Recycling of Lignite Coal Fly Ash by its Conversion into Zeolites

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ABSTRACT

The present study emphasized the conversion of fly ash from lignite coals into zeolites by a double-stage fusion-hydrothermal synthesis. The raw and the converted fly ashes were characterized with respect to their morphology, composition, and crystallinity. The effects of process parameters such as fusion temperature, concentration of the alkaline activator, and the duration of the hydrothermal incubation on the zeolitization process were studied. The experimental results indicate that the fusion temperature does not influence the process mechanism in the range 550–850°C, but it has an acceleration effect. The elevation of the sodium hydroxide/fly ash ratio from 1.6 to 2.0 enhances the degree of zeolitization and leads to conversion of the zeolite phase from linde to faujasite type. The observed regularities are discussed taking into consideration thermodynamic and kinetic factors. The best attempt in the selective preparation of faujasite in the framework of this study was observed at a sodium hydroxide/fly ash ratio of 2.0, fusion temperature of 550°C, and a hydrothermal synthesis for 2 hours at 90°C.

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1. Introduction

Fly ash (FA) is a mineral dust created from the combustion of coals, which is carried by the flue gases out of the incineration chambers. FA is separated from gas flows by mechanical filters, cyclones, or electrostatic precipitators installed at the end of the incineration systems (Boycheva, 2011). This residue consists mainly of silica, alumina, glassy and crystalline aluminosilicates, and a large variety of micro- and trace components (Nadkarni, 1980). The disposal of FA is of serious ecological risk because of the infiltration of accumulating toxic elements into the soil, the low level of nutrients, and the undesirable pH value (Kim et al., 2003). The fact that enormous amounts of FA are generated worldwide determines the extraordinary importance for the development of reliable technological decisions and a strategy for FA utilization. This approach also is relevant to the natural materials economy and the environment protection for achievement sustainable economical development. Because of its compositional characteristics, FA is mainly reused in the cement and the concrete industry, but other valuable applications are under investigation (Ahmaruzzaman, 2010; Blissert and Rowson, 2012).

A promising approach for the utilization of FA is its conversion into low-cost synthetic zeolites with high adsorption and ion-exchange capacities, applicable to gas-cleaning and water-purification systems (Lin and His, 1995; Moreno et al., 2001; Ruen-ngam et al., 2009). These materials are able to successfully replace their natural analogues, as well as those produced from pure raw materials. Zeolites can be obtained from FA by a hydrothermal synthesis based on the solubility of Al-Si-containing components in alkaline media, such as solutions of sodium (NaOH) and potassium (KOH) hydroxides or their mixtures with alkaline carbonates (Querol et al., 1997; Shoumkova and Stoyanova, 2013). Different zeolite forms (up to 15) are able to be obtained from one
and the same composition of FA by varying the synthesis conditions (Querol et al., 2001, 2002).

This investigation is part of a broad experimental program on the conversion of lignite fly ash into synthetic zeolites and their further application in flue gas-cleaning systems. Our goal is the selective synthesis of Na-X zeolite, which in its natural form is known as faujasite, and its synthetic commercial analog, called 13X. This zeolite is one of the most valuable types for practical uses because of its high-volume microporous structure created by channels of large diameters. This structure is a prerequisite for the capability of the faujasite to adsorb large gaseous molecules, making it suitable for purification and separation of flue and industrial gases (Querol et al., 2001; Zhang et al., 2012). The high-adsorption capacity of faujasite toward the main gaseous emissions from the incineration of coals, mostly SO₂ and CO₂, has been recently studied for the purposes of the green energy technologies (Suchecki et al., 2004; Liv et al., 2011).

Studies have shown that the Na-X zeolite crystallizes readily at relatively low temperatures due to its simple structure (Gross-Lorgouilloux et al., 2010). The best results for the preparation of faujasite have been achieved by hydrothermal synthesis at 90°C (Fukui et al., 2006). Another critical parameter for the formation of faujasite is the SiO₂/Al₂O₃ ratio in the FA composition (Inada et al., 2005). The selective preparation of Na-X zeolite from FA requires a pre–hydrothermal fusion stage in order to ensure an optimal Si/Al ratio in the reactant solution (Purnomo et al., 2012). The synthesis of the Na-X phase requires a high Si/Al value, while alumina-rich FA gives Na-A zeolite instead of Na-X (Shigemoto et al., 1993). According to some authors, the synthesis of faujasite requires a Si/Al ratio higher than 3.0, and therefore, additional silica has been used in many experiments (Thuadaj and Nuntiya, 2012). Some other investigations have shown that zeolite Na-P1 is predominantly formed from silica-rich fly ashes (Kazemian et al., 2010).

