

α -Pinene oxide and verbenol oxide isomerizations over heterogeneous catalysts

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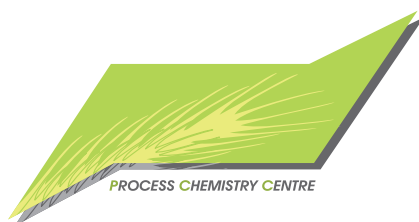
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PREFACE

This work has been performed within an internship in Laboratory of Industrial Chemistry and Reaction Engineering, Process Chemistry Centre, Department of Chemical Engineering at Åbo Akademi University.

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Martina Stekrova
Åbo, December 2014

ABSTRACT

Martina Stekrova

α -Pinene oxide and verbenol oxide isomerizations over heterogeneous catalysts

Doctoral thesis, Laboratory of Industrial Chemistry and Reaction Engineering, Process Chemistry Centre, Department of Chemical Engineering, Åbo Akademi University, 2014.

Keywords: isomerization, α -pinene oxide, campholenic aldehyde, *trans*-carveol, verbenol oxide, iron-modified catalysts, ceria-modified catalysts.

Terpenes are a valuable natural resource for the production of fine chemicals. Turpentine, obtained from biomass and also as a side product of softwood industry, is rich in monoterpenes such as α -pinene and β -pinene, which are widely used as raw materials in the synthesis of flavors, fragrances and pharmaceutical compounds. The rearrangement of their epoxides has been thoroughly studied in recent years, as a method to obtain compounds which are further used in the fine chemical industry. The industrially most desired products of α -pinene oxide isomerization are campholenic aldehyde and *trans*-carveol. Campholenic aldehyde is an intermediate for the manufacture of sandalwood-like fragrances such as santalol. *Trans*-carveol is an expensive constituent of the Valencia orange essence oil used in perfume bases and food flavor composition. Furthermore it has been found to exhibit chemoprevention of mammary carcinogenesis.

A wide range of iron and ceria supported catalysts were prepared, characterized and tested for α -pinene oxide isomerization in order to selective synthesis of above mentioned products.

The highest catalytic activity in the preparation of campholenic aldehyde over iron modified catalysts using toluene as a solvent at 70 °C (total conversion of α -pinene oxide with a selectivity of 66 % to the desired aldehyde) was achieved in the presence of Fe-MCM-41. Furthermore, Fe-MCM-41 catalyst was successfully regenerated without deterioration of catalytic activity and selectivity.

The most active catalysts in the synthesis of *trans*-carveol from α -pinene oxide over iron and ceria modified catalysts in *N,N*-dimethylacetamide as a solvent at 140 °C (total conversion of α -pinene oxide with selectivity 43 % to *trans*-carveol) were Fe-Beta-300 and Ce-Si-MCM-41. These catalysts were further tested for an analogous reaction, namely verbenol oxide isomerization.

Verbenone is another natural organic compound which can be found in a variety of plants or synthesized by allylic oxidation of α -pinene. An interesting product which is synthesized from verbenone is (1*R*,2*R*,6*S*)-3-methyl-6-(prop-1-en-2-yl)cyclohex-3-ene-1,2-diol. It has been discovered that this diol possesses potent anti-Parkinson activity. The most effective way leading to desired diol starts from verbenone and includes three stages: epoxidation of verbenone to verbenone oxide, reduction of verbenone oxide and subsequent isomerization of obtained verbenol oxide, which is analogous to isomerization of α -pinene oxide. In the research focused on the last step of these synthesis, high selectivity (82 %) to desired diol was achieved in the isomerization of verbenol oxide at a conversion level of 96 % in *N,N*-dimethylacetamide at 140 °C using iron modified zeolite, Fe-Beta-300. This reaction displayed surprisingly high selectivity, which has not been achieved yet. The possibility of the reuse of heterogeneous catalysts without activity loss was demonstrated.

REFERAT

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α -Pinene oxide and verbenol oxide isomerizations over heterogeneous catalysts

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Nyckelord: isomerisering, alfa-pinenoxid, kamfolenaldehyd, trans-karveol, verbenoloxid, järnmodifierad katalysator, ceriummodifierad katalysator

Terpener utgör en värdefull naturtillgång för framställning av finkemikalier. Terpentiner som utvinns ur biomassa och som också är en biprodukt från skogsindustrin innehåller många monoterpener såsom alfa- och beta-pinen vilka används i omfattande skala för syntes av luktämnen, parfym och farmaceutiska produkter. Omstrukturering av deras epoxider har studerats genomgående under de senaste åren. Målet har varit att preparera kemiska komponenter som kan utnyttjas av finkemikalieindustrin. De industriellt mest eftertraktade produkterna av isomerisering av alfa-pinenoxid är kamferolaldehyd och transkarveol. Kamfolenaldehyd är en mellanprodukt för framställning av luktämnen som santalol. Transkarveol är en dyrbar ingrediens i valenciaolja, som används i parfym och som smakämne i livsmedel. Den har också en förebyggande verkan mot lymfaccancer.

En omfattande samling av järn- och ceriumbaserade katalysatorer preparerades, karakteriserades och testades för isomerisering av alfa-pinenoxid med tanke på att uppnå en selektiv syntes av ovan nämnda produkter. Den högsta katalytiska aktiviteten i preparering av kamfolaldehyd på järnmodifierade katalysatorer erhöles med Fe-MCM-41-katalysatorn i toluen vid 70 °C. Omsättningsgraden av alfa-pinenoxid var 100 % och selektiviteten av den önskade aldehyden blev 66 %. Fe-MCM-41-katalysatorn regenererades framgångsrikt utan att den katalytiska aktiviteten eller selektiviteten skulle ha minskat.

Den mest aktiva katalysatorn i syntes av transkarveol utgående från pinenoxid utgående från alfa-pinenoxid på järn- och ceriumbaserade katalysatorer var Fe-Beta-300 och Ce-Si-MCM-41. *N,N*-dimetylacetamid användes som lösningsmedel vid 140 °C. Omsättningsgraden var 100 % och selektiviteten av trans-karveol var 43 %. Dessa katalysatorer testades ytterligare i en analog kemisk process, nämligen isomerisering av verbenoloxid.

Verbenon är en naturlig organisk komponent som kan hittas i olika slags växter eller prepareras genom allylisk oxidation av alfa-pinen. En intressant produkt som syntetiseras ur verbenon är (1*R*,2*R*,6*S*)-3-metyl-6-(prop-1-en-2-yl)cyclohex-3-ene-1,2-diol. Det har visat sig att denna diol har en anti-Parkinson-effekt. Den mest effektiva reaktionsvägen som leder till den önskade diolen startar från verbenon och innefattar tre steg: epoxidering av verbenon till verbenonoxid, reduktion av verbenonoxid till verbenoloxid och isomerisering av verbenoloxid, vilket är analogt med isomerisering av alfa-pinenoxid. I forskningen som fokuserades på det sista steget av denna syntes uppnåddes en hög selektivitet (82 %) av den önskade diolen i isomerisering av verbenoloxid. Omsättningsgraden var 96 % vid 140 °C då *N,N*-dimetylacetamid användes som lösningsmedel och Fe-Beta-300 som katalysator. Denna reaktion uppvisade en överraskande hög selektivitet, som inte har observerats tidigare. Möjligheten att återanvända dessa heterogena katalysatorer utan någon som helst minskning av aktiviteten demonstrerades i doktorsarbetet.

ABSTRAKT

Martina Štekrová

Izomerace α -pinenoxidu a verbenoxidu pomocí heterogenních katalyzátorů

Disertační práce, Laboratory of Industrial Chemistry and Reaction Engineering, Process Chemistry Centre, Department of Chemical Engineering, Åbo Akademi University, 2014.

Klíčová slova: izomerace, α -pinenoxid, kamfolenický aldehyd, *trans*-karveol, verbenoxid, železem-modifikované katalyzátory, cerem-modifikované katalyzátory.

Terpeny jsou cenným přírodním zdrojem pro výrobu chemických specialit. Terpentýn, získávaný z biomasy či jako vedlejší produkt zpracování dřeva, je bohatý na monoterpeny, jako jsou α -pinen a β -pinen, které jsou široce používanými meziprodukty v syntéze vonných látek a farmaceuticky aktivních substancí. Izomerace jejich epoxidů byla v posledních letech důkladně studována, jako metoda pro získání sloučenin, které jsou dále použity v oblasti chemických specialit. Průmyslově nejžádanějšími produkty izomerace α -pinen oxidu jsou kamfolenický aldehyd a *trans*-karveol. Kamfolenický aldehyd je meziproduktem pro výrobu vonných látek, jako je santalol. *Trans*-karveol je důležitá složka různých esenciálních olejů (Valencia orange essence oil) a navíc vykazuje aktivitu v chemoprevenci rakoviny prsu.

Celá řada heterogenních katalyzátorů na bázi železa a ceru byla připravena, charakterizována a testována pro izomerační reakce s cílem selektivní přípravy výše zmíněných produktů.

Při syntéze kamfolenického aldehydu bylo nejvyšší aktivity (konverze α -pinenoxidu 100 %) a selektivity na aldehyd (66 %) dosaženo s použitím katalyzátoru Fe-MCM-41 v přítomnosti toluenu jako rozpouštědla při 70 °C. Navíc byla úspěšně provedena regenerace tohoto katalyzátoru bez ztráty jeho katalytické aktivity a selektivity.

Nejvyšší aktivity (konverze α -pinenoxidu 100 %) a selektivity na *trans*-karveol (43 %) bylo dosaženo s použitím katalyzátorů Fe-Beta-300 a Ce-Si-MCM-41 v přítomnosti *N,N*-dimethylacetamidu jako rozpouštědla při 140 °C. Tyto katalyzátory byly dále testovány pro analogickou reakci, kterou je isomerizace verbenoxidu.

Verbenon je další přírodní organickou sloučeninou, která je obsažena v rostlinách či lze syntetizovat allylovou oxidací α -pinenu. Významným produktem, který lze z verbenonu syntetizovat je (1*R*,2*R*,6*S*)-3-methyl-6-(prop-1-en-2-yl)cyklohex-3-en-1,2-diol. Bylo zjištěno, že tento diol je potenciální aktivní substancí účinnou při léčbě Parkinsonovy choroby. Nejúčinnější způsob, vedoucí k požadovanému diolu začíná od verbenonu a zahrnuje tři reakční kroky: epoxidace verbenonu na verbenonoxid, redukci verbenonoxidu a následnou izomeraci získaného verbenoxidu, která je analogická s izomerací α -pinenoxidu. V práci zaměřené na izomerační reakci bylo dosaženo vysoké selektivity na žádaný diol (82 %) při konverzi verbenoxidu 96 %, v *N,N*-dimethylacetamidu při teplotě 140 °C s užitím katalyzátoru Fe-Beta-300. Tato reakce vykazuje vysokou selektivitu, které nebylo doposud dosaženo s žádnými publikovanými katalyzátory. Navíc byla prokázána možnost opakovaného použití heterogenních katalyzátorů bez ztráty jejich aktivity.

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CONTRIBUTION OF THE AUTHOR

Martina Stekrova made the experiments and wrote all the articles I-IV.

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1. INTRODUCTION

The utilization of monoterpenes is nowadays widespread because they are inexpensive and mostly safe raw materials for the manufacture of chemical specialties. Turpentine, obtained from biomass and also as a side product of the softwood industry, is rich in monoterpenes such as α -pinene and β -pinene, which are widely used as raw materials in the synthesis of flavours, fragrances, vitamins and pharmaceutical compounds [1,2]. α -Pinene is found in large quantities in the Norway spruce (*Picea abies*) [3], whereas β -pinene is dominant in the western yellow pine (*Pinus ponderosa*) in North America [4]. The rearrangement of their epoxides has been thoroughly studied in the recent years, as a method to obtain compounds which are subsequently used in the fine chemical industry. It has been published that more than 25 % of the global production of α - and β -pinene is used for the manufacture of synthetic fragrances [1].

1.1. α -Pinene oxide

α -Pinene is a biomass derived substrate and, as mentioned above, represents a valuable raw material for the production of compounds further used in the fine chemical industry. Its oxygenated derivative, α -pinene oxide, can be converted into various substances which are used as flavours, fragrances and pharmaceutical compounds. α -Pinene oxide is a very reactive substrate which isomerizes rapidly in the presence of acids, thereby forming many products (Figure 1). The industrially most desired products of α -pinene oxide isomerization are campholenic aldehyde and *trans*-carveol. Campholenic aldehyde is an intermediate for the manufacture of sandalwood fragrances such as santalol [5]. *trans*-Carveol is an expensive constituent of the Valencia orange essence oil used in perfume bases and food flavor composition. Furthermore, it has been found to exhibit chemoprevention of mammary carcinogenesis [6,7]. Preparation of campholenic aldehyde has been intensively investigated throughout the years [8-13]. On the other hand, only few publications tackled the preparation of *trans*-carveol [14-16].

