



ISSN: 0976-3376

Available Online at <http://www.journalajst.com>

ASIAN JOURNAL OF
SCIENCE AND TECHNOLOGY

Asian Journal of Science and Technology
Vol. 08, Issue, 06, pp.4985-4995, June, 2017

RESEARCH ARTICLE

MODIFIED FORMS OF NATURAL ZEOLITES– CLINOPTILOLITE AND HEULANDITE AS AN EFFECTIVE CATALYSTS FOR SYNTHESIS OF ACETYLSALICYLIC ACID

^{1,*}Tsiuri M. Ramishvili, ¹Vladimer G. Tsitsishvili, ²Nino G. Kokiashvili,
¹Vakhtang M. Gabunia and ³Natia M. Inanashvili

¹Petre Meikishvili Institute of Physical and Organic Chemistry, Ivane Javakhishvili Tbilisi State University, Georgia

²Department of Physical and Analytical Chemistry, Ivane Javakhishvili Tbilisi State University, Georgia,

³Department of Applied Geology, Georgian Technical University, Tbilisi, Georgia

ARTICLE INFO

Article History:

Received 28th March, 2017

Received in revised form

04th April, 2017

Accepted 21st May, 2017

Published online 30th June, 2017

Key words:

Natural zeolites,
Clinoptilolite,
Heulandite,
Esterification,
Acetylsalicylic acid.

ABSTRACT

The solvent-free o-esterification of salicylic acid (SA) with the acetic acid anhydride (AAA) in the acetylsalicylic acid (ASA) was studied over the modified clinoptilolite (CL) and heulandites: natural heulandite itself (HEU) and monomineral natural heulandite (HEU-M) of Dzegvi and Akhaltsikhe (Georgia) deposits, respectively; simultaneously decationized and dealuminated forms of catalysts were prepared by acid leaching of initial zeolites. It was demonstrated using the methods of gravimetric, UV-FTIR-spectral and HPLC analysis, also by catalysts acidity measurements the symbatic change of ASA yield in the amount of proton acid centers (Al-(OH)-Si) of catalysts: H-CL (Si / Al = 10.7) > H-HEU (Si / Al = 5.4) ≥ H-HEU-M (Si / Al = 4.1); yields of ASA on H-CL (Si / Al = 10.7) was about 92% and on heulandites – 75% at 80 °C; these solid acid catalysts were prepared from natural zeolites and therefore they are cheap, have high activity, are easy to prepare and reusable.

Copyright©2017, Tsiuri M. Ramishvili et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

INTRODUCTION

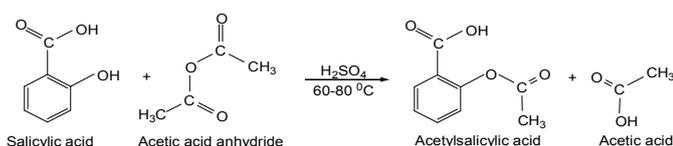
HEU and CL are naturally occurring medium pore zeolites, belonging to the heulandite class; they have isomorphic framework structure and different chemical formula—for HEU (Na,K)Ca₄(Al₉Si₂₇O₇₂) × 24H₂O and for CL (Na,K)₆(Al₆Si₃₀O₇₂) × 20H₂O (Gottardi, et al., 2013). They differ in thermal stability, spectroscopic properties, their Si/Al ratio, the content of cations, optical property, unit-cell parameters (Koyama, et al., 1977) and (Yang, et al., 2010). Clinoptilolite is stable up to 700 °C, it has a Si/Al molar ratio ≥ 4, mainly comprises of cations Na and K; heulandite undergoes a phase transition to a B form already at 250–300 °C, has a Si / Al molar ratio < 4 and mainly contains calcium cations (Alberti, 1973). Wide-line proton NMR revealed the difference between HEU and CL; the proton spectrum of CL is of Gaussian in shape and for HEU it is (reduced splitting) Pake doublet form (Ward, et al., 1994). Three dimensional aluminum silicate structures of CL and HEU consist of a system of channels and

micropores. There are three kinds of two-dimensional channels (A, B, C) confined with 8- and 10-member ring windows with following dimensions: 3.0 x 7.6 Å (10-rings) and 3.3 x 4.6 Å (8-rings), both parallel to the c-axis, of 2.6 x 4.7 Å (8-rings), parallel to the a-axis (Wise, 2013). CL and HEU pore network consists of micro-, meso- and macropores. The primary porosity of natural heulandite/c clinoptilolite material is connected with their structural features (cavities and channels); the secondary porosity of this material is determined by their meso- and macroporosity. Mesoporosity is associated with splitting phenomenon of the CL crystallite. Macropores are formed between the blocks of the zeolite crystallite and other minerals of rock (Inglezakis, et al., 2012), (Mansouri, et al., 2013) and (Cobzaru, et al., 2015). Natural zeolite industrial deposits are all over the world, among them 15 kinds of zeolite minerals (especially of clinoptilolite-heulandite, heulandite, mordenite, chabasite and laumontite) are discovered in Georgia for the moment and they are of economic value (Skhirtladze, 1997). Application of these modified zeolite minerals as catalysts in the reaction of production of ASA gives opportunity of their effective use in the large-tonnage production of acetylsalicylic acid (C₉H₈O₄).

*Corresponding author: Tsiuri M. Ramishvili,

Petre Meikishvili Institute of Physical and Organic Chemistry, Ivane Javakhishvili Tbilisi State University, Georgia.

ASA is widely used in medicine as a versatile material with analgesic, antipyretic, anti-inflammatory and anti-thrombotic properties (Schrör, 2016). For example, annual ASA demand in USA is 12 thousand tons (Rainsford, 2004). Today ASA is produced in amounts of about 50 000 tons per year and in the world the considerable part falls on Germany (Bayer Group, Bitterfeld); here ASA is produced under the name of aspirin – trademark of Bayer Group (Der Aspirin-Wirkstoff, 2014). ASA is produced by two-stage process according to the so-called salicylic acid/acetic anhydride method (Rainsford, 2004). At the first stage SA is produced using Kolbe-Schmitt reaction; at the second stage SA acetylation with AAA takes place either in a solvent (e.g., acetic acid or aromatic, acyclic, or chlorinated hydrocarbons) or in the presence of catalysts: acids (e.g., sulfuric acid, alkyl sulfonic acids, phosphorous oxychloride, phosphoric acid) or bases (tertiary amines e.g., pyridine, calcium carbonate (Rainsford, 2004), (Wasson, 1977) and (Friderichs, *et al.*, 2011), calcium or zinc oxide (Handal-Vega, *et al.*, 2001); more effective acid catalysts are concentrated sulfuric acid (Brown, *et al.*, 1973) and (Pavia, *et al.*, 1976) or phosphoric acid (Miller, *et al.*, 1982) and (Olmsted, 1998) at 60–80°C temperatures; the reaction is shown on the Scheme 1:



Scheme 1. Reaction for obtaining of acetylsalicylic acid

Synthesized ASA is removed from co-product – acetic acid, which returns again in the operating cycle. Yield of aspirin is 90–94%. Widely used sulfuric and phosphoric acid has extremely harmful and corrosive effect on the environment, but it is used as catalyst in production of the substance of great demand – ASA large-tonnage production; 60 kg of concentrated sulfuric acid are spent for getting 1 ton of ASA. In researches (Hung, *et al.*, 1997) and (Pandita, *et al.*, 1998) was made an attempt to replace acid catalysts with other processes, with application of an acetyl chloride and pyridine, however both are harmful to the environment. The drawback of the synthesis of ASA by using 12-tungsten phosphoric acid as homogeneous catalyst at room temperature was unrecovered catalyst and formation gum like polymeric byproduct (Peng, *et al.*, 2000). There is a problem of searching for stable, non-toxic, regenerated solid acids that will be an alternative for toxic acid catalysts for production of ASA. Ecologically clean synthesis of ASA by o-acetylation of SA with AAA is carried out on some solid synthesized strong acidic catalysts: sulfated nanocrystalline ZrO₂ and TiO₂, yield of ASA is equal to 95%; it is equal to 85–65% respectively, for zeolites H-BEA, H-FAU(Y), H-ZSM-5 (MFI), K-10 clay at 120 °C, (Jasra, *et al.*, 2009) and (Tyagi, *et al.*, 2010) to 91% for superacid WO₃/ZrO₂ at 85 °C (Zhang, *et al.* 2011), while yield of ASA in the presence of Preyssler type heteropolyacids is 78% with 100% selectivity at room temperature in 10 minutes (Bamoharram, *et al.*, 2007); the best yield of aspirin (85%) was attained with silica-supported Preyssler nano structures (Nazari, *et al.*, 2012). It was recently shown, that on ZrO₂-Al₂O₃, containing 80% ZrO₂, yield of ASA is 96.7% in 45 min at 130 °C (Thimmaraju, *et al.*, 2015). For platinumed zeolite catalysts (H-Y, H-ZSM-5, H-β) (Pratap, *et al.*, 2013) yield of