Extensive work has been done on the zeolitization of different FA compositions, but the rules of the selective synthesis of a determinant zeolite phase have not yet been fully clarified. According to the performed investigations on the thermodynamic consequences in coal ash zeolitization (Nascimento et al., 2012), Na-X appears as a metastable phase determined by the temperature of the hydrothermal synthesis.

The present study was aimed at the synthesis of Na-X from lignite FA containing SiO₂ and Al₂O₃ in a ratio of 2.25, and without any additional silica. This is a pioneer study on the zeolitization of FA generated by Maritza East 2, the biggest thermal power plant in Bulgaria, which is supplied by domestic lignite. In our research, the thermodynamic consequence in the crystallization of the zeolite phases were considered a key parameter for the selective synthesis of faujasite. It was assumed that the Na-X zeolite appears as an intermediate phase in the reaction system studied as determined by the process kinetics.

2. Materials and Methods

2.1. Starting material

Fly ash generated from the combustion of local lignite coals in the Maritza East 2 power plant was subjected to zeolitization. FA used as a raw material for these experiments was studied with respect to its chemistry and mineralogy. Analytical titrimetric techniques and instrumental atomic absorption spectroscopy (IAAS) were applied for the determination of the major chemical constituents of the FA. Phase analysis was performed by X-ray diffraction (XRD) using a Brucker D2 Phaser diffractometer with CuKα-radiation and a Ni filter (λCuKα = 1.5418 Å). Morphological observations and elemental analyses were carried out by scanning electron microscopy (SEM), model JEOL JSM6390, coupled with an Oxford Instruments energy-dispersive X-ray (EDX) analyzer.

2.2. Zeolite synthesis and investigation

Mixtures of FA and NaOH were prepared in different ratios and were treated in two steps: fusion and hydrothermal synthesis. The first stage was performed at three temperatures of 550°C, 750°C, and 850°C for 1 hour. The calcinations of the mixtures of FA and NaOH were performed in corundum crucibles in a muffle furnace with thermal regulation. Thereafter, the sintered materials were ground in a mortar, mixed with 100 mL of distilled water, and subjected to magnetic stirring for 12 hours. Such prepared water suspensions were poured into an autoclave, where the hydrothermal synthesis stage was performed at 90°C with durations of 2, 4, and 6 hours for the separate experiments. The synthesis conditions for each attempt are summarized in Table 1. Then, the solid part of the suspensions was separated by filtration, thoroughly washed with distilled water, and dried at 105°C. The nature and the composition of the synthesized materials were characterized by XRD, SEM, and EDX techniques. X-ray diffractograms were interpreted by the help of the X-ray powder pattern database of the International Zeolite Association (IZA). The specific surface of selected sample was evaluated by Brunauer-Emmett-Teller (BET) analysis using Micro-meritics TriStar II 3020 equipment. The adsorption isotherm was measured in five points using 5 N nitrogen as adsorbate, and at 77.35 K controlled by liquid nitrogen.

3. Results and Discussion

The untreated FA used in this study is a powder of Fe-enriched aluminosilicate particles. SEM images of the raw FA samples are presented in Figure 1. The particles are spherical (Figure 1a) or oval-shaped with a relatively smooth (Figure 1b) or sponge-like (Figure 1c) surface. Plerospheres filled inside and covered with crystallized gypsum (Figure 1d) were also observed. Backscattered electron analysis reveals separation of ferrous phases by anisotropic crystallization into an aluminosilicate matrix (Figure 1e).

The untreated FA was studied with respect to its chemical composition, and the results are summarized in Table 2. The SiO₂/Al₂O₃ ratio in the investigated FA is about 2.25. According to the standard specification ASTM C618 (ASTM International, 2008), this FA is class F, as the total content of SiO₂ + Al₂O₃ + Fe₂O₃ is higher than 70 wt%, while the content of CaO is 5.75 wt%. The fact that ashes of lignite coals from Maritza East basin contain a low percentage of CaO has been also established in other studies (Vassileva and Vassilev, 2005).