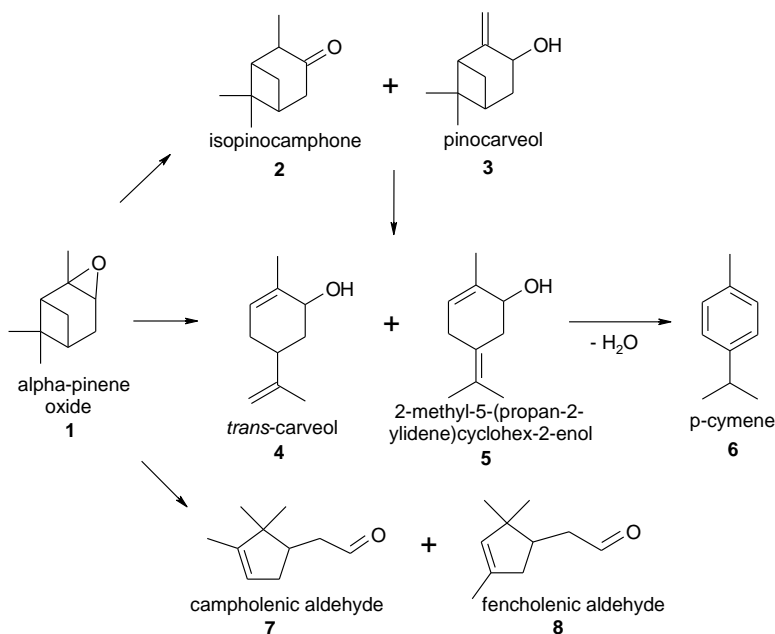


Fig. 1: Reaction scheme of α -pinene oxide **1** isomerization to *trans*-carveol **4** and 2-methyl-5-(propan-2-ylidene)cyclohex-2-enol **5** and *p*-cymene **6** (product of subsequent dehydration), to isopinocampone **2** and pinocarveol **3** and to campholenic **7** and fencholenic **8** aldehydes

The rearrangement of α -pinene oxide yields various aldehydes and alcohols by acid catalysis. This reaction can be homogeneously catalyzed by Lewis acids, and a conventional process based on zinc bromide yields selectivity to campholenic aldehyde of 85 % [8-9].

Preparation of campholenic aldehyde is also possible using heterogeneous catalysts based on various metals such as Fe and Ti. Several articles have been published focusing on the influence of Lewis and Brønsted acid sites of heterogeneous catalysts in this reaction [11,13]. A selectivity of about 78 % to campholenic aldehyde has been achieved using strongly dealuminated H-US-Y zeolite at 0 °C in toluene [11]. Zeolite titanium Beta has been identified as an effective catalyst for rearrangement of α -pinene oxide to campholenic aldehyde, giving selectivities up to 89 % [11]. The highest selectivity to campholenic aldehyde over iron modified catalysts was achieved using Fe-Y-12, specifically 68 % at a 78 % conversion level [13].

In this work several iron supported heterogeneous catalysts were tested for campholenic aldehyde preparation. A wide range of supports with varying structures such as zeolites, silica, alumina and MCM-41 was modified by iron and thoroughly characterized. The results of this study showed that the parameters influencing the activity and selectivity to campholenic aldehyde are the amount and type of Brønsted and Lewis acid sites, content and method of Fe introduction, support type and structural properties of the catalysts [I].

Selective preparation of another product of α -pinene oxide rearrangement, *trans*-carveol, still remains a challenging task. *trans*-Carveol is a highly valuable compound used in perfume bases, food flavor compositions and as an active pharmaceutical substance in chemoprevention of mammary carcinogenesis [6,7].

Few heterogeneous catalysts were studied for the selective preparation of *trans*-carveol. Selectivity to *trans*-carveol of 73 % at 98 % conversion was achieved using cerium and tin supported catalysts in a polar basic solvent, *N,N*-dimethylacetamide [14]. As reported, due to the leaching problems with Sn/SiO₂ and Ce/SiO₂ catalysts, the synthesis of *trans*-carveol was performed under homogeneous conditions using CeCl₃ or SnCl₂ [14]. Selectivity to *trans*-carveol of around 90 % was obtained in *N,N*-dimethylformamide using silica supported hetero polyacids, however, this reaction was also performed under homogeneous conditions because of high solubility of phosphotungstic acids in polar solvents [15]. *trans*-Carveol was obtained with a 45 % yield using molecularly imprinted polymers as a protic catalyst with *N,N*-dimethylformamide as a solvent [16].

In the present work, iron and ceria supported heterogeneous catalysts were tested for *trans*-carveol preparation in the presence of different solvents. Besides catalysts, tested previously in campholenic aldehyde preparation (Fe-SiO₂, Fe-Al₂O₃, Fe-MCM-41, Fe-Y-12), also zeolites beta *per se* with different SiO₂/Al₂O₃ molar ratio were modified by iron, characterized and tested in the iron modified form for *trans*-carveol preparation from α -pinene oxide. The evaporation impregnation method using aqueous solutions of ferric nitrate was used for the preparation of the

catalysts: Fe-Beta-25, Fe-Beta-150 and Fe-Beta-300. The number in the catalyst code indicates the SiO₂/Al₂O₃ molar ratio in the zeolite structure. The characterization of tested catalysts was carried out using various methods [II].

Follow-up experiments focused on the preparation and characterization of cerium modified mesoporous silica materials MCM-41 and SBA-15, namely 32 wt. % Ce-Si-MCM-41 (32 wt.% of cerium), 16 wt. % Ce-H-MCM-41 and 20 wt. % Ce-Si-SBA-15 and on their studies in the selective preparation of *trans*-carveol by α -pinene oxide isomerization [III].

1.2. Verbenol oxide

Verbenone is another natural organic compound classified as a terpene. Verbenone is one of the natural organic compounds which can be found in a variety of plants or synthesized by allylic oxidation of α -pinene [17]. An interesting product, which is synthesized from verbenone, is (1*R*,2*R*,6*S*)-3-methyl-6-(prop-1-en-2-yl)cyclohex-3-ene-1,2-diol (Figure 2, compound **1**). It has been discovered that this diol possesses potent anti-Parkinson activity [7]. Note that Parkinson disease is one of the most common neurological diseases. A decisive influence of the absolute configuration of compound **1** (Figure 2) on its biological activity was discovered [7].

(1*R*,2*R*,6*S*)-Diol **1** can be synthesized from carvone [18], but the most effective method to obtain compound **1** with high stereoselectivity starts from (-)-verbenone and includes three stages: epoxidation of verbenone to verbenone oxide with hydrogen peroxide in alkali/methanol solution, reduction of verbenone oxide using LiAlH₄ [19,20] and subsequent isomerization of obtained verbenol oxide which is analogous to isomerization of α -pinene oxide (Figure 3). The last stage is characterized by the lowest selectivity in the synthesis because of formation of a number of side products, such as compounds with the cyclopentane framework: 1-(2,2,3-trimethylcyclopent-3-enyl)-2-hydroxyethanone **2** and 2-(2,2,4-trimethylcyclopent-3-enyl)-2-hydroxypropanal **3** (Figure 2) and resinification products.

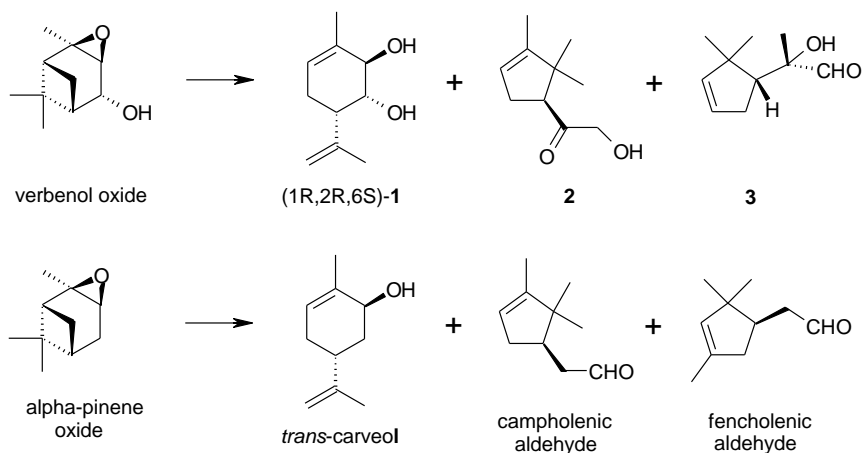


Fig. 2: Reaction schemes of isomerization reactions of verbenol oxide and α -pinene oxide

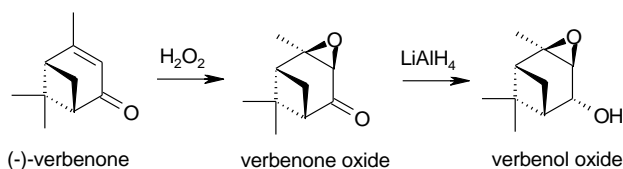


Fig. 3: Reaction scheme of verbenol oxide preparation

The desired diol with the right configuration of all three asymmetric centers has been obtained from verbenol oxide using acidic K10 clay as a catalyst at 25 °C in dichloromethane with a yield of 44-47 % after column chromatography [19,20]. Furthermore, it was found that the use of Co^{2+} -containing montmorillonite clay allowed a slight increase of selectivity for the target compound, from 58 to 65 % [21]. Moreover, a large excess of clays was used in the synthesis and the catalyst could not be regenerated.

This isomerization of verbenol oxide can be catalyzed by homogeneous acidic catalysts with, however, almost no possibility to tune the selectivity. For example isomerization over $ZnBr_2$ leads to ketoalcohol **2** (Figure 2) as a major product [22], while a complex mixture of products was obtained during isomerization in the presence of sulphuric acid [21]. Rearrangement of verbenol epoxide in supercritical fluid CO_2 /isopropyl alcohol led to a preferable formation of compound **2**

Introduction

[23]. An almost unseparable mixture of compound **1** and its partly hydrogenated derivatives in a ratio of 2 : 3 was obtained with the radical catalyst Cp_2TiCl [24].

Hence, although isomerization of verbenol oxide is well studied, there are no effective ways to obtain compound **1** with required yields. Diol **1** was obtained as the main product only in the presence of montmorillonite clays but with moderate selectivity.

The presented research focuses on the isomerization of verbenol oxide to the desired diol **1**. Heterogeneous iron and ceria supported catalysts were examined in this reaction since they were the most active catalysts in the preparation of *trans*-carveol from α -pinene oxide. The reaction conditions for verbenol oxide (synthesized at the Vorozhtsov Novosibirsk Institute of Organic Chemistry, with a purity of 98.5%) isomerization were selected by analogy to α -pinene oxide isomerization [IV].

2. EXPERIMENTAL

2.1. Materials

α -Pinene oxide (97 %) was supplied by Sigma-Aldrich (Germany) and used as received. Toluene, *N,N*-dimethylacetamide, *N*-methylpyrrolidone, acetonitrile, tetrahydrofuran and pentan-2-ol applied as solvents for α -pinene isomerization, were supplied by Sigma-Aldrich (Germany) and used as obtained or distilled at Laboratory of Organic Chemistry of Åbo Akademi University.

The NH₄-ZSM-5, NH₄-Y-12, NH₄-Beta-25, NH₄-Beta-150 (150 = SiO₂/Al₂O₃ molar ratio, also denoted in the original paper [I] as NH₄-Beta-75, 75 = Si/Al molar ratio) and NH₄-Beta-300 zeolites were obtained from Zeolyst International. The NH₄⁺ form of zeolites were transformed to proton forms at 500 °C in a muffle oven using a step calcination procedure.

Silica gel (Merck & Co., Inc.) and aluminum oxide (UOP Inc.) were used as other supports.

Ferric nitrate and cerium nitrate used as an iron and cerium precursors, respectively, were purchased from Fluka.

Verbenol oxide was synthesized at the Vorozhtsov Novosibirsk Institute of Organic Chemistry, with a purity of 98.5 %.

2.2. Catalysts synthesis

2.2.1. Fe-modified catalysts

Zeolites ZSM-5, Y-12, Beta-25, Beta-150 and Beta-300, silica gel, aluminium oxide and H-MCM-41 were modified by iron.

MCM-41 was synthesized in the sodium form (Na-MCM-41) using a Parr autoclave (300 mL) as mentioned in [25] with few modifications [26]. After synthesis of MCM-41, it was filtered, washed with distilled water, dried overnight at 100 °C and calcined. Proton form H-MCM-41 was prepared by ion-exchange with ammonium chloride, followed by washing with distilled water, drying and calcination at 450 °C.

Experimental

Two methods of iron introduction in the catalysts were used, namely conventional evaporation impregnation (IMP) and solid state ion exchange (SSIE). Ferric nitrate ($\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$) was used as an iron precursor in all cases. The impregnation method from the aqueous solutions was used for preparation of the following catalysts: Fe-SiO₂ IMP and Fe-Al₂O₃ IMP, Fe-Beta-25, Fe-Beta-150 and Fe-Beta-300. In the evaporation impregnation method aqueous solutions of ferric nitrate were applied. The mixtures were stirred for 24 hours at 60 °C. The other steps of the synthesis were evaporation, drying at 100 °C overnight and calcination at 450 °C for 4 hours.

Fe modification of ZSM-5, Y-12 and H-MCM-41 materials was performed using the solid state ion exchange method without any solvent. The mixtures of a support and the iron precursor were ball-milled for 8 h. The other steps of synthesis were drying (100 °C overnight) and calcination (450 °C, 4 h).