ASA was 85–98% at 85 °C as well as for cordierite honeycomb monolith coated with Pt-SO₄²⁻/ZrO₂–98% (Shyamsundar, *et al.*, 2013). A similar result was reached on the zirconium phosphate nanoparticles (Hajipour, *et al.*, 2014) at 100 °C for 75 minutes and on the nano-crystalline catalyst from fly ash, activated with H₂SO₄ for 4 h at 90–140 °C (Khatri, *et al.*, 2008). The use of microwave (MW) irradiation in the synthesis of ASA appeared as a new green methodology compared with the conventional synthesis of ASA with o-acetylation of SA (Bose, *et al.*, 1997), (Mirafzal, *et al.*, 2000) and (Montes, *et al.*, 2006); in particular, microwave-assisted o-acetylation of SA with AAA into ASA on acid and basic catalysts (H₂SO₄, H₃PO₄, AlCl₃, MgBr₂·OEt₂, CaCO₃, NaOAc, Et₃N, 4-N, N-dimethylaminopyridine) showed the highest yield of ASA (77%) obtained under CaCO₃ in five minutes (Montes, *et al.*, 2006); also, in the absence of catalyst under MW irradiation the reaction is completed in 10–13 minutes without polymer formation producing the highest yield (80%). As is seen from scientific literature review, solid acids – medium- and wide-porous zeolite catalysts (H-ZSM-5 (MFI), H-BEA, H-FAU(Y), etc) or oxides are the good alternative for homogenous catalytic method of production of ASA by esterification with high yield or high selectivity. But these zeolites and also active catalysts of other classes (oxide, heteropolyacids) are synthetic materials, getting of which is multi-step process, with the use of a variety of solvents, presence of waste waters and as a result is connected with harmful effect on the environment and needs additional expenses.

The present work is devoted to the receipt of ASA by solvent-free esterification of SA with AAA over solid strong acid catalysts – dealuminated and decationated forms (i.e. the forms in which the exchangeable cations of the zeolite is substituted with H⁺ ions) of natural zeolites – heulandite and clinoptilolite, which are catalytically highly active, recyclable and not aggressive to the environment; unlike other active catalysts – synthetic zeolites and oxides they are easily prepared and inexpensive.

Experimental

Chemicals and Materials

In the studied o-acetylation reaction of salicylic acid, the following substances and materials were used: salicylic acid (99.65%, “Stanchem”, Poland) and acetic acid anhydride (>99%), n-butylamine (>99.5%), ethanol, (99.8%), benzene (for HPLC 99.9%), purchased at Sigma-Aldrich. Reaction catalysts were solid acids – H-forms of heulandite family natural zeolites – clinoptilolite and heulandite.

Catalysts preparation

The catalysts have been prepared from the museum samples of natural zeolites of Georgia – clinoptilolite-containing rock (CL, SiO₂/Al₂O₃ = 8.9) from Dzegvi deposit and heulandite (HEU, SiO₂/Al₂O₃ = 7.6) originated from the Akhaltsikhe deposit. Light pink crystals of monomineral heulandite sample (HEU-M, SiO₂/Al₂O₃ = 6.8), 0.5 cm in size) were selected from natural heulandite manually under a binocular microscope. The CL contains about 95% of clinoptilolite, a minor amount of α-quartz and feldspars (Skhirtladze, 1991); natural HEU contains 85% of heulandite, also a bit of

montmorillonite, chlorite, feldspars, α -quartz. Starting forms of natural clinoptilolite (CL), natural heulandite (HEU) and natural monomineral heulandite HEU-M were ground down to a powder finer than 6 μm , washed with distilled water and dried. The catalysts obtained from them and denoted respectively, H-CL, H-HEU, H-HEU-M were prepared in the manner described below.

Catalyst H-CL. Natural CL was leached once with 1M HCl solution (10 ml solution/g zeolite) for 3 h at reflux temperature; the suspension was filtered and the precipitate was washed with hot distilled water and dried in air at 40 °C (Ramishvili, *et al.*, 2017).

Catalysts H-HEU and H-HEU-M. These were prepared also as a catalyst H-CL from starting forms respectively, HEU and HEU-M; in order to prevent destruction of the HEU crystal structure the 0.25 M solution of hydrochloric acid (10 ml solution/g zeolite) was taken.

Before the experiments, the catalysts were heated for 3 hours in a clean air stream at 310 °C for H-CL and at 210 °C for H-HEU and H-HEU-M to prevent structural change from heulandite A to heulandite B (Alberti, 1973), (Breger, *et al.*, 1970), (Mortier, *et al.*, 1981) and (Joshi, *et al.*, 1997).

Catalysts characterization

The partial chemical composition of catalysts was determined with X-ray fluorescence analysis (EDX3600B, Skyray Instrument Ltd., China). The zeolite catalysts crystalline phases were identified by the X-ray powder diffraction analysis (DRON-4 with Cu-K α , $\lambda = 0.15406$ nm; 40 kV, 16 mA, in the range $2\theta = 5 - 50^\circ$ at a scanning rate of $2^\circ/\text{min}$). Fourier transform infrared spectroscopy (FTIR) studies of catalysts were conducted on a FTIR spectrometer Varian 660-IR in the infrared region 2000-400 cm^{-1} . Samples were prepared with KBr in a weight ratio of 1/100-1/350. Except for spectroscopic characteristics of the catalysts samples, by FTIR spectra the degree of crystallinity of zeolite catalysts were also evaluated (Charkviani, *et al.*, 1976) and (Tsitsishvili, *et al.*, 1983). Total surface acidity and acid strength distribution was measured by the method of butylamine (n-BA) nonaqueous titration in the presence of Hammett (H_0) and Hirschler (H_R) indicators using the procedure described by Benesi (Benesi, 1956), (Benesi, 1957) and (Hirschler, 1963). The value of total acidity was determined by the Hammett acidity function $H_0 \leq + 5.0$. The value of proton acidity was determined by the Hirschler acidity function (H_R).

Investigations of catalytic activity

The o-acetylation reaction of salicylic acid with acetic anhydride were performed in the liquid phase in a 50 ml three-necked round bottomed glass flask with a reflux condenser, thermometer and a port for periodical sampling of reaction mixture with a capillary and further analysis by using the method of UV spectroscopy; catalytic experiments were carried out under solvent-free condition at temperatures in the range of 40 – 120 °C and under ambient pressure; duration of run was from 0.5 – 5 h, catalyst mass – 0.025 – 0.200 g, molar ratio of reagents – SA and AAA was 1/4 – 1/8; mass ratio of catalyst with SA was 1/10 – 1/80 i.e. 0.07 – 0.56 mol SA/g catalyst. The catalyst was separated from the reaction mixture

using vacuum filtration, then it was washed with hot distilled water; the washed catalyst after regeneration in air at 310 °C for CL and for heulandites at 210 °C was tested for reuse in separate experiments. The ASA was separated from the reaction products, containing non-converted SA, excess of AAA and ASA, in a known manner (Miller, *et al.*, 1982), (Olmsted, 1998), and (Synthese von Acetylsalicylsäure, 2010). Generated white crystals of ASA (crude products) were washed with chilled water, dried in air, weighed and then for the purpose of purification its re-crystallization from warm ethanol/water (10/1) solution was carried out. Re-crystallized air-dried sample of ASA was weighed; the SA content in the filtrate was determined using a method of UV-spectroscopy (Sanyal, *et al.*, 1996) and (Iwunze, 2008). The determination of the yield of ASA (Y, %), conversion of SA (C, %) and selectivity on ASA (S, %) was carried out according to the formulas given in study (Ramishvili, *et al.*, 2017). The progress of the o-acetylation reaction was monitored using the method of UV-spectroscopy (Specord UV-VIS, German; Carry 100, Varian, USA, quartz cell, layer thickness 1 cm, solvent-ethanol); in the mixture ASA and SA was identified by their absorption bands at $\lambda_{\text{max}} = 274-283$ and 301-303 nm, respectively (Sanyal, *et al.*, 1996) and (Iwunze, 2008). Synthesized aspirin was identified also by FTIR spectra on Ge plate (Thermo Nicolet, Avatar 370) or in KBr (Varian 660-IR), as well as by definition of the melting point. For detection of impurity of salicylic acid in the received aspirin was also applied the test with 1% solution of iron (III) chloride. Re-crystallized product – ASA was characterized also by high-performance liquid chromatography (HPLC) on Agilent 1200 Series HPLC system with DAD detector and column Zorbax Eclipse-C18, 5 μm , Analytical, 250 mm x 4.6 mm I.D., column temperature – ambient; mobile phase – phosphoric acid R, acetonitrile R for chromatography, water (2:400:600 v/v/v). ASA and SA were detected at 237 nm and 205 nm, respectively; quantitative analysis was carried out with the use of certified reference substance (European Pharmacopoeia, 8th ed., 2013).