The experimental X-ray diffractogram of the investigated FA is plotted in Figure 2. The characteristic reflections of several crystalline phases were identified, such as quartz (α-SiO₂), mullite (3Al₂O₃·2SiO₂), gypsum (CaSO₄·2H₂O), hematite (α-Fe₂O₃), and magnetite (Fe₃O₄).

This FA was subjected to zeolitization by an alkaline double-stage fusion and hydrothermal conversion. The conditions of the performed experiments are listed in Table 1. The effect of the
concentration of the NaOH as an alkaline activator on the conversion process of the FA was studied, keeping constant other synthesis conditions: fusion at 550 °C, followed by a hydrothermal synthesis at 90 °C for 2 hours. The X-ray diffractograms of the samples obtained at elevated NaOH/FA ratios are plotted in Figure 3, while their morphology is revealed by the SEM micrographs presented in Figure 4.

The morphology of sample Z9, obtained at the lowest NaOH concentration, differs completely from that of the raw FA, even though almost no zeolitization was registered. The surface of the...
ash particles is covered with a gelatin-like material, and only traces of initial crystallization were observed (Figure 4a). The corresponding X-ray diffractogram plotted in Figure 3 is typical for a predominantly amorphous matrix mixed with some crystallized parts, as confirmed by the presence of an amorphous plateau and broad weak peaks.

The SEM image of sample Z11 reveals cubic crystallites (Figure 4b), for which characteristic XRD reflections correspond to zeolite A (linde, LTA) (Figure 3). On the experimental X-ray pattern, no intensive peaks that can be associated with other crystalline phases were observed. Despite this, some non-crystallized amorphous gel can be seen on the surface of the crystalline particles, which is evidence for incomplete zeolitization of the FA. Moreover, the amorphous plateau is still pronounced.

By elevating the concentration of the alkaline activator in sample Z12, the FA is transformed into faujasite. This is indicated by the well-expressed characteristic reflections of zeolite X on the X-ray pattern (Figure 3). Some reflections of zeolite A are still preserved, but with weaker intensities. Undoubtedly, zeolite Na-X is the dominant phase. The SEM micrograph of Z12 (Figure 4c) reveals the typical hexaoctahedral crystallites of faujasite. The surface of the crystallites is free of amorphous residues, while the amorphous plateau on the corresponding diffractogram is diminished (Figure 3). These results indicate higher zeolitization degree for Z12 in comparison with Z9 and Z11.

As the best attempt for this study, the sample Z12 was characterized with respect to its zeolitization degree. The yield of zeolite X was calculated on the basis of the experimental X-ray diffractograms of commercial 13X zeolite and the studied sample. The obtained value is 190 g/kg FA. The specific surface area of Z12 measured by the BET isotherm at a relative pressure $p/p_0 = 0.1991$ is on the order of $42.05 \text{ m}^2/\text{g}$.

Taking into account the above observations, it can be summarized that the increase of the NaOH/FA ratio from 1.6 to 2.0 enhances the degree of zeolitization and converts the zeolite from type A to type X.

The compositions of the investigated samples obtained by integral EDX analyses, scanning their entire surface, are listed in Table 3. Evidently, the concentration of SiO$_2$ in the converted coal ash is much lower than in the parent material, which indicates that significant quantities of silicates were retained in the reactant solution. The losses of Al$_2$O$_3$ from the starting FA are lower in comparison to those of SiO$_2$. The proportion of Fe$_2$O$_3$ in the zeolites is enhanced on account of the latter two components, as the composition of the samples is expressed in normalized wt%, and/or due to its concentration on the studied surfaces. Usually the content of Na$_2$O into the alkaline-treated FA is significantly higher than its initial value (Tables 2 and 3).

The dependence of the concentrations of Al, Si, Na, and O in samples Z9, Z11, and Z12 on the NaOH/FA ratio is presented in Figure 5. Basically, the content of Al, Si, and Na slightly increases

### Table 2

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>52.66</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>23.37</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>8.72</td>
</tr>
<tr>
<td>CaO</td>
<td>5.75</td>
</tr>
<tr>
<td>MgO</td>
<td>2.75</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>2.40</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.08</td>
</tr>
<tr>
<td>MnO</td>
<td>0.06</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.04</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.01</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.01</td>
</tr>
<tr>
<td>PbO</td>
<td>0.01</td>
</tr>
<tr>
<td>Weight loss (at 800°C)</td>
<td>3.53</td>
</tr>
</tbody>
</table>

Fig. 2. X-ray diffractogram of lignite fly ash.