2.2.2. Ce-modified catalysts

32 wt.% Ce-Si-MCM-41 and 16 wt.% Ce-H-MCM-41 materials were prepared by evaporation impregnation. Mesoporous materials were synthesized in the forms of Na-Si-MCM-41 and Na-Al-MCM-41 using the procedure mentioned above and previously published in [25] with few modifications [26]. After synthesis of MCM-41, it was filtered, washed with distilled water, dried overnight at 100 °C and calcined. Proton form H-MCM-41 was prepared by ion-exchange with ammonium chloride, followed by washing with distilled water, drying and calcination at 450 °C. Ceria modification of Na-Si-MCM-41 and of H-MCM-41 mesoporous materials was carried out using the evaporation impregnation method and a rotator evaporator. Cerium nitrate ($\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$) was used as a cerium precursor. After modification the catalysts were dried at 100 °C and calcined at 550 °C.

Ce-Si-SBA-15 was prepared by the deposition-precipitation method. Si-SBA-15 mesoporous material was synthesized as mentioned in the references [27,28]. The solid product was

filtered, washed with deionized water, dried overnight at 90 °C and calcined at 550 °C in order to remove the organic template. Si-SBA-15 mesoporous material modified by CeO₂ was prepared by the deposition-precipitation method [29]. The prepared and calcined Si-SBA-15 was dispersed in an aqueous solution of urea. An appropriate amount of the precursor (cerium nitrate) was dissolved in deionized water and added to the suspension of urea and the support. The suspension was stirred for 5 h at 70 °C. In the next step, aqueous ammonia was added into the suspension in order to increase pH to 9 and stirring was continued for an hour. The final catalyst was filtered, washed by deionized water, dried overnight at 100 °C and calcined at 600 °C.

2.3. Catalyst characterization

2.3.1 Scanning electron microscope analysis

Morphological studies were performed by scanning electron microscopy. The scanning electron microscope (Zeiss Leo Gemini 1530) was used for determining the crystal morphology of the supports and metal-modified catalysts.

2.3.2 Nitrogen adsorption measurements

The specific surface areas of supports and of metal modified catalysts were determined by nitrogen adsorption using Sorptometer 1900 (Carlo Erba instruments). The samples were outgassed at 150 °C for 3 h before each measurement. The BET equation was used for calculation of the specific surface area of mesoporous materials, silica and alumina and the Dubinin equation was used for calculation of the specific surface area of microporous zeolites.

2.3.3 Pyridine adsorption-desorption with FTIR

The acidity of the proton and metal modified catalyst was measured by infrared spectroscopy (ATI Mattson FTIR) using pyridine ($\geq 99.5\%$) as a probe molecule for qualitative and quantitative determination of both Brønsted and Lewis acid sites. The samples were pressed into

Experimental

thin pellets (10 – 25 mg), which were pretreated at 450 °C before the measurements. Pyridine was first adsorbed for 30 min at 100 °C and then desorbed by evacuation at different temperatures. Three different temperatures were used for desorption of pyridine. Namely desorption at 250 °C – 350 °C corresponds to all (weak, medium and strong) sites, while 350 °C – 450 °C interval reflects medium and strong sites. Pyridine stays adsorbed after desorption at 450 °C only on strong sites [30]. The amount of Brønsted and Lewis acid sites was calculated from the intensities of the corresponding spectral bands, 1545 cm⁻¹ and 1450 cm⁻¹ respectively, using the molar extinction parameters previously reported by Emeis [31]. The catalyst weights were taken into account in the calculations.

2.3.4 X-ray absorption spectroscopy measurements

FeK edge (7111 eV) XAS measurements were carried out at HASYLAB on the beamline X1 and on CLÆSS beamline of ALBA synchrotron facility. Si (111) double crystal monochromator was used for the energy scan along with Rh-coated toroid mirror for unwanted harmonics elimination. The spectra were recorded in the transmission mode at ambient temperature. For the measurements the samples were pressed in self-supporting pellets and wrapped with Kapton tape. Spectra were measured simultaneously with the reference spectrum of Fe foil placed between the second and third ionisation chambers, allowing the absolute energy calibration. Data for Fe foil and α -Fe₂O₃ (hematite), which were used as references, were collected at the same conditions. All spectra were measured two times to ensure their reproducibility.

Analysis of the EXAFS spectra was performed with the software VIPER for Windows [32]. In the spectra of the absorption coefficient μ , a Victorean polynomial was fitted to the pre-edge region for background subtraction. A smooth atomic background μ_0 was evaluated using a smoothing cubic spline. The Fourier analysis of k^2 -weighted experimental function $\chi = (\mu - \mu_0)/\mu_0$ was performed with a Kaiser window. The required scattering amplitudes and phase shifts were calculated by the *ab initio* FEFF8.10 code [33] for α -Fe₂O₃ (hematite) structure. The fitting was

done in the k - and r -spaces simultaneously. The shell radius r , coordination number N , Debye-Waller factor σ^2 and adjustable “muffin-tin zero” ΔE were determined as fitting parameters. The errors of the fitting parameters were found by decomposition of the statistical χ^2 function near its minimum, taking into account maximal pair correlations.

2.3.5 XPS-analysis

The photoemission spectra were measured using a Perkin-Elmer PHI 5400 spectrometer with a monochromatized Al K α X-ray source that was operated at 14 kV, 300 W. The analyzer pass energy was 17.9 eV and the energy step was 0.1 eV. The vacuum chamber base pressure was 10^{-9} mbar. The use of charge neutralizer was necessary and its power was set in a way that Si 2p peak was at 103.5 eV, corresponding to SiO₂ binding energy. The studied peaks were Fe 2p, Si 2p and Al 2p. A 1400 - 0 eV survey spectrum was also taken for each sample. The step length was 0.5 eV. The peaks were calibrated using binding energy (BE) of SiO₂ which is 103.3 - 103.7 eV.

3.3.6 ²⁹Si MAS NMR and ²⁷Al MAS NMR

NMR spectra were recorded at 9.4 T on a Bruker Avance-400 spectrometer equipped with broad-band double-resonance-MAS probe. ²⁷Al MAS NMR spectra were acquired with a short $\pi/12$ radio frequency pulse (0.6 μ s), and about 1000 scans were accumulated with a 0.5 s recycle delay. ²⁹Si MAS NMR spectra were recorded with a $\pi/2$ excitation pulse of 5.0 μ s duration and 20 s repetition time, and 1000 scans were acquired for signal accumulation. Both ²⁷Al and ²⁹Si NMR spectra were recorded with the use of 4 mm rotors and a spinning rate of 10–15 kHz.

2.3.7 X-ray diffraction

Powder X-ray diffraction (XRD) of the samples was measured using Philips X'Pert Pro MPD using monochromated CuK α radiation at 40 kV/50 mA. The divergence slit was 0.25° with a

Experimental

fixed 20 mm mask. The diffractograms were analyzed by Philips X'Pert HighScore MAUD programs.

2.4. Catalytic tests

2.4.1. Campholenic aldehyde preparation

Liquid phase campholenic aldehyde from α -pinene oxide over the Fe modified catalysts was carried out in the batch-wise operating glass reactor. In a typical experiment using toluene as a solvent ($V_L=150$ ml) the initial concentration of α -pinene oxide and the catalyst mass were 0.013 mol/l and 75 mg, respectively. The kinetic experiments were performed at 70 °C under the following conditions to avoid external mass transfer limitation: the catalysts particle size below 90 μm and the stirring speed of 390 rpm. The catalyst was activated in the reactor at 250 °C under an inert argon atmosphere for 30 min before the reaction to remove adsorbed water from its surface. The samples were taken at different time intervals and analyzed by GC using a DB-Petro column with a capillary column of 100 m x 250 μm x 0.50 μm nominal (Agilent 128-1056) and with a FID detector. The products were confirmed by GC-MS.

2.4.2. *trans*-Carveol preparation

Preparation of *trans*-carveol by α -pinene oxide isomerization over Fe modified catalysts, over the parent beta materials (H-Beta zeolites) and over Ce modified mesoporous materials was carried out in the liquid phase using a batch-mode operated glass reactor. In a typical experiment the initial concentration of α -pinene oxide and the catalyst mass were 0.02 mol/l and 75 mg, respectively. The polar solvents with various basicity were tested for α -pinene oxide isomerization ($V_L = 100$ mL). The reaction temperature was 140 °C, or the reaction was performed under reflux when the boiling point of the used solvent was lower than 140 °C. The kinetic experiments were performed under the following conditions to avoid external mass transfer limitation: the catalysts particle size below 90 μm and the stirring speed of 390 rpm. The catalyst was activated in the

reactor at 250 °C under an inert argon atmosphere for 30 min before the reaction to remove adsorbed water from its surface. The samples were taken at different time intervals and analyzed by GC using a DB-Petro column with a capillary of 100 m × 250 μm × 0.50 μm nominal (Agilent 128–1056) and with a FID detector. The products were identified and confirmed by GC-MS using an Agilent 7890A gas chromatograph equipped with a quadrupole mass spectrometer Agilent 5975C as a detector. Quartz column HP-5MS (copolymer 5%-diphenyl-95%-dimethylsiloxane) of length 30 m, internal diameter 0.25 mm and stationary phase film thickness 0.25 μm was used for the analysis.

In order to study the reaction in the presence of trace amounts of a homogeneous catalyst, a few additional experiments were performed. As a homogeneous catalyst FeCl₃.6H₂O was applied in a typical experiment at 140 °C using 0.02 mol/l α-pinene oxide as a reactant in 100 ml of *N,N*-dimethylacetamide.

2.4.2. Verbenol oxide isomerization

The isomerization of verbenol oxide over the Fe- and Ce-modified catalysts was carried out in the liquid phase using a batch-wise glass reactor. In a typical experiment the initial concentration of verbenol oxide and the catalyst mass were 0.02 mol/L and 75 mg, respectively. The catalyst was kept in the reactor at 250 °C in an inert argon atmosphere for 30 min before the reaction. *N,N*-dimethylacetamide was used as a solvent ($V_L=100$ mL). The samples were taken at different time intervals and analyzed by GC. The products were confirmed by GC-MS and NMR.

2.5. Catalyst reuse and regeneration

In order to evaluate a possibility of catalyst reuse and regeneration, the spent catalyst was filtered from the reaction mixture after isomerization, washed by acetone and dried overnight at 100 °C and reused in the reaction. In the case of catalyst regeneration, calcination at 400 °C was done prior to the reaction.

3. RESULTS AND DISCUSSION

3.1. Selective α -pinene oxide isomerization to campholenic aldehyde [I]

As mentioned in the Introduction, selective preparation of campholenic aldehyde has been previously tested using a range of heterogeneous catalysts based on various metals such as Fe and Ti. However, activities and selectivity of these heterogeneous catalysts have not reached as good results as in the case of homogeneous Lewis acids. The highest selectivity to campholenic aldehyde over iron modified catalysts was obtained using Fe-Y-12, namely 68 % at 78 % conversion [13].

Different iron modified materials with different physico-chemical properties were studied for α -pinene oxide isomerization in this work. A wide range of supports with varying structures such as zeolites (ZSM-5 and Beta-150), silica, alumina and MCM-41 were modified by iron, characterized and tested for campholenic aldehyde preparation. Two methods of catalyst synthesis were used, namely conventional impregnation method and solid state ion exchange method. The in-depth characterization of the tested catalysts was carried out using scanning electron microscopy, nitrogen adsorption, FTIR with pyridine as a probe molecule, X-ray absorption spectroscopy (EXAFS, XANES), XPS, ^{29}Si MAS and ^{27}Al MAS NMR and X-ray diffraction [I].

The influence of iron loading on silica and alumina, the effect of various structures of micro- and mesoporous supports and the influence of Lewis and Brønsted acid sites of the catalysts on the activity and selectivity of catalysts was investigated.

The achieved conversions of α -pinene oxide over all tested iron modified catalysts are shown in Fig. 4. The complete conversion of α -pinene oxide was obtained using Fe-Beta-150 and Fe-MCM-41 within 20 minutes from the beginning of the reaction. Lower conversions were achieved over iron modified silica and alumina. Both supports were modified by iron in order to get different metal loadings targeting 3, 5 and 10 wt.%, however, the amounts of supported iron determined by EDXA were lower in all cases (the loaded amount of iron on the supports is shown in Fig. 4). The achieved conversion over iron supported on silica increased with the iron content.

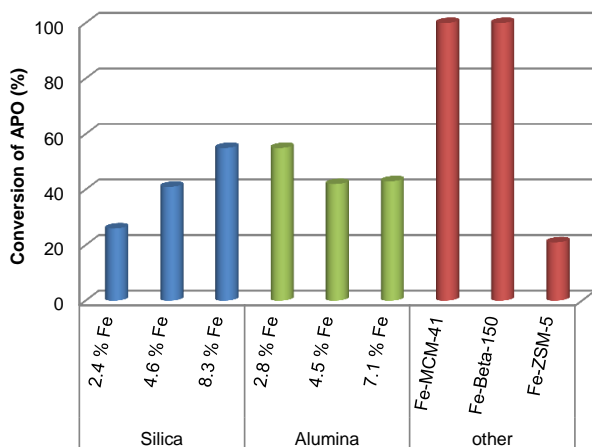


Fig. 4: The conversion of α -pinene oxide after 180 min at 70 °C in toluene over all tested catalysts

conversions obtained using these catalysts were lower, 42 % and 43 %, respectively, than for 2.8 % Fe on alumina.