RESULTS AND DISCUSSION

Chemical composition of the catalysts

From the Table 1 it is visible that by treatment of natural cationic forms of CL and HEU with 1 M and 0.25 M hydrochloric acid solutions, respectively, their simultaneously dealumination and decationization takes place; whereas natural CL was dealuminated to nearly 47%, HEU – 20% and HEU-M – 11%. Towards cations indicated in the Table 1 overall total degree of decationization for H-CL, H-HEU and H-HEU-M is about 46, 16 and 13%, respectively. The dealumination and decationization of a clinoptilolite and heulandite at their processing by hydrochloric acid is also in agreement with literature data (Charkviani, *et al.*, 1976), (Barrer, 1971), (Tsitsishvili, *et al.*, 1973), (Arcoya, *et al.*, 1994), (Christidis, *et al.*, 2003), (Rozic, *et al.*, 2005), (Garcia-Basabe, *et al.*, 2010), (Cakicioglu-Ozkan, *et al.*, 2005). It is established that by mineral acids leaching (HCl (Barrer, *et al.*, 1964) and (Cakicioglu-Ozkan, *et al.*, 2005), HNO $_3$ (Dumitriu, *et al.*, 2009) and (C. Cobzaru, *et al.*, 2008), H $_2$ SO $_4$ (Yamamoto, *et al.*, 1996) of heulandite/c clinoptilolite the increase of their micropore volumes and specific surface area takes place; this is caused by unblocking of zeolites channels from cations, that were exchanged with hydronium cations of a smaller size; also

by acid treatment dealumination of zeolites occurs – a hydrolysis of Al-O-Si bonds, resulting in partial amorphization of HEU family zeolites and formation of secondary micropores with a greater diameter than in the initial raw material (Arcoya, *et al.*, 1994), (Christidis, *et al.*, 2003), (Barrer, *et al.*, 1964), (Yamamoto, *et al.*, 1996), (Wust, *et al.*, 1999) and (Rivera, *et al.*, 2013). Thus in dealuminated and decationized clinoptilolite and heulandite occurs an increase of adsorption of various adsorbates including the largest molecules (benzene, pentane, isopentane, n-hexane, ascorbic acid), also of SA and ASA molecules with minimum and maximum lengths: for SA – 8.7 and 4.04 Å, and for ASA – 10.43 and 5.47 Å (Properties viewer - Geometry of aspirin molecule, 2014), probably, in secondary macro- and mesopores (Mansouri, *et al.*, 2013) and (Cobzaru, *et al.*, 2015), (Barrer, *et al.*, 1964), (Cobzaru, *et al.*, 2008) and (Rakić, *et al.*, 2013).

are shown in Figures 3 and 4. Approximate quantitative estimation of the crystalline phases in the H-form zeolites were carried out by the method of optical density (D) ratio of bands that characterize the zeolite topology (wave numbers 520 cm^{-1} – 650 cm^{-1}) and bending vibration inside the (Al, Si) O_4 tetrahedrons (wave numbers 420 cm^{-1} – 475 cm^{-1}) which practically do not depend on the zeolite phase composition (Flanigen, *et al.*, 1971), (Tsitsishvili, *et al.*, 1983) and (Che, *et al.*, 2011). In the samples of catalysts H-CL, H-HEU-M and H-HEU content of zeolite crystal phase is high and of the same order – 81, 80 and 87% as can be seen from the Table 2. In the FTIR spectra of all investigated H-forms of zeolites in comparison with the original samples in the region of 400 cm^{-1} – 800 cm^{-1} , specific for the topology of zeolite (Joshi, *et al.*, 1997), (Flanigen, *et al.*, 1971), (Mozgava, *et al.*, 2011), (Pechar, *et al.*, 1981) and (Rodriguez-Fuentes, 1998), changes are observed.

Table 1. Incomplete chemical composition of the catalysts based on the natural zeolites – clinoptilolite and heulandites

Chemical composition wt. %	Clinoptilolite		Heulandite		Monomineral heulandite	
	CL	H-CL	HEU	H-HEU	HEU-M	H-HEU-M
Si	32.44	40.71	30.53	34.47	29.98	32.16
Al	7.03	3.68	7.72	6.16	8.51	7.59
Na	2.48	2.21	2.23	2.35	2.49	2.19
Ca	2.61	0.79	3.85	2.72	4.60	3.95
K	0.53	0.18	0.12	0.14	0.10	0.09
Mg	0.38	0.06	trace	trace	trace	trace
Molar ratio $\text{SiO}_2/\text{Al}_2\text{O}_3$	8.9	21.3	7.6	10.8	6.8	8.2

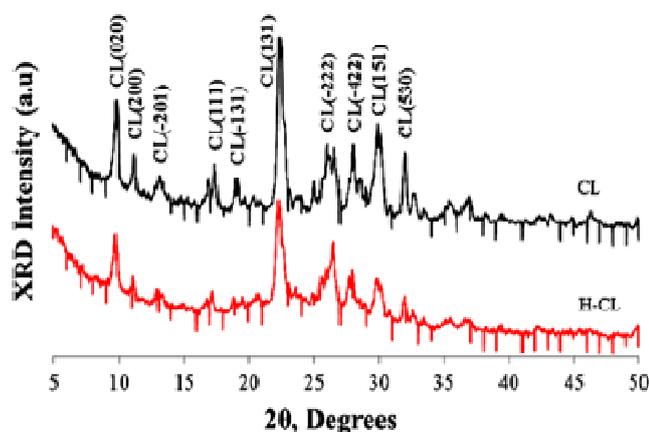


Figure 1. Powder XRD patterns of catalysts – natural clinoptilolite CL and its acid-treated form H-CL

Powder XRD patterns and FTIR spectra of catalysts

From the Figures 1 and 2 it is evident that powder X-ray diffraction (XRD) patterns all of the studied catalysts correspond, mainly, to the HEU-type zeolites – heulandite and clinoptilolite (Baerlocher, *et al.*, 2001). The broadening of the diffraction maxima and the decrease in their intensities observed on the X-ray diffraction pattern of the H-CL sample are explained by its high degree of dealumination (by 47%) in comparison with the initial sample. Comparison of X-ray powder patterns of heulandites shows that the crystal structure of acid-treated samples H-HEU-M and H-HEU does not change significantly, as can be seen in Figure 2. The degree of structure amorphization of zeolites H-CL, H-HEU-M and H-HEU associated with the decrease in the intensity of their diffraction lines was estimated from their FTIR spectra, which

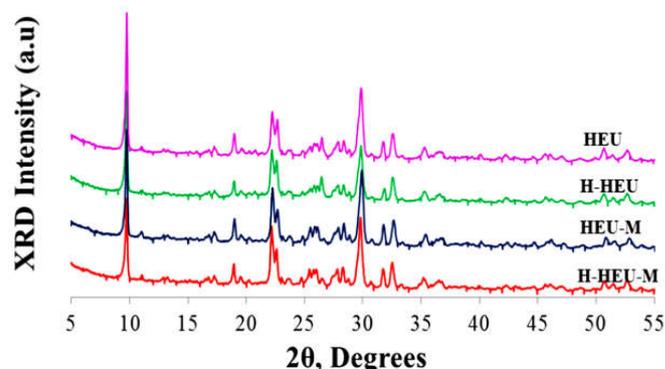


Figure 2. Powder XRD patterns of catalysts – natural heulandite HEU, monomineral heulandite HEU-M and their acid-treated forms, respectively H-HEU and H-HEU-M

In particular, disappear spectral bands for H-CL 467.5, 521.1, 671.1, 780.5 cm^{-1} ; for H-HEU – 520.1, 598.7, 780.1 cm^{-1} ; for the H-HEU-M – 408.3, 520.8 cm^{-1} , Figures 3 and 4. Reducing of the intensity of some spectral bands also were observed, respectively for H-CL (604.6, 723.4 cm^{-1}), for H-HEU-M (596.9 cm^{-1}) and for H-HEU (598.7 cm^{-1}). From the Table 2 it is evident that the acid treatment causes structural changes in the investigated zeolites (H-CL, H-HEU and H-HEU-M), which lead to a partial amorphization of the zeolite structure; the studied samples of catalysts contain, respectively 19, 20 and 13 % of an amorphous phase.

Measurements by n-butylamine titration method

Surface acidity and acid strength distribution of investigated zeolites are given in Table 3. In the starting forms of natural zeolites are weak acid sites ($-3.0 \leq \text{Ho} \leq +5.0$) and these

catalysts showed very small activity. With decationization and dealumination of investigated natural zeolites expands the range of acidity. In particular, in the H-forms appear strong and medium-strength acid proton centers ($-13.3 \leq H_R \leq -6.6$), the total number (ΣH_R) of which in H-CL is greater than in H-HEU and H-HEU-M. In the series of catalysts: (H-HEU-M) – (H-HEU) – (H-CL) with growth of degree of dealumination of the zeolite total acidity (ΣH_0) decreases from 1.3 to 0.8 meq / g, but the total number of proton acid sites (ΣH_R) rises from 0.35 to 0.75 meq/g, Table 3.