Fig. 3. X-ray diffractogram of fly ash samples treated at different concentrations of the alkaline reagent. A = linde; X = faujasite; Q = quartz.

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with the increase of the NaOH concentration, while oxygen decreases.

The effect of the duration of the hydrothermal synthesis on the zeolitization at a low NaOH/FA ratio of 1.2 can be revealed considering samples Z9 and Z14. Almost no formation of zeolites was observed in sample Z9, while a significant zeolite fraction was crystallized from the alkaline FA reactant mixture after three-times-longer hydrothermal incubation (6 hours) at constant conditions. Mixtures of zeolites A, X, chabasite, and Na-P, as well as unconverted FA, were obtained for samples synthesized at a NaOH/FA ratio of 1.2, as confirmed by SEM (Figure 6) and XRD (Figure 7) analyses. XRD patterns of the FA zeolites are noisy due to the multicomponent character of the raw material and were deconvoluted for each sample in combination with the SEM analyses. The SEM images of Z14 reveal a typical radial fibrous structure of Na-P crystallites (Figure 6a) and the cubes of zeolite A (Figure 6b) as the two types of zeolites crystallized in a mixed structure (Figure 6c). On the experimental X-ray pattern of sample Z14, the presence of Na-P is only indicated by its strongest characteristic reflection.

XRDs plotted in Figure 7 reveal small yields of zeolites in the corresponding samples because of the low NaOH/FA ratio used for their syntheses.

In general, the process of zeolite synthesis, applying a fusion stage before the hydrothermal treatment, passes through the following reaction scheme (Ojha et al., 2004):

$$\text{NaOH} + x\text{Al}_2\text{O}_3 \cdot y\text{SiO}_2 \xrightarrow{\text{fusion}} \text{Na}_2\text{SiO}_3 + \text{Na}_2\text{AlO}_2$$
$$\xrightarrow{\text{dilution}} \text{NaOH}_{(aq)} + \text{Na}_2\text{Al(OH)}_{3(aq)} + \text{Na}_2\text{SiO}_3_{(aq)}$$
$$\xrightarrow{\text{stirring}} [\text{Na}_x(\text{AlO}_2)_y(\text{SiO}_2)_z]_{(\text{aq})} \text{NaOH-H}_2\text{O}_{(gel)}$$
$$\xrightarrow{90 \degree \text{C}} \text{Na}_p(\text{AlO}_2)_a(\text{SiO}_2)_q \text{H}_2\text{O}_{(zeol)}$$

The fusion is used to obtain soluble sodium silicate and aluminate that, after dissolution under continuous stirring, are converted into gel. Further, crystallization occurred from the gel medium during the hydrothermal synthesis.