The conversion for Fe-ZSM-5 catalyst was the lowest among all iron supported catalysts being only 21 % within 180 minutes from the beginning of the reaction. The tested supports as well as iron modified supports exhibited high surface areas. Since ZSM-5 is characterized by a small

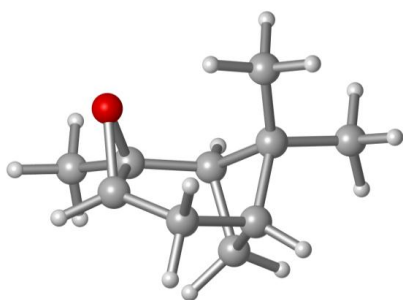


Fig. 5: The structure of α -pinene oxide optimized using Gaussian 09 program

pore diameter (0.5 nm), it is usually not suitable for preparation of specialty chemicals with larger kinetic diameters. α -Pinene oxide is a relatively large molecule not fitting into the pores of zeolite ZSM-5 therefore its isomerization proceeds only on the external catalyst surface and not in the pores. The molecule of α -pinene oxide was calculated to fit into a cylinder of 4.7 Å in

diameter. By adding a van der Waals radius (1.2 Å) of hydrogen to each side of the cylinder, the total critical diameter was determined to be 7.1 Å, which proved that it did not fit into the pores of ZSM-5. (Computations were performed using Gaussian 09 in connection with GaussView. DFT level of theory along with the rB3LYP functional were employed. Basis set 6-311g was used for all

The highest conversion of α -pinene oxide over iron supported on alumina was noticed for Fe-Al₂O₃ (3 wt.%) being 55 % within 180 min. Alumina with a higher content of iron (5 and 10 wt.%) displayed high magnetism, therefore the catalyst remained on the thermocouple and was not well stirred in the reaction mixture. As a consequence the

atoms. The structure of α -pinene oxide was optimized to a minimum (Fig. 5), the diameter of the smallest cylinder to contain the molecule was then measured in GaussView.)

3.1.1. Effect of loaded amount of Fe on silica and alumina

The influence of the loaded amount of iron on the activity and selectivity of catalysts was investigated using silica and alumina as the supports. As mentioned above, both supports were modified by iron in order to achieve a different metal loading of 3, 5 and 10 wt.%. Obtained results were compared with previously reported ones showing that the isomerization rates increased with increasing iron loading using Fe on mesoporous silica [34].

Iron supported on silica and alumina exhibited low initial reaction rates, which could be explained by a low concentration of Brønsted acid sites and furthermore by lower specific surface areas of these catalysts. The initial reaction rates of α -pinene oxide transformation over iron

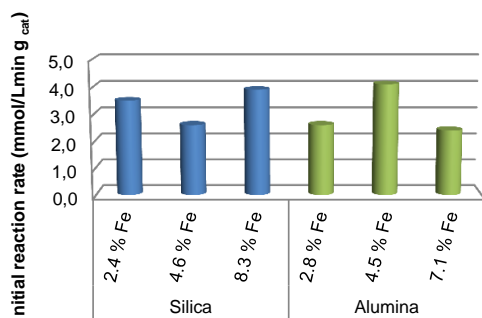


Fig. 6: The initial reaction rates of α -pinene oxide transformation over Fe-SiO₂ (2.4, 4.6 and 8.3 wt.%) and Fe-Al₂O₃ (2.8, 4.5 and 7.1 wt.%)

supported on silica and alumina are depicted in

Fig. 6. The initial reaction rate was calculated

according to $r_0 = \left(\frac{(c_0 - c_t)}{t} \frac{1}{m_{cat}} \right)$, where c_0, c_t

are initial and actual concentration of α -pinene oxide (mmol/L), t is reaction time (3 min in our case) and m_{cat} is mass of catalyst (g). As

obvious in the figure, the initial isomerization rate did not depend on the iron loading. It

should, however, be pointed out here that the final conversion of α -pinene oxide over Fe-SiO₂ catalysts increased with increasing iron loading showing that the final activity of the catalysts was in line with iron loading. These results are therefore consistent with those published in ref. [34]. As mentioned above, alumina with a higher content of iron (5 and 10 wt.%) became magnetic and thus no conclusions can be drawn.

The selectivity to campholenic aldehyde and to often encountered minor products, such as fencholenic aldehyde, *trans*-carveol, isopinocampnone, pinocarveol and *p*-cymene, obtained over iron supported on silica and alumina is depicted in Fig. 7 and 8, respectively. The highest selectivity

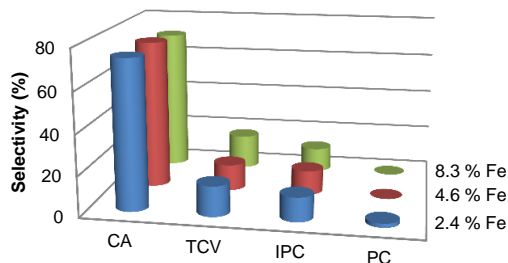


Fig. 7: The selectivity to campholenic aldehyde (CA), *trans*-carveol (TCV), isopinocampnone (IPC) and pinocarveol (PC) over Fe-SiO₂ (2.4, 4.6 and 8.3 wt.%) (at 25 % conversion)

amount of different types of active sites changes with time [34]. Fencholenic aldehyde is formed at higher conversions of α -pinene oxide. *Trans*-carveol and isopinocampnone were the main by-products using Fe-SiO₂ catalysts which contain very low amounts of Brønsted acid sites. Formation of *trans*-carveol and isopinocampnone is similar using all three Fe-SiO₂ catalysts. Fe-SiO₂ with 5 wt.% Fe contained the main part of iron in the state 2+, showing that Fe²⁺ is quite selective for production of campholenic aldehyde analogously to Fe in Fe-Beta-300 made by ion exchange [13].

The selectivity to campholenic aldehyde ranged from 51 to 58 % at 40 % conversion (Fig. 8) but it further decreased with increasing conversion of α -pinene oxide using all Fe-Al₂O₃ catalysts because of by-products formation. Isopinocampnone and pinocarveol were the main by-products

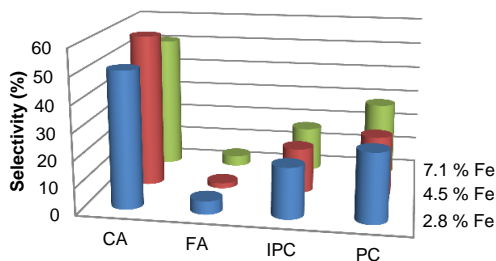


Fig. 8: The selectivity to campholenic aldehyde (CA), fencholenic aldehyde (FA), isopinocampnone (IPC) and pinocarveol (PC) over Fe-Al₂O₃ (2.8, 4.5 and 7.1 wt.%) (at 40 % conversion)

to the desired campholenic aldehyde at 25 % conversion of α -pinene oxide from all tested catalytic systems was obtained using Fe-SiO₂ with different loading amounts of iron being around 73 % at 25 % conversion. It decreased,

however, with increasing conversion of α -pinene oxide, which can be a sign that the

amount of different types of active sites changes with time [34]. Fencholenic aldehyde is formed at higher conversions of α -pinene oxide. *Trans*-carveol and isopinocampnone were the main by-products using Fe-SiO₂ catalysts which contain very low amounts of Brønsted acid sites. Formation of *trans*-carveol and isopinocampnone is similar using all three Fe-SiO₂ catalysts. Fe-SiO₂ with 5 wt.% Fe contained the main part of iron in the state 2+, showing that Fe²⁺ is quite selective for production of campholenic aldehyde analogously to Fe in Fe-Beta-300 made by ion exchange [13].

The selectivity to campholenic aldehyde ranged from 51 to 58 % at 40 % conversion (Fig. 8) but it further decreased with increasing conversion of α -pinene oxide using all Fe-Al₂O₃ catalysts because of by-products formation. Isopinocampnone and pinocarveol were the main by-products using Fe-Al₂O₃ catalysts. Characteristic for these products is that they are formed by opening only the epoxide ring of α -pinene oxide (see Fig. 1). The selectivity to campholenic aldehyde was thus lower because of their formation than with other types of catalysts being below 60 % for all Fe-Al₂O₃ catalysts.

3.1.2. Effect of various structures of micro- and mesoporous supports

The influence of support micro- and mesoporous structures on the activity and selectivity of catalysts was investigated using two types of zeolites (ZSM, Beta-150) and mesoporous molecular sieve (MCM-41).

The initial reaction rates of α -pinene oxide transformation over iron supported on ordered structures are depicted in Fig. 9. The high initial reaction rates were achieved using Fe-MCM-41

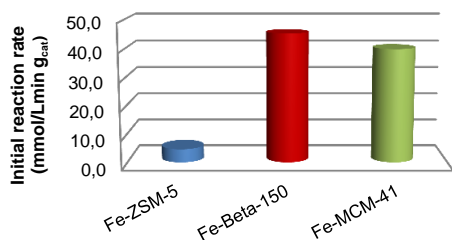


Fig. 9: The initial reaction rates α -pinene oxide transformation over Fe-ZSM-5, Fe-Beta-150 and Fe-MCM-41

and Fe-Beta-150 with materials with ordered mesoporous and microporous structure. The highest initial reaction rate was achieved using Fe-Beta-150, the catalyst with the highest Lewis and Brønsted acidity. Iron supported on zeolite ZSM-5 exhibited a low initial reaction rate and also a low conversion of α -pinene oxide. This fact was explained above by a very small pore diameter of the parent zeolite.

The selectivity to campholenic aldehyde and to often encountered minor products, such as fencholenic aldehyde, *trans*-carveol, *p*-cymene, isopinocampnone and pinocarveol, obtained over

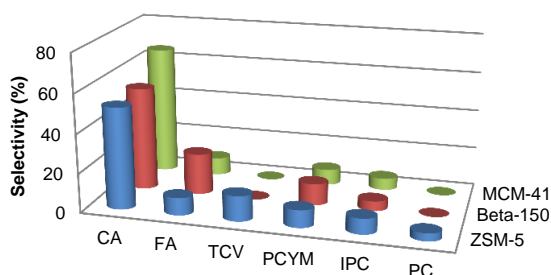


Fig. 10: The selectivity to campholenic (CA) and fencholenic aldehyde (FA), *trans*-carveol (TCV), *p*-cymene (PCYM), isopinocampnone (IPC) and pinocarveol (PC) over Fe-ZSM-5 (at 20 % conversion), Fe-Beta-150 and Fe-MCM-41 (at 100 % conversion)

iron supported on ordered materials is depicted in Fig. 10. The selectivity to campholenic aldehyde slightly increases with increasing conversion of α -pinene oxide for all three iron containing catalysts.

The highest selectivity to the desired campholenic aldehyde was obtained

over Fe-MCM-41 being 66 % at total conversion of α -pinene oxide. It should also be pointed out that with Fe-MCM-41 a relatively constant selectivity with conversion was obtained contrary to the

decreasing selectivity over Fe on silica or alumina. The lowest selectivity to campholenic aldehyde was exhibited by Fe-Beta-150 at total conversion of α -pinene oxide at the expense of the isomer, fencholenic aldehyde, formed with the highest selectivity using this catalyst, which exhibited the highest Brønsted acidity. Thus lower selectivity achieved with this catalyst compared to Fe-MCM-41 and Fe-ZSM-5 catalysts is in line with the amount of Brønsted acid sites.

Trans-carveol was formed during the isomerization reactions using all three catalysts. It was further transformed via dehydration and dehydrogenation mainly to *p*-cymene for catalysts with higher activity (Fe-Beta-150, Fe-MCM-41). The formation of *p*-cymene increased with increasing conversion of α -pinene oxide and its formation is easier using a mesoporous Fe-MCM-41 catalyst showing that the Brønsted acidity of Fe-MCM-41 is sufficient to catalyze dehydration. Analogously to these results also quite large amounts of *p*-cymene were formed with a mildly acidic Fe-Beta-300-IE catalyst [13] showing that an adequate amount of Brønsted acidity is required.

3.1.3. Effect of Lewis and Brønsted acid sites of the catalysts

As discussed above, the acidity of catalysts influenced the activity and mainly the selectivity towards different products. It was concluded, that the presence of an adequate amount of Lewis acid sites as well as an adequate concentration of Brønsted acid sites is beneficial. Fe-Beta-150, the catalyst with the highest Lewis and Brønsted acidity, was evaluated as the most active in the isomerization reaction. It can be concluded that the activity of the catalyst increases with the increasing amount of Brønsted acid sites. This corresponds to previously reported results [13] for α -pinene oxide isomerization over iron-modified zeolites under similar reaction conditions. The highest initial rate was achieved using Fe-Y-12 SSIE catalyst, which is characterized by a very high concentration of Brønsted acid sites [13]. On the other hand, the selectivity to campholenic aldehyde can decrease with increasing concentration of Brønsted acid sites.

It was observed that Lewis acidity is crucial for selective formation of campholenic aldehyde. The influence of the Lewis acid sites on the formation of campholenic aldehyde is

depicted in Fig. 11 (a). Lewis acid sites can react with the oxygen atom of epoxide ring causing splitting of an adjacent C-C bond in the 6-member carbon-ring forming thereby the desired campholenic aldehyde. On the other hand, Fig. 11 (b) shows a possible interaction of Brønsted acid sites represented by H^+ atom with α -pinene oxide and a mechanism of *trans*-carveol formation [1].