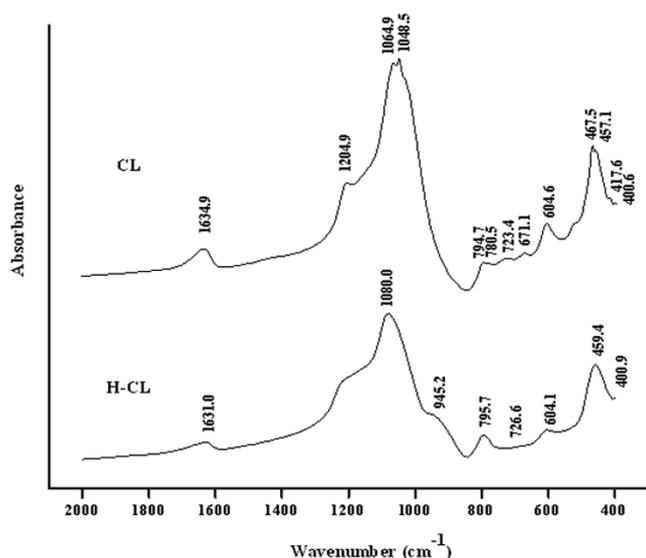


Figure 3. FTIR spectra of the natural clinoptilolite (CL) and its acid form (H-CL) in the 2000-400 cm^{-1} range. Zeolite and KBr powder mixture mass ratio 1/100

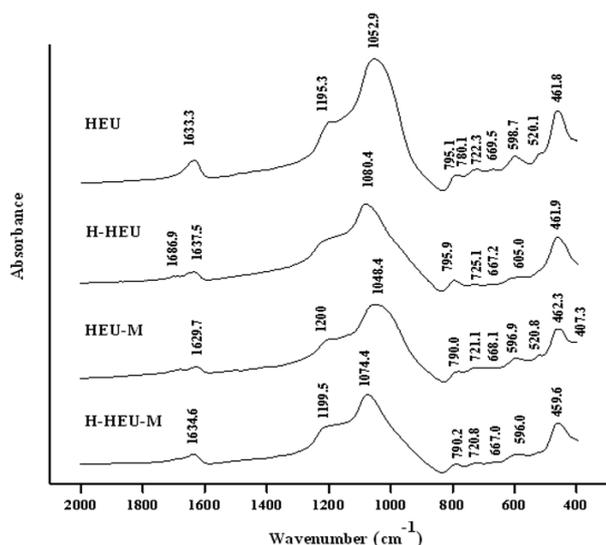


Figure 4. FTIR spectra of natural heulandites (HEU, HEU-M) and their acid forms (H-HEU, H-HEU-M) in the 2000-400 cm^{-1} range. Zeolite and KBr powder mixture mass ratio 1/350

Catalytic activity

In the o-acetylation of SA natural zeolites CL, HEU and HEU-M exhibit little catalytic activity (yield ASA is 3-5% at 80 °C and molar ratio $v(\text{SA})/v(\text{AAA}) = 1/4$). From Table 3 it is evident, that their decationized and dealuminated forms, representing strong solid acids (total protonic acidity equal to

0.35 – 0.75 meq n-butylamine /g), are active in this reaction; up to 80 °C the ASA is formed, and above this temperature also condensation products are formed. The effect of reaction time on yield of ASA in the range from 0.5 to 5 h at 55 °C and 80 °C, showed optimal reaction time of 3 h. During this time a certain state of equilibrium value of the ASA yield is attained, and then it decreases because of side condensation processes. The effect of various factors (the molar ratio of the reactants, temperature, mass of catalyst, acidity) on the catalytic activity was investigated. *Dependence of the yield of ASA on the molar ratio of reagents $v(\text{SA})/v(\text{AAA})$ and mass of catalysts.* Figure 5 shows that in the range of $v(\text{SA})/v(\text{AAA})$, equal to 1/2–1/8, the maximum yield of ASA on all catalysts is available at $v(\text{SA})/v(\text{AAA}) = 1/4$. As shown in the Figure 6, for all investigated zeolite catalysts yield of ASA from the mass of catalyst (0.025 – 0.3 g) at $v\text{SA} / v\text{AAA} = 1/4$ (i.e. 0.014 mol SA/0.058 mol AAA) increases and reaches a maximum with 0.1 – 0.2 g; their activities were compared for masses of 0.2 g. of the catalysts. Highest yield (89.4%) of ASA was achieved for H-CL ($\text{SiO}_2/\text{Al}_2\text{O}_3 = 21.3$) at 55 °C.

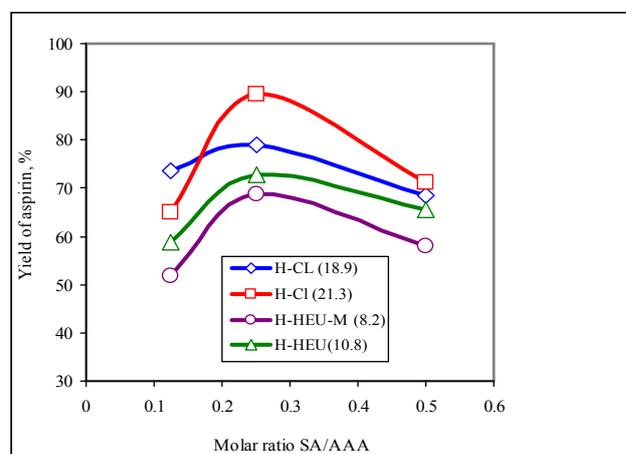


Figure 5. Effect of SA and AAA molar ratio on the yield of ASA for reaction conditions: $m_{\text{catalyst}} = 0.2$ g, reaction temperature 55 °C, $m_{\text{catalyst}}/m_{\text{SA}} = 1/10$. Duration of run–3h. Yields of ASA are calculated on the product after re-crystallization. For comparison data for H-CL (18.9) are taken from (Ramishvili, *et al.*, 2013)

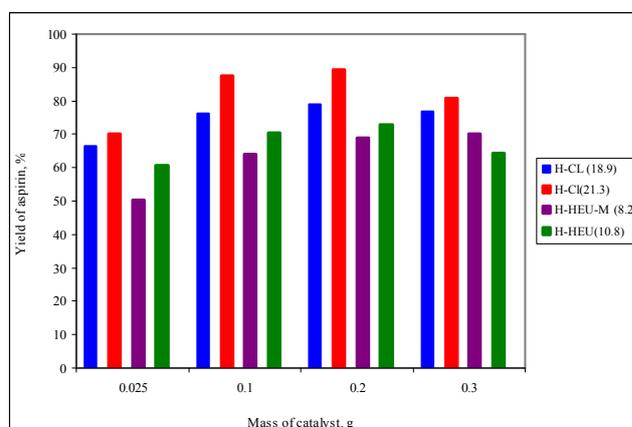


Figure 6. Effect of catalyst mass on the yield of ASA. Reaction conditions: 55 °C, $v\text{SA} / v\text{AAA} = 1/4$, (2g/6 g), $m_{\text{catalyst}}/m_{\text{SA}} = 1/80$; 1/20; 1/10; 1/6.6. Duration of run–3h

Dependence of the yield of ASA on the reaction temperature and acidity of catalysts; reusability of catalysts. The dependence of the catalysts activity on temperature was investigated at 40–120 °C; from Figure 7 it is evident, that

yield of ASA from 40 to 80 °C increases from 50.8 to 92.2% and then decreases for H-CL (21.3), H-HEU (10.8) and H-HEU-M (8.2), probably due to the side processes of molecular association of SA and of ASA.

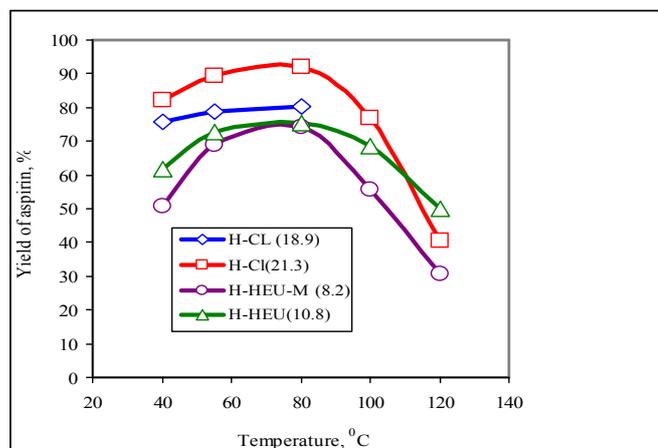


Figure 7. Effect of reaction temperature on the yield of ASA. Reaction conditions: $vSA / vAAA = 1/4$ (mol/mol), $m_{catalyst} = 0.2$ g, $m_{catalyst}/m_{SA} = 1/10$

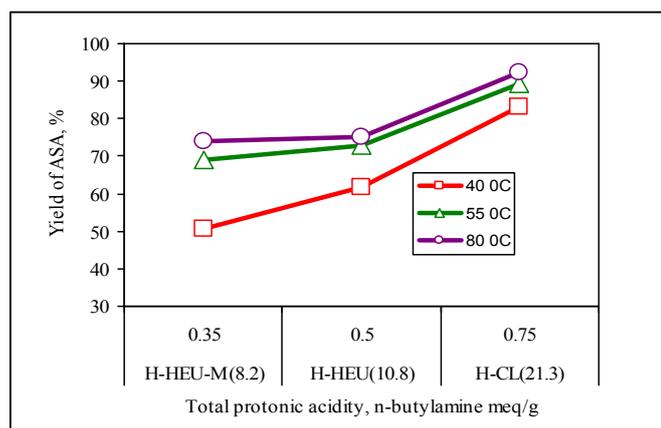


Figure 8. Dependence of catalytic activity of zeolite catalyst in the esterification reaction on the number (ΣH_R) of the strong and medium-strength acid proton centers ($-13.3 \leq H_R \leq -6.6$); reaction conditions: $m_{catalyst} = 0.2$ g, $vSA/vAAA = 1/4$ (mol/mol), $m_{catalyst}/m_{SA} = 1/10$, temperature 40-80 °C