### Table 3
Composition of treated fly ash obtained by integral energy-dispersive X-ray analyses (in wt%, normalized)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Na$_2$O</th>
<th>MgO</th>
<th>Al$_2$O$_3$</th>
<th>SiO$_2$</th>
<th>Fe$_2$O$_3$</th>
<th>CaO</th>
<th>TiO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z9</td>
<td>12.16</td>
<td>2.33</td>
<td>19.45</td>
<td>32.90</td>
<td>23.76</td>
<td>9.40</td>
<td>–</td>
</tr>
<tr>
<td>Z11</td>
<td>13.91</td>
<td>2.63</td>
<td>18.82</td>
<td>31.45</td>
<td>23.78</td>
<td>8.65</td>
<td>0.75</td>
</tr>
<tr>
<td>Z12</td>
<td>17.21</td>
<td>1.73</td>
<td>22.11</td>
<td>35.55</td>
<td>16.01</td>
<td>7.39</td>
<td>–</td>
</tr>
<tr>
<td>Z4</td>
<td>9.10</td>
<td>2.49</td>
<td>20.00</td>
<td>33.10</td>
<td>24.13</td>
<td>10.38</td>
<td>0.80</td>
</tr>
<tr>
<td>Z14</td>
<td>14.42</td>
<td>2.89</td>
<td>16.54</td>
<td>31.41</td>
<td>24.66</td>
<td>9.29</td>
<td>0.79</td>
</tr>
<tr>
<td>Z15</td>
<td>13.71</td>
<td>1.40</td>
<td>18.54</td>
<td>28.81</td>
<td>27.58</td>
<td>9.93</td>
<td>–</td>
</tr>
<tr>
<td>Z16</td>
<td>12.98</td>
<td>2.17</td>
<td>16.49</td>
<td>27.48</td>
<td>32.36</td>
<td>7.75</td>
<td>0.85</td>
</tr>
</tbody>
</table>
The importance of the SiO$_2$/Al$_2$O$_3$ ratio and the mineralogical composition for the zeolitization behavior of FA has been studied (Querol et al., 1997). Different zeolitization performance has been established for fly ashes with a similar SiO$_2$/Al$_2$O$_3$ value, which has been ascribed to the different percentages of these constituents in the amorphous matrix and as crystalline phases. Owing to the differences in the rates of conversion into soluble silicates and aluminates of the amorphous and the crystalline aluminosilicates, the selective formation of determined zeolitic forms by one-stage hydrothermal synthesis is impossible (Molina and Poole, 2003). Moreover, quartz and mullite, which are normally present in significant quantities in the FA, remain unconverted in the low-temperature hydrothermal synthesis (Franus, 2012). Thus, significant amounts of raw silicate and aluminosilicate materials are lost.

Gibb’s diagram of the Na$_2$O-Al$_2$O$_3$-SiO$_2$ system at a constant H$_2$O content of 80 mol% is presented in Figure 8 (Penchev, 1973). The reactant FA-NaOH system, which is a subject in this study, can be considered as a ternary Na$_2$O-Al$_2$O$_3$-SiO$_2$ system because of the low concentration of the alkaline and alkaline earth components in the raw material. As was mentioned already, the lignite FA is class F because of its low CaO content. The FA investigated is rich in iron oxides (Table 2), but they do not participate in the formation of the structural framework of the faujasite. The dashed line in Gibb’s diagram outlines the borders of the gel formation from the sodium aluminate and silicate solution. The concentration fields for the crystallization of different zeolite forms by the hydrothermal synthesis at 90°C are shown. On the diagram, the composition of FA used as a raw material in the present study is indicated, taking into account the measured concentrations of SiO$_2$ and Al$_2$O$_3$. The percentage ratios between the components in the ternary Na$_2$O-Al$_2$O$_3$-SiO$_2$ system used for the performed synthesis are also indicated on the diagram.

Evidently, all of the treated mixtures of FA and the alkaline reagent fall into the concentration region of hydrosodalite. As Gibb’s diagram describes an equilibrium state, this means that, at the investigated NaOH/FA ratios, when the time of hydrothermal synthesis is exceeded, the crystallization process, striving for equilibrium, will continue further to formation of hydrosodalite. The obtained results reveal the sequence in the thermodynamic stability of the crystallized zeolitic forms from the investigated NaOH/FA mixtures at the settled synthesis conditions, which can be expressed as follows:

![Fig. 5. Dependence of the concentration of Al, Si, Na, and O (in wt% normalized) in the converted fly ash on the NaOH/FA ratio.](image)

![Fig. 6. Scanning electron micrographs of sample Z14: (a) Na-P crystallites; (b) linde cubes; and (c) a mixture of crystallites of both types.](image)
Most probably, the thermodynamic sequence will be specific, not only for different alkaline reagents, but also for different SiO₂/Al₂O₃ ratios in the FA composition. The transformation of faujasite into the more stable phases such as chabazite or Na-P at longer retention times of the crystallized phase into the reactant liquor has been also observed by other authors (Ferret et al., 1999; Ojha et al., 2004). The synthesis of zeolite X takes place at low temperatures due to its metastable behavior, and its formation is always competitive with hydrosodalite, which is the dominant phase at higher temperatures (Belviso et al., 2010).

The higher the sodium content in the reaction mixture during the fusion stage, the higher the yield of water-soluble silicates and aluminates achieving full conversion of the Si- and Al-containing compounds from raw FA, and the faster the crystallization process is (comparing samples Z9 and Z12). It could be expected that above some critical concentration level, the crystallization will pass immediately into hydrosodalite rather than to a less stable phase, such as faujasite. This means that the synthesis of faujasite proceeds with a limited rate. According to Figure 8, an equilibrium process leading to the crystallization of Na-X as a final phase can be realized in the concentration regions of the corresponding field. In this case, a technological problem due to a rather slow process could be expected. It has been supposed that NaOH plays an additional function as a stabilizer of the Si- and Al-structural units constituting the zeolite structure, and the Si-O-Al bridges are more stable in alkaline media (Penchev, 1973).

