis. For all samples three major weight loss regions were observed in the range of 30–200 °C, 350–550 °C and >550 °C. All samples showed high initial lost effect which gradually decrease at higher temperatures. The first major weight loss observed in the range of 30–200 °C is due to removal of physically absorbed water molecules present in the interlayer. A modest weight loss in the range of 350–550 °C and the major weight loss around 650 °C are attributed to the water molecules coordinated to the pillars as well as the chemically bound OH groups. The total weight losses of samples are given in Table 1.
Table 1
Chemical composition of the samples.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Concentration (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
</tr>
<tr>
<td>Bentonite</td>
<td>58.27</td>
</tr>
<tr>
<td>H–C</td>
<td>60.30</td>
</tr>
<tr>
<td>H₂–C</td>
<td>61.67</td>
</tr>
<tr>
<td>H₂–Al–PILC</td>
<td>56.98</td>
</tr>
<tr>
<td>H₂–Al–PILC</td>
<td>56.12</td>
</tr>
</tbody>
</table>

* Loss on ignition determined by DTG method.

Table 2
Physicochemical properties of the samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>S_BET (m²/g)</th>
<th>TPFV* (cm³/g)</th>
<th>Vp b (cm³/g)</th>
<th>Acidity (mequiv. NH₃/g)</th>
<th>d001 (Å)</th>
<th>CEC d (mequiv./100 g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentonite</td>
<td>34</td>
<td>0.123</td>
<td>–</td>
<td>0.04</td>
<td>11.86</td>
<td>74.73</td>
</tr>
<tr>
<td>H–C</td>
<td>129</td>
<td>0.270</td>
<td>–</td>
<td>0.78</td>
<td>12.27</td>
<td>68.21</td>
</tr>
<tr>
<td>H₂–C</td>
<td>127</td>
<td>0.279</td>
<td>–</td>
<td>0.87</td>
<td>11.78</td>
<td>67.47</td>
</tr>
<tr>
<td>H₂–Al–PILC</td>
<td>296</td>
<td>0.298</td>
<td>0.155</td>
<td>0.96</td>
<td>18.21</td>
<td>23.02</td>
</tr>
<tr>
<td>H₂–Al–PILC</td>
<td>278</td>
<td>0.299</td>
<td>0.135</td>
<td>1.42</td>
<td>18.31</td>
<td>20.15</td>
</tr>
</tbody>
</table>

* Total pore volume at a relative pressure of 0.99.

The spectrum of the untreated bentonite shows an intensive band at 1045 cm⁻¹ which is attributed to the Si–O in-plane stretching vibration and other bands at 526 and 470 cm⁻¹ assigned to Al–O–Si (octahedral Al) and Si–O–Si bending vibrations respectively. The shoulder at 1115 cm⁻¹ shows Si–O out-of-plane stretching vibration. Stretching vibration of the hydroxyl groups of physisorbed water molecules appeared at 3438 cm⁻¹. The band at 3623 cm⁻¹ is assigned to hydroxyl groups coordinated to octahedral Al³⁺ cations [23]. Three peaks in the hydroxyl bending region around 920 cm⁻¹ for Al₂O₃, 885 cm⁻¹ for AlFeOH, and 845 cm⁻¹ for AlMgOH reflect that octahedral Al³⁺ is partially replaced by Fe³⁺ and Mg²⁺. Furthermore, The band at 793 cm⁻¹ together with a shoulder near 1115 cm⁻¹ may reflect the presence of cristobalite and the shoulder near 620 cm⁻¹ was attributed to the Al–O–R (R = Al and Mg) vibration of octahedral atoms [24]. The band at 692 cm⁻¹ confirmed presence of quartz which already confirmed by XRD [20].

After acid treatment the band at 1045 cm⁻¹ is shifted to higher wavenumbers (Δv = 6 cm⁻¹). The intensity of hydroxyl bending vibration at 845 cm⁻¹ (Al–Mg–OH) and 885 cm⁻¹ (Al–Fe–OH) was reduced. This was related to the reduction of Mg²⁺ and Fe²⁺ cations which is in agreement with chemical analysis data (Table 1). In acid treated samples the band at 793 cm⁻¹ (cristobalite) was shifted to 796 cm⁻¹ with increased intensity. The band at 692 cm⁻¹ (quartz) also showed higher intensity after acid treatment.