From the Figure 7 it is visible that on the ascending branch of the temperature dependence curve of the activity the relative series of catalytic activity has the following form: H-CL (21.3) > H-HEU (10.8) \geq H-HEU-M (8.2), in brackets are shown molar ratios SiO_2/Al_2O_3 ; from Table 3 and Figure 8 the same sequence can be seen in the change of values of total protonic acidity ΣH_R (strong and intermediate-strength centers: $-13.3 \leq H_R \leq -6.6$). According to Figures 5-7, there is a tendency to increase the catalytic activity of ASA formation with increasing molar ratio of SiO_2/Al_2O_3 in clinoptilolite (compare H-CL (21.3) and H-CL (18.9), (Ramishvili *et al.*, 2013); this is, probably, also due to the increase of strength of acidic centers and their availability in the H-CL(21.3). Figure 9 shows the linear dependence of the yield of ASA on conversion of SA within the temperature interval of 40–80 °C; in this range of temperatures all studied catalysts (H-CL, H-HEU and H-HEU-M) are alike in selectivity towards ASA with regard to converted SA (it comes nearer to 100%), that points to the identical nature of the active centers in catalysts;

greater activity of H-CL(21.3) is explained by a larger number of the acid proton centers (0.75 meq n-butylamine/g) in it.

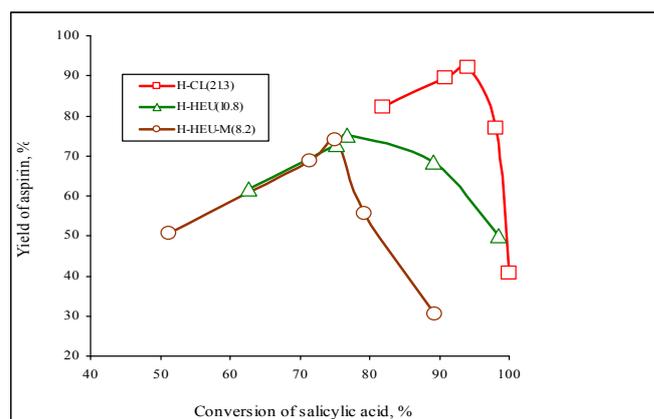


Figure 9. Dependence of the yield of ASA from the conversion of SA. The points of the curves corresponds initial to 40 °C, the maximum to 80 °C, and minimum to 120 °C; $vSA / vAAA = 1/4$ (mol/mol, 2g/6g), $m_{catalyst}/m_{SA} = 1/10$, $m_{catalyst} = 0.2$ g

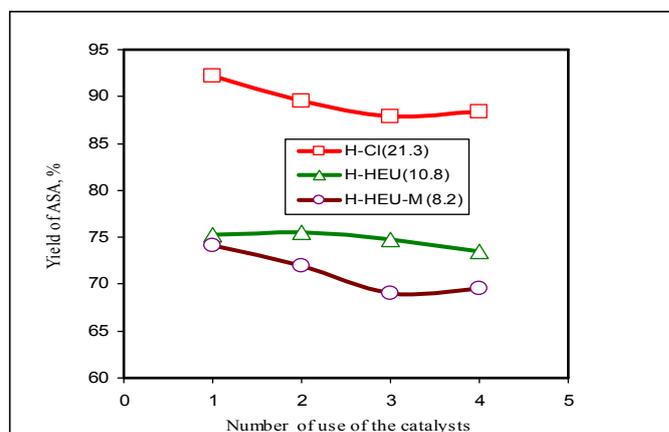


Figure 10. The effect of use number of the catalyst on the yield of ASA. Reaction conditions: temperature 80 °C, $m_{catalysts} = 0.2$ g, the mass ratio $m_{catalyst} / m_{SA} = 1/10$, molar ratio of $vSA/vAAA = 1/4$. Reaction time – 3h. Activity of a freshly prepared sample corresponds to the abscissa point 1

Over 80 °C sharp falling of the yield of ASA probably is connected with the course of secondary reactions of polymerization-condensation of ASA and SA (Rainsford, 2004). In the above described optimal conditions the reuse of the catalysts was tested. For that, they worked out catalyst before repeated application was separated from the reaction media by filtration, was washed with ethanol and water, then was heated in a stream of clean air at 310 °C in case of H-CL (21.3) and in case of H-HEU (10.8), H-HEU-M (8.2) – at 210 °C; further, it again was tested as a catalyst. Yield of aspirin after fourfold use of the catalysts with intermediate regeneration differs from the original by 2–6% as can be seen from Figure 10. This indicates a satisfactory reproducibility of activity of regenerated zeolite catalysts: H-CL, H-HEU and H-HEU-M when they were used 4 times in the reaction of o-acetylation of SA in ASA. *Identification of synthesized acetylsalicylic acid.* Typical UV spectrum of reaction mixture is shown on Figure 11. Absorption bands were at λ_{max} (ASA)/nm 277($\epsilon/dm^3 \text{ mol}^{-1} \text{ cm}^{-1}$ 1150) and λ_{max} (SA)/nm 303($\epsilon/dm^3 \text{ mol}^{-1} \text{ cm}^{-1}$ 3880). Re-crystallized aspirin samples obtained by catalytic o-esterification on the studied catalysts:

Table 2. Quantitative evaluation of the zeolites crystallinity determined by the optical density ratio spectroscopic method (Charkviani et al., 1976)

Clinoptilolite				Heulandite				Monomineral heulandite			
CL		H-CL		HEU		H-HEU		HEU-M		H-HEU-M	
D604.6	C, %	D604.1	C, %	D598.7	C, %	D605.0	C, %	D596.9	C, %	D596.0	C, %
D457.1		D459.4		D461.8		D461.9		D462.3		D459.6	
0.5570	95	0.4710	81	0.5736	85	0.5390	80	0.5544	100	0.4839	87

C, % – the percentage of zeolitic phase; D – optical density of bands.

Table 3. Surface acidity (meq n-butylamine per g of catalyst) defined by Hammett (H_0) and Hirschler (H_R , arylmethanol) indicators

Catalysts (molar ratio SiO ₂ /Al ₂ O ₃)	Acidity (n-BA, meq/g cat.) in terms of pK _a of H _R indicators		Acidity (n-BA, meq/g cat.) in terms of pK _a of H ₀ indicators					ΣH_R	ΣH_0
	less than -13.3	from -13.3 to -6.6	less than -8.2	from					
				from -8.2 to -5.6	from -5.6 to -3.0	from -3.0 to +3.3	from +3.3 to +5.0		
H-CL (21.3)	0.35	0.40	0.10	0.10	0.10	0.15	0.35	0.75	0.80
H-HEU (10.8)	0.25	0.25	0.15	0.15	0.20	0.30	0.40	0.50	1.20
H-HEU-M (8.2)	0.15	0.20	0.15	0.15	0.20	0.30	0.50	0.35	1.30

ΣH_0 – the value of the total (protonic and aprotic) acidity**;

ΣH_R – the value of protonic acidity***

**Total acidity: Indicators: -8.2 – anthraquinone, -5.6 – benzalacetophenone, -3.0 – dicinnamalacetone,

+3.3 – p- dimethylaminoazobenzene, +5.0 – p-ethoxychrysoidin.