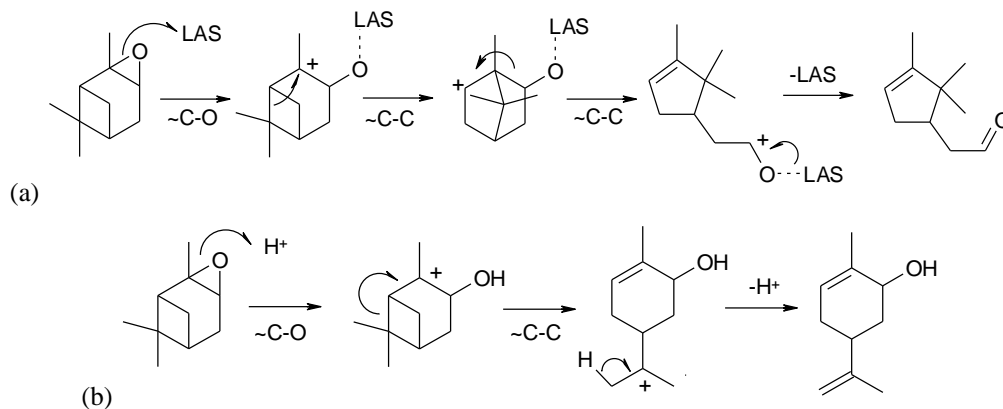


Fig. 11: Formation of (a) campholenic aldehyde over Lewis acids sites and (b) *trans*-carveol over Brønsted acid sites [1]

However, it should be pointed out that there is no linear dependence between the concentration of Lewis acid sites and selectivity to campholenic aldehyde. The catalysts exhibiting the highest concentration of Lewis acid sites, Fe-Bea-150 and Fe- Al_2O_3 , showed lower selectivity to campholenic aldehyde in comparison with Fe-MCM-41 catalyst, which is characterized by mild Lewis acidity.

3.1.4. Possibilities of catalyst reuse and regeneration

The best evaluated catalyst, Fe-MCM-41, was tested to determine its possible reuse and regeneration. The results of the catalytic experiments focused on the preparation of campholenic aldehyde by α -pinene oxide isomerization over fresh, spent and regenerated Fe-MCM-41 materials are depicted in Fig. 12. The total conversion of α -pinene oxide was achieved using all three catalysts despite the fact that reused and regenerated catalysts exhibited lower surface areas. The

highest initial reaction rate was achieved using fresh Fe-MCM-41 being comparable to the initial reaction rate obtained using regenerated catalyst. The activity in the case of the spent catalyst was

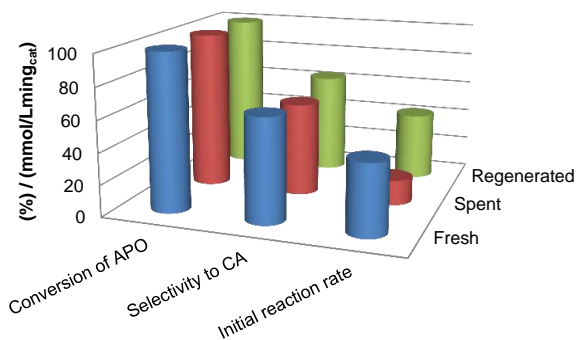


Fig. 12: The conversion of α -pinene oxide after 180 min, selectivity to campholenic aldehyde (CA) and initial reaction rate over fresh, spent and regenerated Fe-MCM-41

lower. The total conversion of α -pinene oxide was achieved using the fresh and regenerated Fe-MCM-41 catalysts within 20 min. The reused catalyst exhibited a decrease of its activity by about 30 % and the total conversion was obtained after 180 min. The activity decrease of the reused catalyst can be caused by deactivation of the Brønsted acidic centers

responsible for α -pinene oxide transformation which can be than reactivated by regeneration.

The selectivity to the desired campholenic aldehyde at 100 % conversion of α -pinene oxide decreased just slightly and it can be seen that selectivity to campholenic aldehyde does not change for the deactivated catalyst.

3.2. Selective α -pinene oxide isomerization to *trans*-carveol [II,III]

Selective preparation of another product of α -pinene oxide rearrangement, *trans*-carveol, still remaining a challenging task in the presence of heterogeneous catalysts, was examined over iron and ceria supported catalysts.

The investigation was focused on the testing of iron modified catalysts, which were previously used in selective campholenic aldehyde synthesis but under different reaction conditions. Besides iron supported on silica, alumina, ZSM-5, Beta-150 ($\text{SiO}_2/\text{Al}_2\text{O}_3 = 150$) and MCM-41, also iron supported on zeolites Y-12 ($\text{Si}/\text{Al} = 12$), Beta-25 and Beta-300 ($\text{SiO}_2/\text{Al}_2\text{O}_3 = 25$ and 300, respectively) was tested. In addition, zeolites beta *per se* with different $\text{SiO}_2/\text{Al}_2\text{O}_3$ molar ratios were investigated for *trans*-carveol preparation from α -pinene oxide.

Based on the data from literature [14], ceria supported on mesoporous materials MCM-41 and SBA-15 catalysts were also utilized in the current research, namely Ce-Si-MCM-41 (32 wt.%), Ce-H-MCM-41 (16 wt.%) and Ce-Si-SBA-15 (20 wt.%). The basic properties of these catalysts were discussed previously [26, 29]. It should be mentioned that these catalysts were tested for the first time in the reaction, typically catalyzed by acids.

The characterization of the applied catalysts was carried out using various characterization methods (scanning electron microscopy, X-ray photoelectron spectroscopy, nitrogen adsorption and FTIR pyridine adsorption).

It is known that the α -pinene oxide transformation into various products is strongly influenced by the basicity of the solvent. The optimal solvent for campholenic aldehyde preparation is toluene [13]- a solvent with no Lewis basicity. On the other hand, in order to achieve high yields of *trans*-carveol, the usage of polar basic solvent is necessary. Because of that fact, mainly *N,N*-dimethylacetamide (DMA) was used in this study. In addition, activity and selectivity of the chosen catalysts was evaluated using the following solvents: acetonitrile, tetrahydrofuran (THF), pentan-2-ol and *N*-methylpyrrolidone (NMP). The reaction temperature was 140 °C, or the reaction was performed under reflux when the boiling point of the used solvent was lower than 140 °C.

The activity and the selectivity of catalyst were related by their acidity, basicity, morphology and presence of iron. Because of the fact that the tested catalysts differ in many factors, it is very difficult to find an exact impact of each factor.

The achieved conversions of α -pinene oxide over all tested iron and ceria modified catalysts are shown in Fig. 14. The total conversion of α -pinene oxide was obtained using three Fe modified

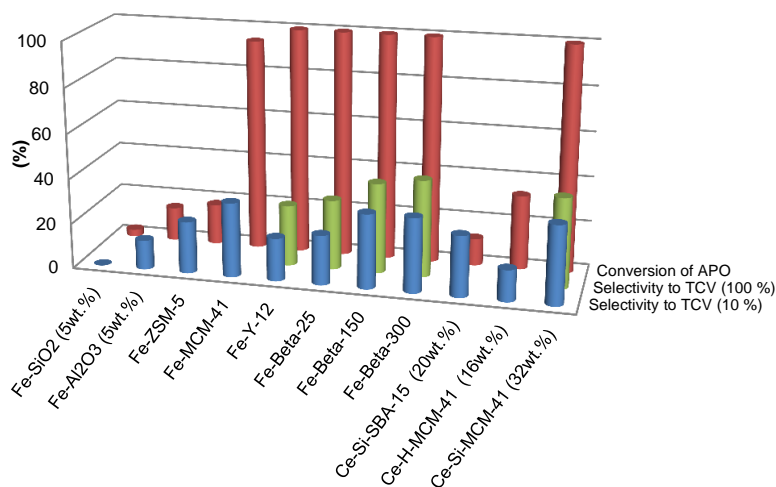


Fig. 14: The conversion of α -pinene oxide after 180 min at 140 °C in DMA and selectivity to *trans*-carveol at 10 % conversion (in case of Fe-SiO₂ at 3 % conversion) and at 100 % conversion

under the reaction conditions chosen for the preparation of *trans*-carveol. The highest selectivity to *trans*-carveol at low conversion level (10 %) was obtained over Fe-MCM-41, Fe-Beta-150, Fe-Beta-300 and Ce-Si-MCM-41 (32 wt.%) even if the selectivity was only around 33 %. The selectivity to the desired alcohol increased during the reaction being ca. 40 % at 100 % conversion of α -pinene oxide over these catalysts. An in-depth study focused on the influence of physico-chemical properties of catalysts on their activity and selectivity will be discussed below.

beta zeolites, Fe-Y-12 and 32 wt.% Ce-Si-MCM-41 within 180 min. Very high conversion (94 %) was achieved over Fe-MCM-41, the best evaluated catalyst in campholenic aldehyde preparation. On the other hand, iron supported on silica and alumina showed very low activity

3.2.1. Fe-supported catalysts [III]

3.2.1.1 Effect of structure of supports

The influence of support micro- and mesoporous structures on the activity and selectivity of the catalysts was investigated using zeolites (ZSM-5, Y-12, Beta-25, Beta-150 and Beta-300), mesoporous molecular sieve (MCM-41), silica and alumina.

High catalytic activity and total conversion of α -pinene oxide was achieved using iron supported on zeolites with exception of ZSM-5. As mentioned above (chapter 3.1), ZSM-5 is characterized by a small pore diameter and therefore it is not suitable for preparation of specialty chemicals with larger kinetic diameters such as α -pinene oxide. Therefore, isomerization reaction proceeds only on the external surface of ZSM-5 and not in its pores. Iron modified zeolites beta and zeolite Y-12 exhibited very high specific surface areas in the range 580 – 760 m²/g. 94 % conversion of α -pinene oxide was obtained over Fe-MCM-41 which is characterized by the highest surface area, amounting to 807 m²/g. On the contrary, silica and alumina, the least active catalysts are characterized by specific surface area below 400 m²/g. Therefore, it could be noted here, that surface area can partially affect the activity of the catalysts.

No specific influence of support morphology on selectivity to *trans*-carveol could be established.

3.2.1.2 Effect of Lewis and Brønsted acid sites of the catalysts

As discussed above, the acidity of catalysts influenced their activity in isomerization reactions and mainly the selectivity toward different products. It was concluded in chapter 3.1, that the presence of an adequate amount of Lewis acid and a relatively low concentration of Brønsted acid sites are beneficial in selective formation of campholenic aldehyde.

Concentrations of Brønsted and Lewis acid sites were determined by FTIR using pyridine as a probe molecule. The Brønsted acidity of iron modified catalysts is shown in Table 1. The catalysts with the lowest catalytic activity, namely iron supported on silica and alumina, are characterized by

Table 1: Brønsted acidity of Fe-modified catalysts

Catalysts	Brønsted acidity ($\mu\text{mol/g}$)		
	250 °C	350 °C	450 °C
Fe-SiO ₂	3	4	2
Fe-Al ₂ O ₃	11	12	6
Fe-MCM-41	22	8	0
Fe-Beta-300	90	57	0
Fe-ZSM-5	138	124	0
Fe-Beta-150	192	162	14
Fe-Y-12	216	128	15
Fe-Beta-25	272	214	3

a very low Brønsted acidity. On the other hand, the catalysts for which the complete conversion of α -pinene oxide was achieved (iron modified beta zeolites and Y-12), are characterized by the concentration of Brønsted acid sites above 90 $\mu\text{mol/g}$.

The conclusion from chapter 3.1.2 that the catalyst activity increases with an increasing amount of Brønsted acid sites, corresponds also with the results achieved in a study focused on the selective preparation of *trans*-carveol by α -pinene oxide isomerization over iron modified catalysts performed at 140 °C in *N,N*-dimethylacetamide as a solvent. This fact is clearly depicted in Figures 15 and 16 showing the increasing conversion of α -pinene oxide and initial reaction rates with increasing concentration of Brønsted acid sites. Fe-ZSM-5 catalyst is the only one exception. The reasons for its low activity have been already explained.

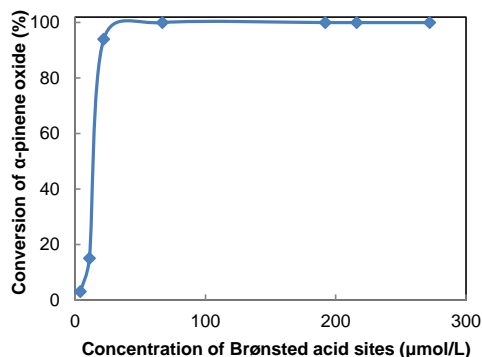


Fig. 15: The conversion of α -pinene oxide as the function of the concentration of Brønsted acid sites over iron modified catalysts except Fe-ZSM-5.

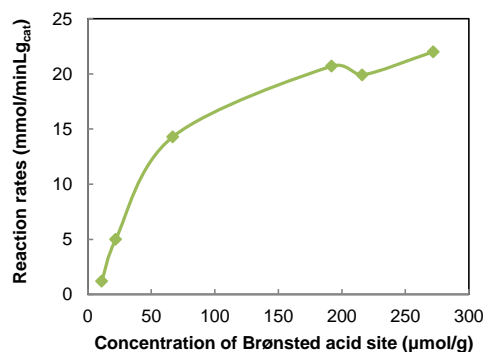


Fig. 16: The initial reaction rates of α -pinene oxide transformation as the function of the concentration of Brønsted acid sites over iron modified catalysts except Fe-ZSM-5.