Presence of aluminum oxocations in the sample concentrates surface charge on oxygen involved in Si–O–Si linkages and

![Fig. 2. FT-IR spectra of bentonite (a), H–C (b), H₂–C (c), H₂–Al–PILC (d) and H₂–Al–PILC (e).](image-url)
enhancing the breadth and intensity of 3438 cm⁻¹ peak of acid treated samples. Introducing of more positively charged aluminum groups cause a change in the electric field around Si groups and consequently a change in the symmetry of the surface Si–O–Si vibration could be happen and the band at 1045 cm⁻¹ shifted to higher frequencies [5,25]. In H–Al–PILC and H2–Al–PILC asymmetric stretching vibrations of SiO₂ tetrahedra were shifted to 1060 cm⁻¹.

N₂ adsorption–desorption isotherms of the samples according to the IUPAC classification are of IV type with a well defined H4 hysteresis loop, denoting a slit-shaped porosity between plate-like particles (Fig. 3). H4 hysteresis loops are generally observed with complex materials containing both micropores and mesopores [26]. The activated samples had much larger BET surface area and total pore volume (TPV) compared to the untreated bentonite (Table 2).

The voids in a solid structure with widths smaller than 2 nm, between 2 nm and 50 nm, and greater than 50 nm are respectively called micropores, mesopores, and macropores [26]. The mesopore size distributions of the samples are presented in Fig. 4a. The area under the curve and two known absissa values is related to the relative amount of mesopores having sizes that fall into the range defined by the absissa limits. The most abundant pore size (rP) in untreated bentonite, H–C and H2–C samples were around 1.85 nm. The area of the pore size distribution curve increased in H–C and H2–C samples showing that mesopores are increased by acid activation. Compared to the acid treated samples in the pillared samples a decrease of the mesoporous volume was observed and pore sizes were mostly at 1.64 nm. It is suggested that partial transformation of mesopores to micropores during the intercalating process had been occurred.

To analyze the microporosity of the pillared clay the N₂ adsorption properties of the samples were studied and the Horváth–Kawazoe (H–K) equation was used to determine the micropore distribution (Fig. 4b and c, dVp/ddp versus diameter (dP)). The H–K plot of the H–Al–PILC and H2–Al–PILC samples showed two deviations from linearity indicating the presence of two types of micropores and a bimodal pore size distribution. This was consistent with previously reported distributions for clays [27,28]. The micropore size distribution was centered on two peaks: 0.84 and 1.09 nm. The interlayer spacing for these pillared clays was 1.82 and 1.83 nm respectively (Table 2). Given that the micropores have a distribution centered on 0.84 and 1.09 nm, it is clear that the micropore size is limited by interparticle distance rather than by the interlayer distance.

The acid-activated samples have no significant micropores (Fig. 4b) whereas in pillared acid-activated samples, amount of micropores was increased (Fig. 4c). This is the main reason of the higher surface area of the sample which makes them more efficient as catalyst.

Compensating cations and specific sites at the layer edges are two sources of acidity of untreated bentonite [29]. After acid activation the protons first replace the exchangeable cations and then they attack the layers and increase acidity [30]. Increasing the number of acid sites can also be achieved by loading Lewis acid salts such as AlCl₃ into the samples. The result of TPD measurement showed that total acidity of the pillared samples was higher than that of the acid activated samples (Table 2).

SEM images of the samples are shown in Fig. 5. Bentonite consisted of thick aggregate of smectites with irregular shape and partly a mass of flake-shape were observed (Fig. 5a and b). After acid treatment the particles become smaller and thinner but the lamellar structure of the bentonite was still remained (Fig. 5c for H–C) and (Fig. 5d for H2–C). In H–Al–PILC (Fig. 5e) and H2–Al–PILC (Fig. 5f) samples, leaf like agglomerate is appeared. The morphology change indicated that some Al₃⁺ ions are incorporated to interlayer space of acid-activated samples.