***Protonic acidity: Indicators: -13.3 – diphenylmethanol, -6.6 – triphenylmethanol.

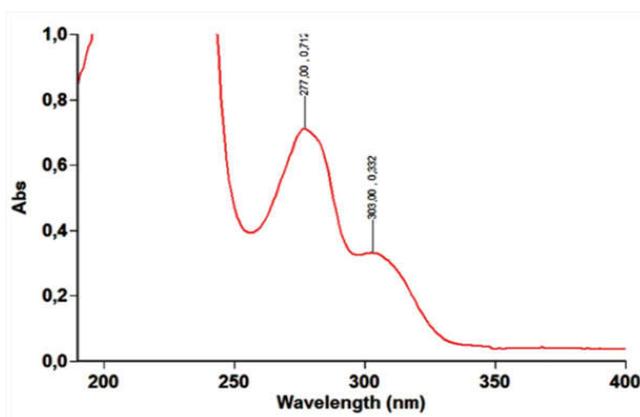


Figure 11. UV-spectrum of SA esterification reaction products on H-HEU (10.8), reaction conditions: $m_{\text{catalyst}} = 0.2$ g, reaction temperature 55 °C, $m_{\text{catalyst}}/m_{\text{SA}} = 1/10$. Duration of run – 2 h

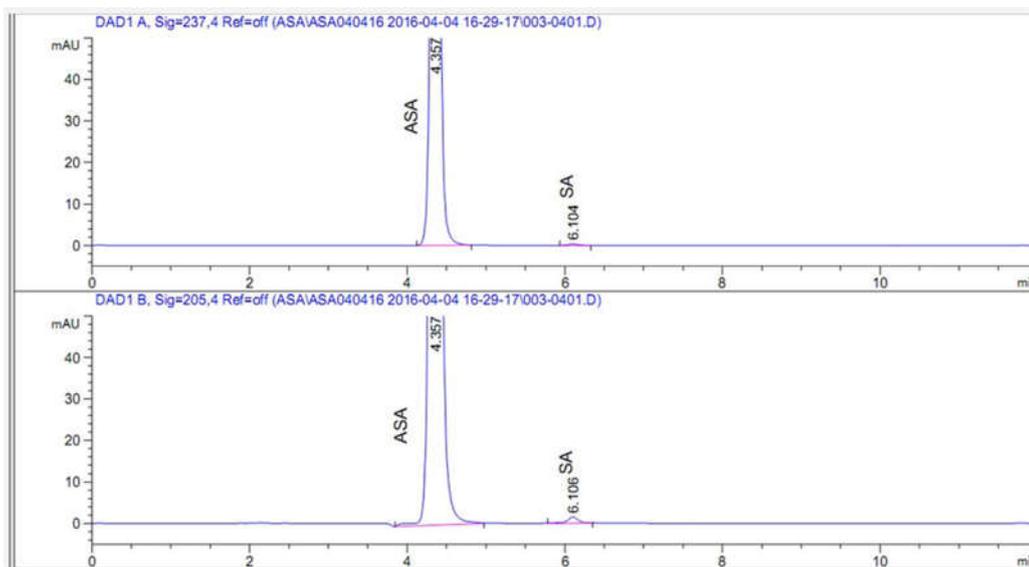


Figure 12. HPLC chromatograms of re-crystallized aspirin (product of esterification reaction on catalyst H-CL (21.3) at 55 °C; $m_{\text{catalyst}} = 0.2$ g, reaction temperature 80 °C, $m_{\text{catalyst}}/m_{\text{SA}} = 1/10$. Duration of run – 3 h. ASA and SA were detected at 237 and 205 nm, respectively; injection volume – 10 μ l

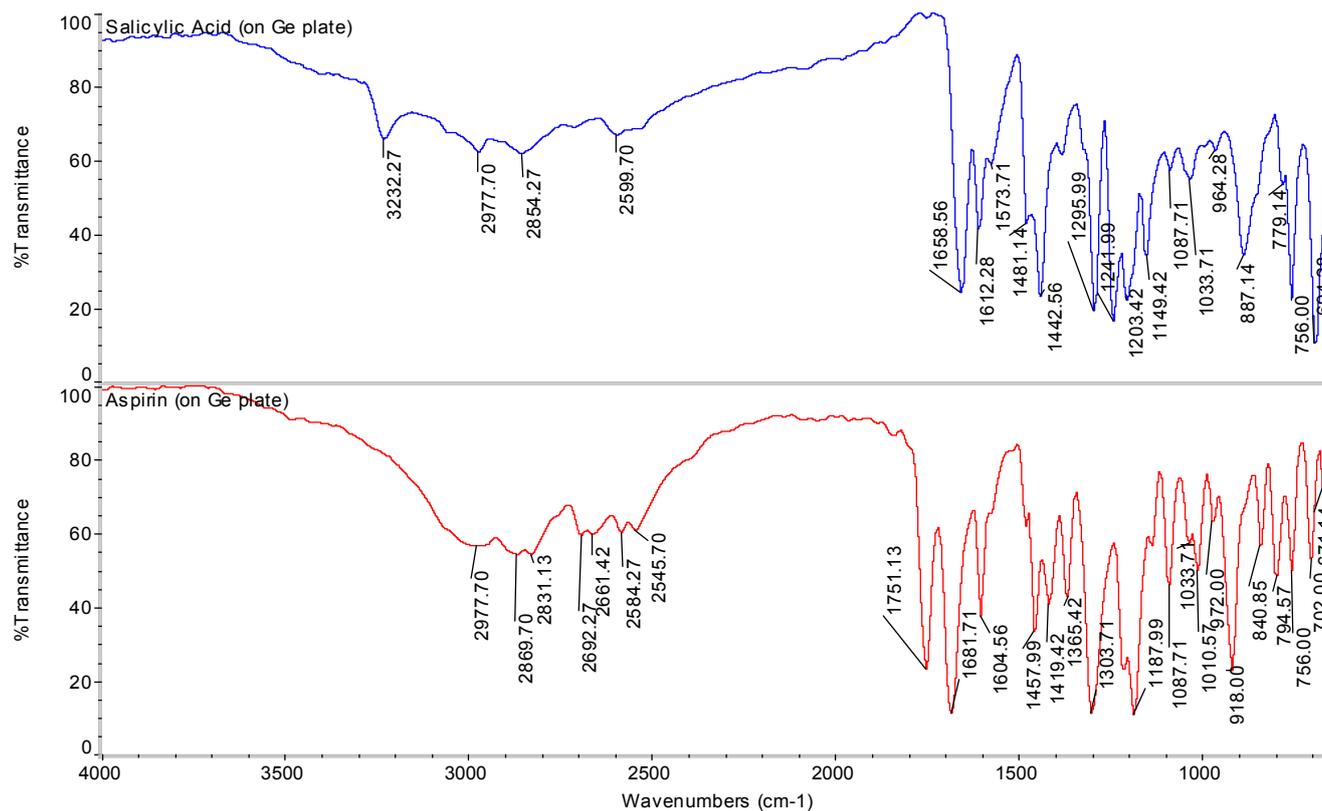


Figure 13. FTIR spectrum (on Ge plate) of starting SA (blue) and reaction product on H-HEU(10.8) – ASA, re-crystallized in warm ethanol/water (10/1) solution (red); reaction conditions: $m_{\text{catalyst}} = 0.2$ g, reaction temperature 55°C , $m_{\text{catalyst}}/m_{\text{SA}} = 1/10$. Duration of run – 3 h

H-CL, H-HEU and H-HEU-M, contain very small amount (up to 0.1 wt %) of SA according to HPLC analysis, Figure 12. Synthesized acetylsalicylic acid was identified also by its melting point; melting point of crude aspirin, obtained on catalysts H-CL, H-HEU and H-HEU-M, was equal to $128\text{--}133^{\circ}\text{C}$, for samples re-crystallized in ethanol it was equal to 135°C . The FTIR spectra of initial SA and ASA, obtained on zeolite catalysts, shown on Figure 13, are similar; but there are principal peaks in the spectrum of ASA; in particular: $\nu_{\text{max}}/\text{cm}^{-1}$ 2545.7–2977.7 (COOH, lit.: 2546.18–3013.28), 1751.1 (C=O of $-\text{COOCH}_3$, lit.: 1749.78), 1681.71 (C=O of $-\text{COOH}$, lit.: 1680.34), 1604.56 (benzene ring, lit.: 1604.13), 1187.99 (C-O of ester/carboxylic acid, lit.: 1181.03, 1190), 918 and 756 (o-substituted benzene, lit.: 913.91, 918 and 758.06, 766); absence of $\nu_{\text{max}}/\text{cm}^{-1}$ 3230 peak (OH-group of SA, 3240) in the spectrum points to the purity of the obtained aspirin. These spectral characteristics are in consent with literature data for acetylsalicylic acid (IR spectra of Aspirin, 2011) and (AIST: Spectral database for organic compounds SDBS, 2016).

Conclusion

In the presented study the alternative heterogeneous, low-temperature and completely environmentally friendly new catalysts are offered. They are used for synthesis of acetylsalicylic acid by the liquid phase o-esterification of salicylic acid with acetic acid. The catalysts represent simultaneously decationized and dealuminated forms of natural zeolites – clinoptilolite (CL, 95%, Si /Al = 4.4) and heulandite (HEU, 85%, Si /Al = 3.8) of Dzegvi and Akhaltsikhe (Georgia) deposits, respectively.

They were prepared by a simple method – acid leaching of clinoptilolite and heulandite; the studied zeolite catalysts H-CL ($\text{SiO}_2/\text{Al}_2\text{O}_3 = 21.3$), H-HEU ($\text{SiO}_2/\text{Al}_2\text{O}_3 = 10.8$) and H-HEU-M ($\text{SiO}_2/\text{Al}_2\text{O}_3 = 8.2$) were identified and characterized by the methods of X-ray fluorescence, XRD and FTIR spectral analysis. The difference in the catalytic properties of these catalysts, belonging to the same class of zeolites – to the class of heulandite, is explained by their different spectrum of acidity; in the most active catalyst H-CL ($\text{SiO}_2/\text{Al}_2\text{O}_3 = 21.3$) there is a greater number of a strong and medium-strength acid proton centres ($-13.3 \leq \text{HR} \leq -6.6$) than in the heulandites. The best yield of acetylsalicylic acid (92% at 94% conversion) was available on H-CL ($\text{SiO}_2/\text{Al}_2\text{O}_3 = 21.3$) in 3 h at 80°C ; in case of heulandites this value was about 75%. Re-crystallized in ethanol synthesized ASA had melting point equal to 135°C , their UV and FTIR spectra were in full agreement with literature data. The HPLC analysis confirmed the production of high purity (>99%) ASA. Unlike existing homogeneous acidic catalyst (H_2SO_4 , H_3PO_4 , HCl) and active heterogeneous catalysts (synthetic zeolites and oxides), the preparation of which is associated with the formation and multi-stage waste water, active forms of the natural zeolites are obtained in one step without formation of toxic products, in real green chemistry way. The novelty of the present material is the development of active, cheap catalyst for the sustainable catalytic processes to produce the acetylsalicylic acid, widely used in medicine and produced in amounts of tens of thousand tons annually.