On the other hand, it was concluded (in chapter 3.1.2) that an adequate amount of Lewis acidity is crucial for selective formation of campholenic aldehyde. The Lewis acidity of iron

Table 2: Lewis acidity of Fe-modified catalysts

Catalysts	Lewis acidity ($\mu\text{mol/g}$)		
	250 °C	350 °C	450 °C
Fe-SiO ₂	5	3	1
Fe-MCM-41	45	17	0
Fe-Y-12	57	5	5
Fe-Beta-300	67	16	0
Fe-ZSM-5	81	32	5
Fe-Beta-25	123	60	15
Fe-Al ₂ O ₃	140	62	12
Fe-Beta-150	165	45	2

(over 100 $\mu\text{mol/L}$).

The relationship between Lewis acidity of the tested catalysts and the selectivity to *trans*-carveol and other products were investigated. The selectivity to *trans*-carveol as a function of

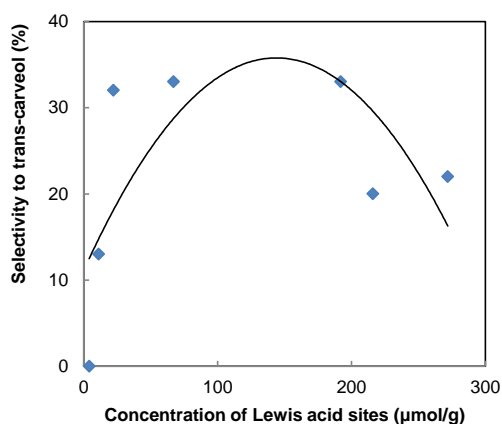


Fig. 17: The selectivity to *trans*-carveol at 10 % conversion of α -pinene oxide as the function of the concentration of Lewis acid sites over iron modified catalysts except Fe-ZSM-5

specific influence of Lewis acidity on the selectivity to *trans*-carveol.

3.2.1.3 Effect of presence of Fe on zeolites Beta [III]

As mentioned above, three beta zeolites with SiO₂/Al₂O₃ molar ratios 25, 150 and 300 were modified by iron and tested for selective *trans*-carveol preparation. The parent materials, proton

modified catalyst is shown in Table 2. Iron supported on silicate materials exhibited the lowest Lewis acidity. On the contrary, iron supported on zeolite Beta-25 and Beta-150 and on alumina are the catalysts with the highest concentration of Lewis acid sites

concentration of Lewis acid sites is showed in Fig. 17. The dependence of selectivity to *trans*-carveol on the amount of Lewis acid sites exhibits a maximum but no obvious trends were found. It might be that there is a range of Lewis acidity of catalysts which is optimal for preparation of *trans*-carveol with high selectivity. Since the catalysts differed in many other properties besides Lewis acidity, it is difficult to draw a clear conclusion about the

forms of beta zeolites, were also used for comparison. The activities and selectivity of the catalysts were correlated with their acid properties and iron content. The total conversion of α -pinene oxide was obtained using all 6 beta materials.

The initial reaction rates for proton forms of zeolites (Fig.18) were higher than for their iron

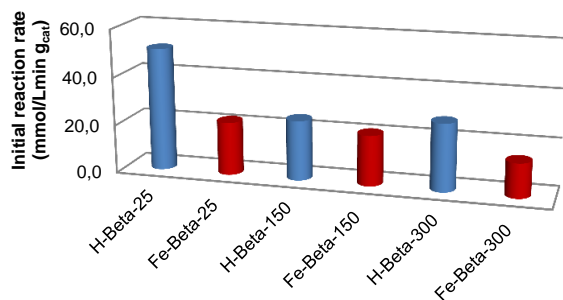


Fig. 18: The initial reaction rate of α -pinene oxide transformation over parent Beta materials and their iron modified forms

modified forms. The highest initial reaction rates were achieved using H-Beta-25 and using Fe-Beta-25, the catalysts with the highest Brønsted acidity. The initial reaction rate and activity of the Fe modified catalysts decreased with increasing $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio and decreasing Brønsted acidity.

The selectivity to *trans*-carveol at 25 % and 100 % conversion of α -pinene oxide over parent beta materials and their iron modified forms is depicted in Fig. 19. The highest selectivity to the

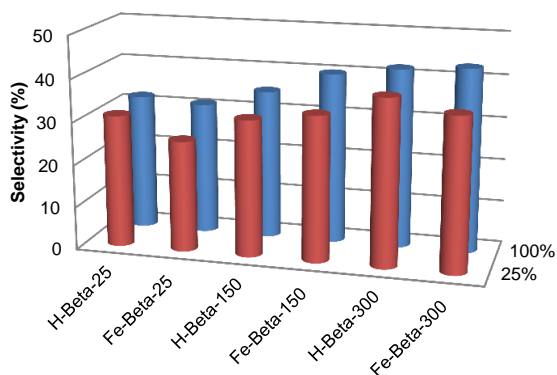


Fig. 19: The selectivity to *trans*-carveol over parent Beta materials and their iron modified forms at 25 % and 100 % conversion of α -pinene oxide

desired *trans*-carveol at moderate (25 %) and complete conversion of α -pinene oxide was obtained using H-Beta-300 and Fe-Beta-300, the catalysts with the lowest Brønsted and Lewis acidity. The selectivity to *trans*-carveol increases slightly during the reaction using all tested catalysts being an indication of a consecutive pathway in *trans*-carveol formation (see Fig. 13).

The selectivities to side products at total conversion of α -pinene oxide over parent beta materials and their iron modified forms are depicted in Fig. 20. Minor products are campholenic

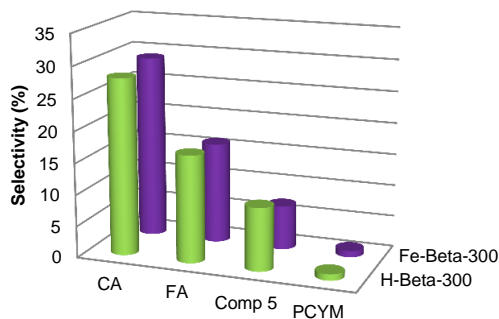
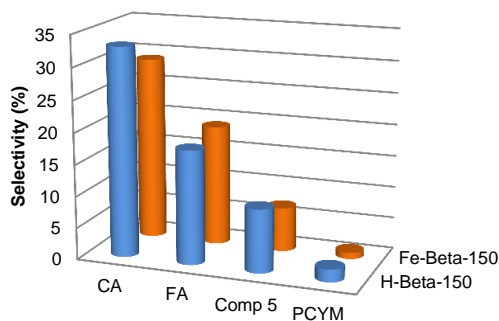
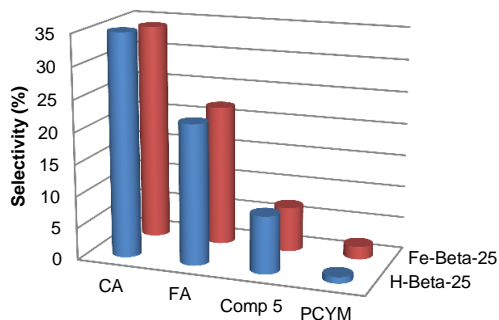


Fig. 20: The selectivity to campholenic aldehyde (CA), fencholenic aldehyde (FA), 2-methyl-5-(propan-2-ylidene)cyclohex-2-enol (Comp 5), and *p*-cymene (PCYM) over parent beta materials and their iron modified forms

and fencholenic aldehyde, 2-methyl-5-(propan-2-ylidene)cyclohex-2-enol and *p*-cymene. The highest selectivity to campholenic aldehyde was achieved using proton and iron modified forms of zeolite Beta-25. The selectivity to fencholenic aldehyde, an aldehyde with cyclopentane framework, increases with increasing alumina content in the case of parent zeolites and their Fe-modified forms. The formation of 2-methyl-5-(propan-2-ylidene)cyclohex-2-enol seems to be independent on the catalyst properties being 7 % using all Fe-modified catalysts and around 10 % with parent zeolites at the total conversion of α -pinene oxide. The transformation of *trans*-carveol and 2-methyl-5-(propan-2-ylidene)cyclohex-2-enol, products with *para*-menthene structure, to *p*-cymene is the same for all six tested catalysts. Other products, such as isopinocampnone and pinocarveol were present in the reaction mixture with selectivities around 1 % using proton and Fe-modified forms of beta-zeolites.

Monocyclic products of α -pinene oxide isomerization can be classified into two groups: compounds with 6-member carbon-ring (*trans*-carveol, 2-methyl-5-(propan-2-ylidene)cyclohex-2-

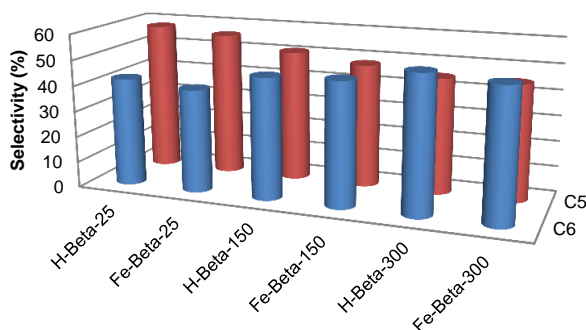


Fig. 21: The selectivity to C5 and C6 products over parent Beta materials and their iron modified forms

and C5 products, respectively, is obvious. The formation of C5 products increases with increasing alumina content. The ratio between the concentrations of *trans*-carveol and campholenic aldehyde increases during the reaction over three Fe-beta zeolites as well as over H-beta zeolites. The same trend was observed for the concentrations of the products with 6-member carbon-ring and 5-member carbon-ring. Such behaviour is another evidence that C5 products on one hand and C6 and bicyclic compounds on the other hand are formed in the parallel fashion, at the same time C6 products are generated through bicyclic compounds (see Fig. 13). This is consistent with a decrease in selectivity to isopinocampone and pinocarveol as the reaction proceeds.

3.2.1.4 Effect of solvent basicity

As mentioned above and reported in the literature, the reaction is strongly influenced by the basicity and the polarity of the solvent. A polar basic solvent is necessary to be used for the selective preparation of *trans*-carveol [15]. In this work, activity and selectivity of Fe-Beta-300 in *N,N*-dimethylacetamide (DMA) were compared with the results obtained in *N*-methylpyrrolidone (NMP). The latter was chosen because of its higher Lewis basicity according to the Kamlet-Taft scale (B_{KT}) [35]. The results of the catalytic experiments focused on testing of these solvents with Fe-

Beta-300 are shown in Fig. 22. Total conversion of α -pinene oxide was achieved using both solvents within 120 and 180 minutes from the beginning of the reaction using NMP and DMA, respectively. On the contrary, the initial reaction rate was higher using DMA. Therefore, the activity

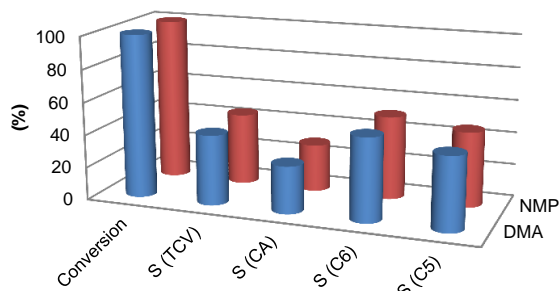


Fig. 22: The conversion of α -pinene oxide after 180 min and the selectivities to *trans*-carveol, campholenic aldehyde and C6 and C5 products over Fe-Beta-300 using two solvents, *N,N*-dimethylacetamide (DMA) and *N*-methylpyrrolidone (NMP)

of Fe-Beta-300 was comparable using both solvents. The basicity of the solvent should influence mainly the selectivity [15] but this trend was not clearly observed. Utilization of NMP slightly enhances selectivity to the desired *trans*-carveol as well as slightly

increases the formation of products with *para*-menthene structure. This fact showed that DMA exhibited

enough high basicity and hence it is useful for preparation of *trans*-carveol.

Experiments with the same catalyst at 70 °C in toluene gave *trans*-carveol and *p*-cymene in minor quantities at full conversion with predominant formation of campholenic and fencholenic aldehydes in almost equal amounts.

3.2.1.5 Influence of iron leaching and presence of homogeneous iron

The previous results on testing of heterogeneous catalysts for *trans*-carveol preparation discussed in the Introduction showed the problems with leaching of active components of supports under reaction conditions. The leaching of iron was thus studied in the present work. Iron loading was determined by EDX-microanalysis for catalysts Fe-Beta-150 after the isomerization to test if leaching of iron occurred during the reaction. Just a slight decrease of iron content (below 9 %) was observed in the spent Fe-Beta-150 (2.85 wt.% of iron) in comparison to the fresh one (3.1 % of

iron) indicating that iron was not significantly leached during isomerization of α -pinene oxide in *N,N*-dimethylacetamide at 140 °C during 3 h reaction time.

In order to study the reaction in the presence of trace amounts of a homogeneous catalyst, a few additional experiments were performed [III]. As a homogeneous catalyst $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ was tested in a typical experiment in *N,N*-dimethylacetamide at 140 °C. The amount of iron corresponded to about 9 wt. % leaching of iron from 3 wt.% Fe Beta-150. The achieved conversion of α -pinene oxide was about 5 % after 20 min under reaction conditions and obtained products were not the same as in the typical catalytic reaction discussed above. The results thus confirmed that contribution of homogenous catalysis by iron species was negligible.