According to the phase diagrams of the binary Na₂O-SiO₂ and Na₂O-Al₂O₃ systems (Levin et al., 1964), no intermediate compounds melting below 1000°C exist. The melting point of NaOH is at 318°C, which means that during the fusion step, the chemical reactions occur in a liquid-solid system. Taking these observations into account, it can be suggested that in the thermal interval 318–850°C, the reaction process between FA and NaOH proceeds on one mechanism and is only governed by kinetic factors. The experimental results presented here, i.e., the similarity in the patterns in Figure 7, reveal that while the fusion between 550°C and 850°C does not influence the mechanism of zeolite synthesis, it slightly accelerates the zeolitization rate. The latter was confirmed by the appearance of the more stable phases of Na-P and chabazite. Moreover, it could be supposed that the acceleration effect of the higher fusion temperature will be stronger at a higher concentration of NaOH. In any case, the small quantity of NaOH and the absence of a fusion stage will result in a nonspecific zeolite mixture due to the differences in conversion rates of the crystalline and the amorphous aluminosilicate constituents. From the experimental X-ray patterns, it is evident that the reflections of...
the quartz and the mullite have disappeared, while the amorphous plateau is still preserved. This is indicative that during the fusion step, chemical interactions between NaOH and the crystalline silicates and aluminosilicates occur, converting them into soluble forms, while the amorphous matrix is continuously diluted depending on the alkalinity of the solution.

The composition of Na-X zeolite can be expressed as Na_{88} (H_{2}O)_{220}[Si_{104}Al_{88}O_{364}]. which corresponds to the ratio of 4.2 Na_{2}O:Al_{2}O_{3}:3SiO_{2} or to 34.33Na:11.57Al:16.43Si (2.97Na:Al:1.42Si) in wt%. The obtained composition for sample 2.12 in wt% (normalized) is 12.6Na:9.68Al:16.43Si (1.3Na:Al:1.7Si), which corresponds to a deficit of Na_{2}O and excess in SiO_{2} against Al_{2}O_{3}, as compared with the referent faujasite. On the basis of this observation, it could be expected that a more defined zeolitic structure can be obtained at higher NaOH concentrations.

This study confirms that the zeolitization is an integral multifactor process, which can be governed mainly by the alkalinity of the reactant medium and the SiO_{2}/Al_{2}O_{3} ratio in the total FA composition and in the amorphous matrix. It could be expected that fusion above the glass-transition temperature will retard the zeolitization because of the phase transitions of the amorphous aluminosilicates. The influence of the fusion temperature on the morphology of the zeolites and its relevance to the adsorption, cation-exchange, and the separation properties has been observed (Liv et al., 2011).

4. Summary

Fly ash from lignite with a SiO_{2}/Al_{2}O_{3} ratio of about 2.25 was converted into zeolites by a double-stage fusion-hydrothermal synthesis. The effects of the fusion temperature, the duration of the hydrothermal synthesis, and the concentration of the alkaline reagent on the zeolitization process were studied. The investigated fly ash is considered to be an appropriate material for the preparation of synthetic Na-X zeolite, as a predominant Na-X phase was obtained at a NaOH/FA ratio of 2.0. The yield of zeolite X at these synthesis conditions is found to be 190 g/kg FA. BET surface area of the sample is measured on the order of 42.05 m^{2}/g. At this composition of the reactant system, zeolite Na-X is crystallized as an intermediate thermodynamically unstable phase. The elevation of the NaOH/FA ratio from 1.6 to 2.0 enhances the degree of zeolitization and converts the zeolite from type A to type X. The conversion at a NaOH/FA ratio below 1.2 takes longer and produces a mixture of zeolites. The obtained zeolitic material can be improved by increasing the NaOH concentration, as a deficit of sodium was incorporated into the resultant material in comparison with the pure faujasite. The fusion stage does not influence the zeolitization mechanism in the interval 550–850°C but has an accelerating effect.

References