Acknowledgments: The authors are grateful to geologists: Prof., Doctor of Geological and Mineralogical Sciences I.

Akhvlediani and M. Kavsadze for the providing of samples of natural zeolites. The authors thank PhD K. Kobakhidze for HPLC chromatograms of re-crystallized acetylsalicylic acid.

REFERENCES

- AIST: Spectral database for organic compounds SDBS. URL for aspirin 2016; to be found under http://sdb.sdb.aist.go.jp/sdbs/cgi-bin/direct_frame_disp.cgi?sdbno=532
- Alberti, A. 1973. *Tschermaks Mineral. Petrogr. Mit.* 9, 173-184.
- Arcoya, A., Gonzalez, J. A., Travieso, N. and Seoane, X. L. 1994. *Clay Miner.* 29, 123-131.
- Baerlocher Ch., Meier, W. M. and Olson, D. H. 2001. *Atlas of zeolite framework types. 5th revised ed.*, Elsevier, Amsterdam - London - New York - Oxford - Paris - Shannon - Tokyo, pp. 152-153.
- Bamoharram, F. F., Heravi, M. M., Roshani, M., Gharib, A. and Jahangir, M. 2007. Catalytic Method for Synthesis of Aspirin by a Green, Efficient and Recyclable Solid Acid Catalyst (Preyssler's Anion) at Room Temperature, *J. Chin. Chem. Soc.* 54, 1017-1020.
- Barrer, R. M. and Cram P. J. in *Molec. Siev. Zeolites - II, Adv. in Chem. Ser., vol. 102* (Eds: E. M. Flanigen, L. B. Sand), American Chemical Society, Washington, D.C., 1971, Chapter 47, *Heats of Immersion of outgassed Ion-Exchanged Zeolites*, 105-131.
- Barrer, R. M. and Makki, M. B. 1964. Molecular Sieve Sorbents from Clinoptilolite, *Can. J. Chem.* 42, 1481-1487.
- Benesi, H. A. 1956. Acidity of Catalyst Surfaces. I. Acid Strength from Colors of Adsorbed Indicators, *J. Am. Chem. Soc.*, 78, 5490-5494;
- Benesi, H. A. 1957. Acidity of Catalyst Surfaces. II. Amine Titration Using Hammett Indicators, *J. Phys. Chem.* 61, 970-973.
- Bose, A. K., Banik, B.K., Lavlinski N., Jayaraman, M. and Manhas, M.S. 1997. More Chemistry in a Microwave, *Chemtech.* 27, 18-24.
- Breger I. A., Chandler, J. C. and Zubovic, P. May- June 1970. An infrared study of water in heulandite and clinoptilolite, *Am. Mineral.*, 55, 825-840.
- Brown, D.B. and Friedman, L.B. 1973. The Aspirin Project. Laboratory experiments for introductory chemistry, *J. Chem. Educ.*, 50, 214 - 215.
- Cakicioglu-Ozkan, F. and Ulku, S. 2005. The effect of HCL treatment on water vapor adsorption characteristics of clinoptilolite rich natural zeolite, *Microporous Mesoporous Mater.* 77, 47-53.
- Charkviani, M. K., Tsistsishvili G.V. and Tsintsikaladze G. P. in *Natural Zeolites. Proceeding of the soviet-bulgarian symposium on studies of physico-chemical properties of natural zeolites, Tbilisi, 29-31 October 1976* (Ed.: F.I. Brouček), Mecniereba, Tbilisi, 1979, Infrared Spectroscopy of Natural High Siliceous Zeolites, pp. 259-263.
- Che, C., Glotch, T. D., Bish, D. L., Michalski, J. R. and Xu, W. 2011. Spectroscopic study of the dehydration and/or dehydroxylation of phyllosilicate and zeolite minerals, *J. Geophys. Res.* 116, E5, 1-19.
- Christidis, G., E., Moraetis, D., Keheyani, E., Akhalbedashvili, L., Kekelidze, N., Gevorkyan, R., Yeritsyan, H. and Sargsyan, H. 2003. Chemical and thermal modification of natural HEU-type zeolitic materials from Armenia, Georgia and Greece, *Appl. Clay Sci.* 24, 79-91.
- Cobzaru, C. Marinoiu, A. and Cernatescu, C. 2015. Sorption of vitamin C on acid modified clinoptilolite, *Rev. Roum. Chim.* 60, 241-247.
- Cobzaru, C., Oprea, S., Dumitriu, E. and Hulea, V. 2008. Gas phase aldol condensation of lower aldehydes over clinoptilolite rich natural zeolites, *Appl. Catal. A.* 351, 253-258.
- Collection of simulated XRD powder patterns for zeolites. 2001. 4th ed., (Eds.: M. M. J. Treacy, J. B. Higgins), Elsevier, Amsterdam - London - New York - Oxford - Tokyo, pp.184-187.
- Der Aspirin-Wirkstoff, <https://www.aspirin.de/de/produkte/der-aspirin-wirkstoff.php>, 2014.
- Dumitriu, E., Cobzaru, C., Hulea, V. and Oprea, S. 2009. Dealuminated natural zeolites with potential applications in catalytical processes with formation of C-C bonds 1. Modification of natural clinoptilolite by dealumination, *Rev. Chim.* 60, 297-300.
- European Pharmacopoeia. 2013. 8th ed., vol. 2 (EDQM Council of Europe, Strasbourg), 1477-1478.
- Flanigen, E. M., Khatami, H. K and Szymanski H. A. in *Molecular Sieve Zeolites-I, vol. 101 Advances in Chemistry* (Eds. E. M. Flanigen and L.B. Sand), ACS, Washington, D.C., 1971, chapter 16, pp. 201-229.
- Friderichs, E., Christoph T. and H. Buschmann in *Ullmann's Encyclopedia of Industrial Chemistry, Vol. 3, Analgesics and Antipyretics, 1. Introduction, 7th online edition* (Editorial board members), Wiley-VCH, Weinheim, 15 oct 2011, 293-297.
- Garcia-Basabe, Y., Rodriguez-Iznaga, I., de Menorval, L.C., Llewellyn, Ph., Maurin, G., Lewis, D. W., Binions, R., Autie, M. and Ruiz-Salvador, A. R. 2010. *Microporous Mesoporous Mater.* 135, 187-196.
- Gottardi, G. and Galli, E. 2013. *Natural Zeolites*, Springer, Berlin and Heidelberg GmbH & Co. KG, p. 412.
- Hajipour, A. R. and Karimi H. 2014. Zirconium Phosphate Nanoparticles for Solvent Free Acetylation of Phenols and Salicylic Acid: An Efficient and Eco-friendly Solid Acid Catalyst for Synthesis of Acetyl Salicylic Acid (Aspirin), *J. Chin. Chem. Soc.* 61, 975-984.
- Handal-Vega, E., Loupy, A.P. D. and Garcia, J. M. C. 2001. Synthetic procedure for the manufacture of aspirin, *US Pat.* 6 278 014 B1.
- Hirschler, A. E. 1963. The measurement of catalyst acidity using indicators forming stable surface carbonium ions, *J. Catal.* 2, 428-439.
- Hung, D.Y., Mellick, G. D., Pranked, M. S. and Roberts R. J. 1997. Synthesis, identification, characterization, stability, solubility, and protein binding of ester derivatives of salicylic acid and diflunisal, *Inter. J. Pharm.* 153, 25-39.
- Inglezakis, V. J. and Zorpas, A. A. in *Handbook of Natural Zeolites, Ch.7, Natural Zeolites Structure and Porosity* (Eds.: V. J. Inglezakis, A. A. Zorpas), Bentham Science Publishers, Oak Park, Ill, 2012, pp. 133-146.
- IR spectra of aspirin, 2011; to be found under <http://www.chemspider.com/Chemical-Structure.2157.html?rid=0343072d-dccb-4d38-9ac8-8bc3d5364755>
- Iwunze, M.O. 2008. Absorptiometric Determination of Acetylsalicylic Acid in Aqueous Ethanolic Solution, *Anal. Lett.* 41, 2944-2953.