3.2.2. Ce-supported catalysts [III]

Three different ceria modified ordered mesoporous silica materials, namely 32 wt.% Ce-Si-MCM-41, 16 wt.% Ce-H-MCM-41 and 20 wt.% Ce-Si-SBA-15, were also studied in *trans*-carveol preparation by α -pinene oxide isomerization performed under the same reaction condition (140 °C, in *N,N*-dimethylacetamide). The activities and selectivities of all catalysts were mainly correlated with acid and base properties of the catalysts as well as their structures. In addition, the influence of the basicity of the used solvents was studied.

3.2.2.1 Effect of structure of supports

The influence of support mesoporous structures on the activity and selectivity of ceria supported catalysts was investigated using Si-MCM-41, H-MCM-41 and SBA-15.

The morphology (shape and size) of the ceria modified catalysts was studied by scanning electron microscopy. The phases typical for MCM-41 material were observed in both cases. On the other hand, for 32 wt.% Ce-Si-MCM-41 sample also a morphologically non-typical phase for Si-MCM-41 was present. It is very probable that a high amount of ceria (32 wt.%) caused a partial collapse of the structure of Si-MCM-41. This partial distortion of the mesoporous phase also caused

lower specific surface area of 32 wt.% Ce-Si-MCM-41, amounting to 384 m²/g. High specific areas were determined for 16 wt. % Ce-H-MCM-41 and 20 wt. % Ce-Si-SBA-15 catalysts being 852 m²/g and 598 m²/g, respectively [III].

No influence of the support morphology on the activity and selectivity was observed because the highest catalyst activity was displayed by 32 wt.% Ce-Si-MCM-41, the material with a partially collapsed structure and the lowest surface area.

3.2.2.3 Effect of Lewis and Brønsted acid sites and of basicity of the catalysts

The amount of Brønsted and Lewis acid sites was determined by pyridine adsorption with FTIR (Table 3). The highest concentrations of Lewis and Brønsted acid sites were exhibited by Ce-Si-MCM-41 catalyst with the highest loading of ceria. The corresponding non-modified mesoporous material, Na-Si-MCM-41, displayed a quite low concentration of Lewis acid sites and no Brønsted acidity [III].

The amount of basic sites was measured by CO₂ desorption in [26,29] and reported in Table 3 as well. The highest basicity was measured for 16 wt.% Ce-H-MCM-41.

Table 3: Brønsted and Lewis acidity and amount of basic sites of Ce-modified catalysts

Catalysts	Brønsted acidity (μmol/g)			Lewis acidity (μmol/g)			Amount of basic sites (mmol/g _{cat}) [26, 29]
	250 °C	350 °C	450 °C	250 °C	350 °C	450 °C	
32 wt.% Ce-Si-MCM-41	80	49	10	67	12	9	2.5
16 wt.% Ce-H-MCM-41	52	9	1	31	3	0	16.3
20 wt.% Ce-Si-SBA-15	17	1	1	50	17	6	4.4

The acidity of the catalysts significantly influenced their activity. The highest initial reaction rate within 10 min from the beginning of the reaction (Figure 23) was achieved using Ce-Si-MCM-41 (32 wt.%). This catalyst is characterized by the highest loading of ceria and the highest amount of Lewis and Brønsted acid sites. Furthermore, this catalyst was the least basic of all the

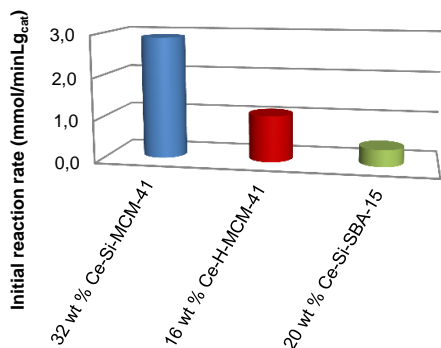


Fig. 23: The initial reaction rates of α -pinene oxide transformation over ceria-supported catalysts

The total conversion of α -pinene oxide was achieved using 32 wt.% Ce-Si-MCM-41 catalyst within 3 h from the beginning of the reaction. As a comparison 98 % conversion of α -pinene oxide was achieved in 8 h over Ce/SiO₂ in [14]. Low conversions of α -pinene oxide were obtained using two other less acidic catalysts, 16 wt.% Ce-H-MCM-41 and 20 wt.% Ce-Si-SBA-15 being 33 % and only 12 %, respectively, after 3 h of reaction.

The conversion of α -pinene oxide as a function of concentration of Brønsted acid sites is

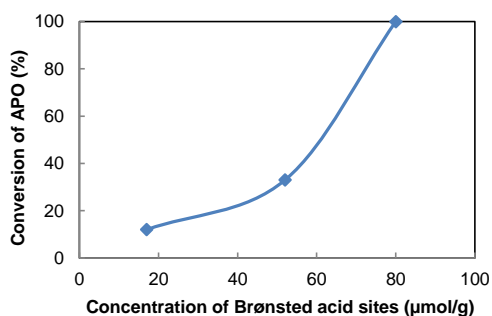


Fig. 24: The conversion of α -pinene oxide after 180 min as the function of the concentration of Brønsted acid sites over ceria modified catalysts

depicted in Fig. 24. Thus, it can be concluded that the activity of the catalyst decreases by decreasing the amount of Brønsted acid sites. This conclusion corresponds to the one from a study focused on the selective preparation of *trans*-carveol over iron modified catalysts under the same reaction condition (see chapter 3.2.1.2.).

Selectivity to *trans*-carveol and to campholenic aldehyde seems to be also influenced by the acid properties of the catalysts. The selectivity to these products is depicted in Fig. 25. The lowest selectivity to *trans*-carveol was seen for 16 wt.% Ce-H-MCM-41, the catalyst exhibiting the lowest

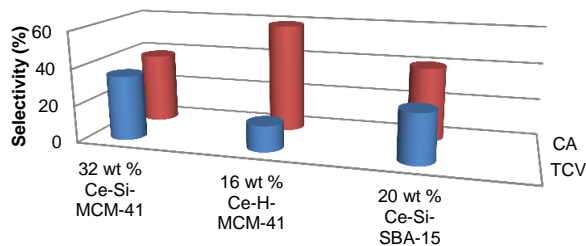


Fig. 25: The selectivity TCV and CA at 10 % conversion of α -pinene oxide of ceria modified catalysts

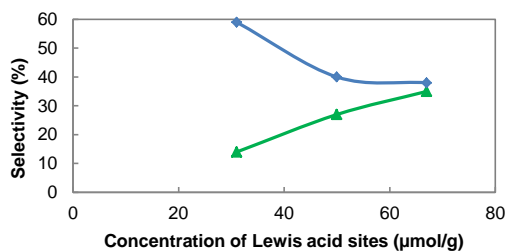


Fig. 26: The selectivity to TCV (green) and to CA (blue) at 10 % conversion of α -pinene oxide as the function of the concentration of Lewis acid sites of ceria modified catalysts

unexpected result because just homogeneous Lewis acids are the ordinary catalysts for campholenic aldehyde synthesis from the epoxide. High selectivity to *trans*-carveol, about 73 % was reported over Ce/SiO₂ in *N,N*-dimethylacetamide as a solvent at 140 °C in [14], but neither catalyst acidity nor basicity were reported in [14].

Furthermore, the selectivity towards campholenic aldehyde increased with increasing basicity of the catalyst, whereas an opposite trend was observed for the selective formation of *trans*-carveol,

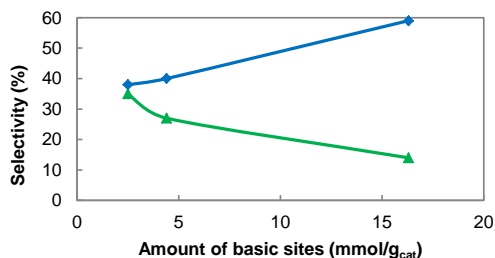


Fig. 27: The selectivity to TCV (green) and to CA (blue) at 10 % conversion of α -pinene oxide as the function of the amount of basic sites of ceria modified catalysts

amount of Lewis acid sites. The highest selectivity to this desired alcohol was achieved using 32 wt.% Ce-Si-MCM-41 with the highest amount of Lewis acid sites and with the lowest basicity. The selectivity to *trans*-carveol and campholenic aldehyde as a function of Lewis acidity is shown in Fig. 26. By decreasing the amount of Lewis acid sites, the selectivity to *trans*-carveol decreased and at the same time the selectivity to campholenic aldehyde increased. It is an unexpected result because just homogeneous Lewis acids are the ordinary catalysts for campholenic aldehyde synthesis from the epoxide. High selectivity to *trans*-carveol, about 73 % was reported over Ce/SiO₂ in *N,N*-dimethylacetamide as a solvent at 140 °C in [14], but neither catalyst acidity nor basicity were reported in [14].

Furthermore, the selectivity towards campholenic aldehyde increased with increasing basicity of the catalyst, whereas an opposite trend was observed for the selective formation of *trans*-carveol, for which the highest selectivity was achieved with the least basic catalyst, 32 wt.% Ce-Si-MCM-41. This trend is obvious in Fig. 27, showing the selectivity to *trans*-carveol and campholenic aldehyde as a function of the amount of basic sites.

3.2.2.4 Effect of solvent basicity

The effect of basicity of used solvents was studied over ceria modified catalysts. Activity and selectivity of 32 wt.% Ce-Si-MCM-41 was evaluated in the following solvents: acetonitrile, tetrahydrofuran (THF), pentan-2-ol and *N*-methylpyrrolidone (NMP) besides *N,N*-dimethylacetamide (DMA). The reaction temperature was 140 °C when DMA and NMP were tested. The reactions with other solvents were performed under reflux because of solvent boiling points below 140 °C. Therefore the reaction was performed at 66 °C with THF, at 82 °C with acetonitrile and at 119 °C with pentan-2-ol.

A comparison of solvent basicity is shown in Table 4. The Lewis basicity of the solvents was measured and evaluated using various methods and equations [35, 36]. The solvent Lewis basicity with a particular consideration and an extension of the Kamlet-Taft scale (B_{KT}) was reported in [35]. B_{KT} values for 70 solvents were measured and additionally combined in [36].

Table 4. Basicity characteristics of solvents according [35,36].

Solvent	Reported B_{KT} values	
	[35]	[36]
Toluene	–	0.00
Acetonitrile	–	0.23
Tetrahydrofuran	0.55	0.47
<i>n</i>-Pentanol	–	0.72
<i>N,N</i>-dimethylacetamide	0.73	–
<i>N</i>-methylpyrrolidone	0.75	–

Note: No data available for pentan-2-ol.

The effect of solvents basicity on the catalysts activity and selectivity to the desired *trans*-carveol was investigated. The achieved conversion of α -pinene oxide during the catalytic experiments focused on testing of the chosen solvents with 32 wt.% Ce-Si-MCM-41 is shown in Fig. 28. The total conversion of α -pinene oxide was achieved using *N*-methylpyrrolidone within 30 min as well as using *N,N*-dimethylacetamide as a solvent within 180 min. The conversion

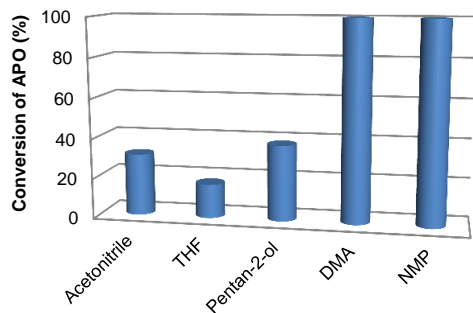


Fig. 28: The conversion of α -pinene oxide after 180 min over 32 wt.% Ce-Si-MCM-41 using different solvents

The selectivity to the desired *trans*-carveol and the side product campholenic aldehyde in the tested solvents is depicted in Fig. 29. The highest selectivity to the desired alcohol was achieved by

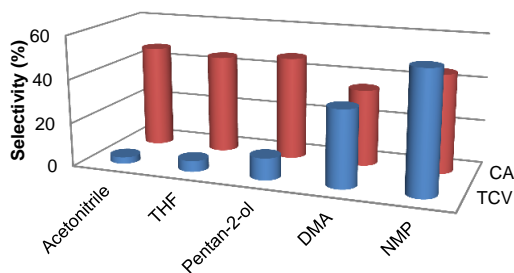


Fig. 29: The selectivities to *trans*-carveol (TCV) and campholenic aldehyde (CA) over 32 wt.% Ce-Si-MCM-41 using different solvents.

using *N*-methylpyrrolidone being 55 % at 10 % conversion of α -pinene oxide and 46 % at the total conversion of α -pinene oxide. The selectivity to *trans*-carveol was 41 % at complete conversion of α -pinene oxide in *N,N*-dimethylacetamide. The selectivity to *trans*-carveol increased with increasing basicity of the solvent, at the same time the selectivity to campholenic aldehyde decreased. The same trend was observed in the formation of C6 (6-member carbon-ring products: *trans*-carveol and 2-methyl-5-(propan-2-ylidene)cyclohex-2-enol) and C5 (5-member carbon-ring products: campholenic aldehyde and fencholenic aldehyde) products [III]. The highest selectivity towards formation of *trans*-carveol in the present study is maximally 46 % at the complete conversion of α -pinene in *N*-methylpyrrolidone. It has been reported in [7] that 73 % selectivity at 98 % conversion towards *trans*-carveol was obtained in *N,N*-dimethylacetamide as a solvent at 140 °C over Ce/SiO₂ catalyst, when ceria was prepared using

increased with increasing solvent basicity except tetrahydrofuran. A lower conversion of α -pinene oxide using tetrahydrofuran was obtained, in comparison with acetonitrile, less basic solvent. This fact can be explained by lower reaction temperature (66 °C) for THF, which could cause lower activity of the tested catalyst.