3.2. Activities of the catalysts

Alkylation of benzene with olefins is commonly considered as proceeding via a carbenium ion mechanism. Firstly, 1-decene forms a carbenium ion over the acid catalyst, and then undergoes a rapid double bond migration, and finally alkylbenzene is produced [31]. The alkylation reactions can be accompanied by a series of side reactions such as oligomerization of the olefin and alkylation with both monomer and the oligomers depending on the reaction conditions, such as olefin to benzene mole ratio, temperature, acidity of the catalyst, and shape selectivity. For industrial application high selectivity for linear 2- and 3-phenyl isomer are the major targets as this isomer yields detergents with better biodegradability properties [32]. The catalytic activity of the samples was examined for alkylation of benzene with 1-decene. The effect of different parameters including temperature, benzene to olefin molar ratio and weight of catalyst were evaluated.

3.2.1. Effect of molar ratio

To discuss the effect of molar ratio on the conversion percentage, two parameters must be considered. When the molar ratio is low (8:75:1), the dominant parameter is the surface area of the catalyst, therefore the conversion in H–C is higher than H2–C due to its higher surface area (Table 2). In the same way H–Al–PILC showed higher conversion than H2–Al–PILC.

When the molar ratio increased (12:1 and 15:1), the total surface acidity of the catalyst became more pronounced in the conversion percentage. Therefore the conversion by H2–C is higher than H–C (Table 3). Since the total acidity of H–Al–PILC and H2–Al–PILC was sufficient, nearly complete conversion was observed.

The conversion percentage obtained by H–Al–PILC and H2–Al–PILC samples were higher than the values reported by other workers for H-Y, H-MOR and L zeolites, K-10 clay, SiO₂–Al₂O₃, Al–PILC and zirconia supported 12-silicotungstic acid (Table 3) [8,33,34].

Pillared acid-activated bentonite allowed complete conversion of 1-decene; side-reactions were not detected and complete selectivity to LAB (monoalkylates) were observed. Performance
Fig. 4. Mesopore size distributions derived from the BJH method (a) and micropore size distributions derived from the H–K model (b and c).

Fig. 5. SEM images of the samples: bentonite (a and b), H–C (c), H2–C (d), H–Al–PILC (e) and H2–Al–PILC (f).
Table 3
Conversion of 1-decene in different benzene to 1-decene molar ratio (catalyst weight = 1 wt%, T = 145 °C, t = 4.5 h).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Benzene:1-decene molar ratio</th>
<th>Conv. (%)</th>
<th>Select. (%)</th>
<th>Yield of LAB (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.75:1</td>
<td>12:1</td>
<td>15:1</td>
<td></td>
</tr>
<tr>
<td>Bentonite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H–C</td>
<td>18.7</td>
<td>21.9</td>
<td>26.1</td>
<td>98.2</td>
</tr>
<tr>
<td>H2–C</td>
<td>85.8</td>
<td>89.8</td>
<td>&gt;98</td>
<td>&gt;99</td>
</tr>
<tr>
<td>H–Al–PILC</td>
<td>82.5</td>
<td>91.8</td>
<td>&gt;98</td>
<td>&gt;99</td>
</tr>
<tr>
<td>H2–Al–PILC</td>
<td>94.1</td>
<td>&gt;98</td>
<td>&gt;98</td>
<td></td>
</tr>
</tbody>
</table>

Table 4
Effect of temperature on benzene alkylation with 1-decene (catalyst weight = 1 wt%, benzene to olefin molar ratio = 12:1, t = 4.5 h).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temperature</th>
<th>Select. (%)</th>
<th>Yield of LAB (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>115 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>130 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>145 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H–C</td>
<td>47.0</td>
<td>31.9</td>
<td>25.9</td>
</tr>
<tr>
<td>H2–C</td>
<td>57.0</td>
<td>29.3</td>
<td>26.2</td>
</tr>
<tr>
<td>H–Al–PILC</td>
<td>55.6</td>
<td>35.1</td>
<td>23.8</td>
</tr>
<tr>
<td>H2–Al–PILC</td>
<td>60.1</td>
<td>32.8</td>
<td>23.7</td>
</tr>
</tbody>
</table>