- Jasra, R. V., Tyagi, B. and Mishra, M. K. 2009. *US Pat. 7544 831*. C07C 67/02, US classes 560/266. Green catalytic process for the synthesis of acetyl salicylic acid.
- Joshi, M. S., Joshi V.V., Choudhari, A. L. and Kasture, M. W. 1997. Structural studies of natural heulandite using infrared spectroscopy, *Mater. Chem. Phys.* 48, 160–163.
- Khatri C. and Rani A., 2008. Synthesis of nano-crystalline solid acid catalyst from fly ash and its catalytic performance, *Fuel*. 87, 2886–2892.
- Koyama K., Takeuchi Y. 1977. Klinoptilolite: the distribution of potassium atoms and its role in thermal stability, *Z. Kristallogr.* 145, 216–239.
- Mansouri N., Rikhtegar, N., Panahi, H.A., Atabi, F. and Shahraki, B. K. 2013. Porosity, characterization and structural properties of natural zeolite-clinoptilolite-as a sorbent, *Environ. Prot. Eng.* 39, 139-152.
- Miller, J. A. and Neuzil, E.F. 1982. *Modern Experimental Organic Chemistry*, D.C. Heath and Company, Lexington, Massachusetts, USA, p. 722.
- Mirafzal, G.A. and Summer, J. M. 2000. Microwave Irradiation Reactions: Synthesis of Analgesic Drugs, *J. Chem. Educ.* 77, 356–358.
- Montes, I., Sanabria, D., Garcia, M., Castro, J. and Fajardo, J. 2006. A Greener Approach to Aspirin Synthesis Using Microwave Irradiation, *J. Chem. Educ.* 83, 628–631.
- Mortier, W. J. Pearce, J. R. 1981. Thermal stability of the heulandite-type framework: crystal structure of the calcium/ammonium form dehydrated at 483K, *Am. Mineral.* 66, 309–314.
- Mozgava W., Kröl, M. and Barczyk, K. 2011. FT-IR studies of zeolites from different structural groups, *Chemik.* 65, 667–674.
- Nazari, H., Ahmadpour, A., Bamoharram, F.F., Heravi, M. M. and Eslami N. 2012. Comparison of Catalysts Preyssler and Silica-Supported Nano Preyssler in the Synthesis of Acetyl Salicylic Acid, *J. Chem. (Hindawi Online)*, 9, 272–276.
- Olmsted, J. 1998. Synthesis of Aspirin, *J. Chem. Educ.* 75, 1261–1263.
- Pandita, S. and Goyal, S. J. 1998. An Efficient Microscale Procedure for the Synthesis of Aspirin, *Chem. Educ.* 75, 770–775.
- Pavia, D. L., Lampman, G. M. and Kriz, G.S. 1976. *Introduction to Organic Laboratory Techniques: A Contemporary Approach*, W.B. Saunders, Philadelphia, p. 699.
- Pechar, F. and Rykl D. 1981. Infrared spectra of natural zeolites of the stilbite group, *Chem. Zvesti.* 35, 189–202.
- Peng, Y. and G. Song. 2000. Heteropolyacid-Catalyzed Synthesis of Aspirin, *Chem. Educ.* 5, 144–158.
- Pratap, S.R., Shyamsundar M., Mohamed Shamsuddin, S. Z. Februar 2013. Green Synthesis of acetylsalicylic acid by using Pt-zeolites catalysts, *Global Journal of Research Analysis.* 2, 102–105.
- Properties viewer - Geometry of aspirin molecule, 2014; to be found under <http://www.chemicalize.org/structure/#!mol=aspirin&source=fp>.
- Rainsford K. D. in *Aspirin and Related Drugs, Ch.3, Occurrence, Properties and Synthetic Developments of Salicylates* (Ed.: K.D. Rainsford), CRC Press, Taylor&Francis, London and New-York, 2004, pp. 70-120.
- Rakić, V., Rajić, N., Daković, A. and Auroux, A. 2013. *Micropor Mesopor. Mat.* 166, 185–194.
- Ramishvili, Ts. M., Tsitsishvili, V. G., Kalabegashvili, N. G., Gabunia, V. M., Samkharadze, L. O., Ioseliani, D. K. and Balarjishvili, G. I. 2013. *Proc. of industrial panel and recent research reports of 17th Int. Zeolite Conf. Zeolites and ordered porous materials: bridging the gap between nanoscience and technology (Moscow, Russian Federation)* 7-12 July, 2013, RRR-3.4-02, pp. 495-496.
- Ramishvili, Ts., Tsitsishvili, V., Chedia, R., Sanaia, E., Gabunia, V. and Kokiashvili, N. 2017. *Am. J. Nano Res. Appl.* 5, 3-1, 26-32.
- Rivera, A., Farias, T., de Ménorval, L.C., Autié –Pérez, M. and Lam, A. 2013. *J. Phys. Chem. C.* 117, 4079–4088.
- Rodríguez-Fuentes, G., Ruiz-Salvador, A. R., Mir, M., Picazo, O., Quintana, G. and Delgado, M. 1998. *Microporous Mesoporous Mater.* 20, 269–281.
- Rozic, M., Cerjan-Stefanovic, S., Kurajica, S., Rozmarie Maeefat, M., Margeta, K. and Farkas, A. 2005. *J. Colloid Interf. Sci.* 284, 48–56.
- Sanyal A. K. and Dutta, A. 1996. Rapid and selective Itraviolet spectrophotometric assay of aspirin in complex tablet formulations, *J. AOAC Int.* 79, 1303–1305.
- Schrör, K. 2016. *Acetylsalicylic Acid*, Wiley-VCH, Weinheim, p. 480.
- Shyamsundar, M., Mohamed Shamsuddin S. Z., Pratap S. R., Venkatesh and Mohan Kumar, T.E. March 2013. O-acetylation of salicylic acid with acetic anhydride over honeycomb coated with zirconia and its modified forms, *Int. J. Innov. Res. Sci. Eng. Technol.* 2, 599-603.
- Skhirtladze, N. 1997. *Genetic Groups of Georgian Zeolites, Their Main Deposits and Manifestations*, Ivane Javakhishvili Tbilisi State University Press, Tbilisi, p. 28.
- Skhirtladze, N. I. 1991. *Sedimentary zeolites of Georgia. Geology and composition of zeolite-containing sedimentary and volcanic-sedimentary rocks*. Publishing House of Tbilisi State University, Tbilisi, in Russian, p. 144.
- Synthese von Acetylsalicylsäure, 2010; to be found under <http://www.swisseduc.ch/chemie/labor/aspirin/docs/aspirin.pdf>
- Synthetic procedure for the manufacture of aspirin, *US Pat. 6 278 014 B1*, 2001.
- Thimmaraju, N., Mohamed Shamsuddin S. Z., Pratap, S. R. and Prasad, K. S. 2015. Effective synthesis of novel O-acetylated compounds over ZrO₂-Al₂O₃ solid acid, *Arab. J. Chem.* Online 3 January 2015.
- Tsitsishvili, G. V. and Charkviani, M. K. 1983. The influence of thermal treatment on IR spectra of some synthetic and natural zeolites in the field of the framework frequencies of vibration, *Dokl. Akad. Nauk SSSR.* 273, 1434–1439.
- Tsitsishvili, G.V., Barnabishvili, D. N. and Koridze, Z. I. 1973. Sorption properties of natural and modified clinoptilolites of Georgian deposits, *Bull. Georg. Natl. Acad. Sci.* 69, 345–348.
- Tyagi B., Mishra, M. K. and Jasra, R.V. 2010. Solvent free synthesis of acetyl salicylic acid over nano-crystalline sulfated zirconia solid acid catalyst, *J. Mol. Catal. A: Chem.* 317, 41–45.
- Ward, W.L. and McKague, H.L. 1994. Clinoptilolite and Heulandite Structural Differences as Revealed by Multinuclear Nuclear Magnetic Resonance Spectroscopy, *J. Phys. Chem.* 98, 1232–1237.
- Wasson, R.L. in *Encyclopedia of Chemical Processing and Design, Vol. 4 Aspirin* (Eds.: J.J. McKetta, W.A. Cannigham), Marcel Dekker, Inc., New-York and Basel, 1977, pp. 24–30.

- Wise W.S. 2013. *Handbook of natural zeolites*, De Frede Editore, Naples, p.334.
- Wust, T., Stolz, J. and Armbruster, T. 1999. Natural and Sodium Clinoptilolites Submitted to Acid Treatments: Experimental and Theoretical Studies, *Am. Mineral.* 84, 1126–1134.
- Yamamoto, S., Matsuoka, O., Kohmura, K., Honda, T. Banno, Y. and Nozove, H. 1996. Dissolution of Zeolite in Acidic and Alkaline Aqueous Solutions As Revealed by AFM Imaging, *J. Phys. Chem.* 100, 18474–18482.
- Yang, S., Lach-hab M., Blastern-Barojas, E., Li, X. and Karen, V.L. 2010. Machine learning study of the heulandite family of zeolites, *Microporous Mesoporous Mater.* 130, 309–313.
- Zhang, C. Liu, T. L., Wang, H. J., Wang, F. and Pan, X.Y. 2011. Synthesis of acetyl salicylic acid over WO_3/ZrO_2 solid superacid catalyst, *Chem. Eng. J.* 174, 236–241.