CeCl_3 as a precursor. It should, however, be pointed out here, that the results from [7] did not correlate with acidity or basicity of the utilized catalysts.

3.3. Selective verbenol oxide isomerization [IV]

Two catalysts, which have been regarded as the most suitable for *trans*-carveol preparation by α -pinene oxide transformation [II, III], namely Fe-Beta-300 and 32 wt.% Ce-Si-MCM-41, were tested in verbenol oxide isomerization. The reaction conditions for verbenol oxide isomerization were selected by analogy to α -pinene oxide isomerization. The isomerization of verbenol oxide (synthesized at the Vorozhtsov Novosibirsk Institute of Organic Chemistry, with a purity of 98.5 %) over the Fe- and Ce-modified catalysts was carried out in *N,N*-dimethylacetamide at 140 °C.

The desired product of verbenol oxide isomerization was 3-methyl-6-(prop-1-en-2-yl)cyclohex-3-ene-1,2-diol (**1**), diol which is a potent anti-Parkinson drug. Minor often encountered products were compounds with cyclopentane framework: 1-(2,2,3-trimethylcyclopent-3-enyl)-2-hydroxyethanone (**2**) and 2-(2,2,4-trimethylcyclopent-3-enyl)-2-hydroxypropanal (see Fig. 2).

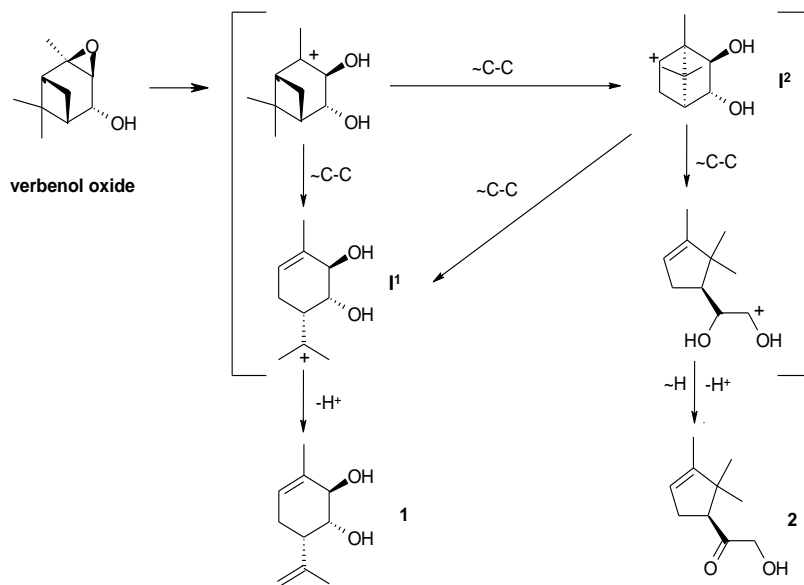


Fig. 30: Reaction mechanism of (-)-*cis*-verbenol oxide isomerization based on [20].

The reaction mechanism based on the concepts advanced in [20] was also studied and modified in order to understand the formation of major and minor encountered products (Fig. 30). Two routes of diol (**1**) formation can be proposed, going through two intermediates **I**¹ and **I**².

The activities and selectivities of both catalysts were mainly correlated with acid properties of the catalysts as well as their structures.

The kinetic results obtained using Fe- Beta-300 and Ce-Si-MCM-41 catalysts are shown in Fig. 31. A higher conversion of verbenol oxide was achieved over Fe-Beta-300 catalyst being 96 %

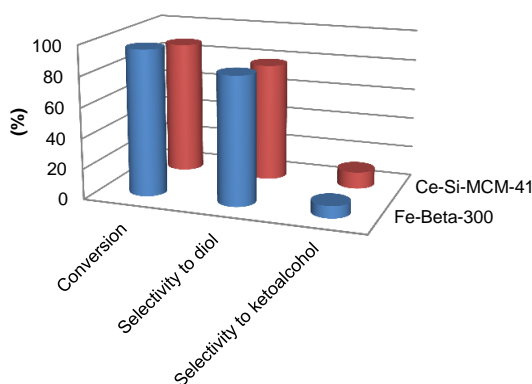


Fig. 31: The conversion of verbenol oxide after 7 h and selectivities to desired diol and side product ketoalcohol over tested catalysts

after 7 h with 84 % selectivity, which was very high compared to the selectivity (up to 65 %) obtained at 25 °C using montmorillonite clays as a catalyst in dichloromethane [21]. Higher selectivity to the desired diol (**1**) was observed in the case of Fe-Beta-300. Obviously a high quantity of weak and medium acid sites favours preferable diol (**1**) formation. For both catalysts the selectivity to diol (**1**) increased

with conversion. The formation of the by-product, ketoalcohol (**2**) with cyclopentane framework, is more prominent with Ce-Si-MCM-41 catalyst. This fact could be explained by the presence of strong Brønsted as well as Lewis acid sites in this catalyst and it will be further discussed.

Linear formation of the desired diol (**1**) was observed after 10 min from the beginning of the reaction. On the other hand, ketoalcohol (**2**) is formed mainly in the beginning of the reaction but its formation stops at 20 % conversion of verbenol oxide (60 min) at a yield level of ca. 8 %.

3.3.1. Possibilities of catalyst reuse and regeneration

A possibility of reusing and regenerating the catalyst Fe-Beta-300 was further investigated.

The specific surface area and micropore volume of the fresh Fe-Beta-300 as well as of the spent and the regenerated catalysts were measured. The surface area of the regenerated catalyst is comparable to the fresh one being $771 \text{ m}^2/\text{g}$ and $761 \text{ m}^2/\text{g}$, respectively. The specific surface area and micropore volume decreased in the case of the reused catalyst (for spent catalyst the surface area was $493 \text{ m}^2/\text{g}$) which may be caused by a partial blockage of the pores by coke during the reaction. The same trend was observed for the micropore volume: $0.27 \text{ cm}^3/\text{g}$ for the fresh Fe-Beta-300, $0.27 \text{ cm}^3/\text{g}$ for the regenerated catalyst and $0.18 \text{ cm}^3/\text{g}$ for the spent catalyst.

The conversion of verbenol oxide and selectivities to the two main products over the fresh Fe-Beta-300 was compared with the regenerated and with reused catalysts and are depicted in Fig.

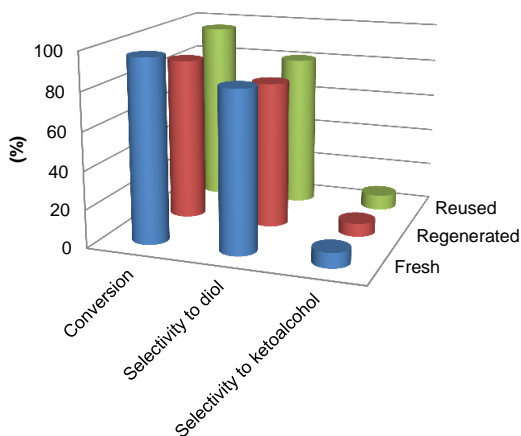


Fig. 32: The conversion of verbenol oxide after 7 h and selectivities to desired diol and side product ketoalcohol over fresh, regenerated and reused Fe-Beta.

32. The activity of the reused Fe-Beta-300 is almost the same as for the fresh one. The selectivity to the desired diol (1) decreases marginally during the reuse from 84 % to 81 %. A decrease of activity and selectivity was observed for the regenerated catalyst (86 % conversion of verbenol oxide and 77 % selectivity to diol (1) after 7 h over regenerated Fe-Beta-300).

The activity decrease of the regenerated catalyst can be caused by the “deprotection” of acidic centres responsible for the reaction.

4. CONCLUSIONS

Iron and ceria catalysts were utilized for isomerization of α -pinene oxide resulting in campholenic aldehyde and *trans*-carveol and for isomerization of verbenol oxide generating 3-methyl-6-(prop-1-en-2-yl)cyclohex-3-ene-1,2-diol.

The first aim of the research focused on α -pinene oxide transformations and targeted selective preparation of campholenic aldehyde. Bi-functional catalysts exhibiting both Lewis and Brønsted acidity and different structures Beta-150 and ZSM-5 zeolites, MCM-41 mesoporous material modified with Fe using solid state ion-exchange method were studied in this reaction. Comparative experiments with Fe-SiO₂ and Fe-Al₂O₃ catalysts were also performed to study the influence of the support in α -pinene oxide isomerization. The aim was to elucidate the nature of active sites, effect of acidity, support and the catalyst structure.

Isomerization of α -pinene oxide at 70 °C using toluene as a solvent shows that the main parameters influencing the activity and selectivity to campholenic aldehyde are the amount and type of Brønsted and Lewis acid sites, content of Fe, type of the support and structural properties of the catalysts. The total conversion of α -pinene oxide was achieved using materials with ordered mesoporous and microporous structures Fe-MCM-41 and Fe-Beta-150. The highest activity was exhibited by Fe-Beta-150, the catalyst with the highest concentration of Lewis and Brønsted acid sites. On the other hand, the lowest selectivity to campholenic aldehyde was displayed using this highly acidic catalyst. During α -pinene oxide isomerization, aside from campholenic aldehyde also fencholenic aldehyde, *trans*-carveol, isopinocampone, pinocarveol and *p*-cymene were formed. The highest selectivity to the desired campholenic aldehyde at a total conversion of α -pinene oxide was obtained over Fe-MCM-41, amounting to 66 %.

Furthermore, Fe-MCM-41, as the most active and selective catalyst, was tested for its possible regeneration and reuse. The activity obtained for the fresh Fe-MCM-41 was comparable to the one of the regenerated catalyst. The selectivity to campholenic aldehyde did not change with catalyst deactivation.

Conclusions

Selective preparation of *trans*-carveol by α -pinene oxide isomerization was the second aim of the research focused on α -pinene oxide isomerization. Preparation of *trans*-carveol was evaluated in the presence of iron and cerium modified catalysts. Reaction selectivity is strongly influenced by basicity and polarity of the solvent. In particular, polar basic solvents should be used for the selective preparation of *trans*-carveol. Therefore, a polar solvent, *N,N*-dimethylacetamide, was used in *trans*-carveol preparation carried out at 140 °C.

The investigation was focused on the testing of iron modified catalysts which were previously applied in selective campholenic aldehyde formation but under different reaction conditions. Besides iron supported on silica, alumina, ZSM-5, Beta-150 and MCM-41, also iron supported on zeolites Y-12, Beta-25 and Beta 300 was tested. In addition, zeolites beta *per se* with different SiO₂/Al₂O₃ molar ratio were investigated for *trans*-carveol preparation from α -pinene oxide. Based on the data from the literature, ceria supported on mesoporous materials MCM-41 and SBA-15 was prepared in the current study, namely Ce-Si-MCM-41 (32 wt.%), Ce-H-MCM-41 (16 wt.%) and Ce-Si-SBA-15 (20 wt.%).

The total conversion of α -pinene oxide was obtained using three iron modified beta materials, iron modified zeolite Y-12 and ceria modified MCM-41 (32 wt.%) within 180 min from the beginning of the reaction. Very high conversion (94 %) was achieved also over Fe-MCM-41, the most active and selective catalyst in campholenic aldehyde preparation. The highest selectivities to *trans*-carveol at a low conversion level (10 %) were obtained over Fe-MCM-41, Fe-Beta-150, Fe-Beta-300 and Ce-Si-MCM-41 (32 wt.%) but the selectivities were only around 33 %. The selectivity to the desired alcohol increased during the reaction and it was around 40 % at 100 % conversion of α -pinene oxide.

The last part of the research was focused on isomerization of verbenol oxide. The desired product of this isomerization reaction is 3-methyl-6-(prop-1-en-2-yl)cyclohex-3-ene-1,2-diol, which possesses a potent anti-Parkinson activity.

Two catalysts that had been evaluated as the most active and selective in the preparation of *trans*-carveol, namely Fe-Beta-300 and Ce-Si-MCM-41, were studied in verbenol oxide isomerization performed at 140 °C in *N,N*-dimethylacetamide as a solvent.

The highest conversion of verbenol oxide was achieved over Fe-Beta-300 catalyst, amounting to 96 % after 7 h with 84 % selectivity to the desired diol.

A possibility to reuse and regenerate the Fe-Beta-300 catalyst was also tested. The activity of reused Fe-Beta-300 was almost the same as for the fresh Fe-Beta-300. The selectivity to the desired diol decreased marginally during the reuse from 84 % to 81 %. A decrease of activity and selectivity was observed for the regenerated catalyst (86 % conversion of verbenol oxide and 77 % selectivity to the desired diol after 7 h over regenerated Fe-Beta-300).

The results obtained and discussed in the thesis have contributed to expanding the current knowledge on the isomerization of oxygenated terpenes and on the application of different types of heterogeneous catalysts in this type of reactions.

There are many possibilities for further studies and some topics such as selective synthesis of *trans*-carveol over heterogeneous catalysts still remain a very challenging task.

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