The effect of different catalysts in the distribution of monoalkylated isomers is illustrated in Fig. 6. The selectivity for the reactions could be explained by the ability of the catalyst to formation phenyldecane isomers. The distribution of isomers found for the reaction catalyzed by H2–Al–PILC sample showed moderately higher amount of 2- and 3-phenyldecane (59.4%) compared to other catalysts at 12:1 molar ratio. There are two main reasons for the differences in product distributions in alkylation of benzene with 1-decene: (i) the existence of two equilibration steps, one for the 1-decene and another for the phenyldecane, and (ii) the differences in the rates of the two reactions (isomerization of olefin and isomerization of alkylbenzene). As these reversible reactions react to equilibrium state, the increase of the benzene to olefin molar ratio leads to the increase of conversion for 1-decene. At the same time, the isomerization of 2 and 3-phenyl isomers to other isomers results decrease of its selectivity [7].

Improvement in the porous network, total pore volume, total specific surface area and total acidity (Table 2) of pillared...
acid-activated samples might be the reason for the improved selectivity for 2- and 3-phenyldecane products.

3.2.2. Effect of reaction temperature

The effect of temperature on the conversion and selectivity of alkylation process was studied at 115, 130 and 145 °C (Table 4). As the olefin conversion for both molar ratios of 15:1 and 12:1 was similar the lower rate was selected for the experiments. Catalysts showed enhanced activity at higher temperature. Maximal selectivity of 65.8 and 76.7% for 2- and 3-phenyldecane was obtained respectively for H-Al–PILC and H2–Al–PILC samples at 130 °C. Decreasing of selectivity at 145 °C may be attributed to the rapid equilibration of the olefin isomer or easy diffusion of the bulkiest linear alkylbenzene isomer out of the catalyst cavities at higher temperature [9].

3.2.3. Effect of catalyst amount

To examine the effect of catalyst amount, the reaction was conducted by changing the catalyst concentration in the range of 0.25–1.75 wt% of total reaction mixture. The catalytic tests were carried out over H–Al–PILC with a molar ratio of 8.75 within the industrial processes range at 145 °C for 4.5 h (Table 5). It was observed that the conversion of 1-decene increased from 79.9% to 94.1% as the catalyst amount increased from 0.25 to 1 wt%. According to the results 1 wt% was selected as the optimized catalyst amount. Beyond this amount, the conversion was steady because of deficiency of the reactant molecules.

3.3. Regeneration of the catalyst

To examine the catalytic activity of the regenerated catalysts, the used H–Al–PILC and H2–Al–PILC samples were separated by filtration and washed with hot benzene. The samples were heated up to 200 °C at a rate of 10 °C min⁻¹ and maintained for 2 h under flowing nitrogen to remove reaction-mixture components. After activation at 500 °C for 3 h in air flow the catalysts were further used for alkylation under optimized reaction conditions. The procedure was repeated for three cycles. The result in showed that no significant decrease in the catalytic activity and product selectivity was observed (Table 6).

4. Conclusions

By acid treatment, the surface area, acidity and the TPV of the bentonite were increased. The number of Lewis and Bronsted acid sites was strongly increased by intercalating of aluminum polyhydroxyl into the acid treated samples. Pillaring also improved micropore volume and consequently specific surface area of the samples. Pillared acid-activated bentonite was used for alkylation of benzene with 1-decene in liquid phase conditions. The main advantage of the method is that no major side reactions such as oligomerization of the olefin, dialkylation and higher alkylbenzene (HAB) production were observed. This enhanced the purity of the LAB products which is an important parameter in LAB production industries. H–Al–PILC and H2–Al–PILC samples showed completely conversion of 1-decene and higher shape selectivity to 2- and 3-phenyldecane. The acid-activated pillared catalysts are recyclable and environmental friendly and were found to be more active than conventional Al–PILC, K–10 clay, L, H–Y and H–MOR zeolites, and SiO2–Al2O3.

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