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Cyclisation of citronellal over zirconium zeolite beta—a highly diastereoselective catalyst to (±)-isopulegol

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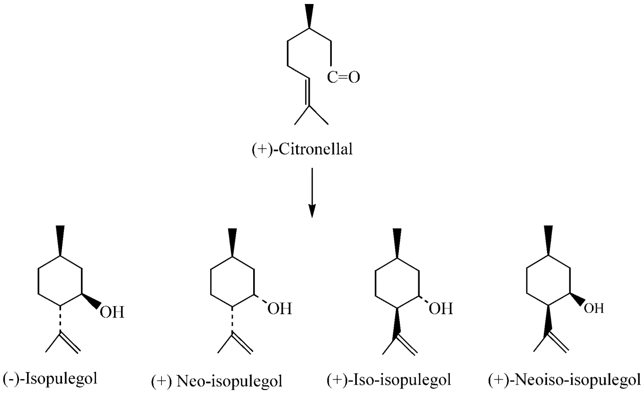
Abstract

The catalytic cyclisation of citronellal was studied over Zr-zeolite beta, micro/mesoporous Al-MSU-S_{FAU}, and microporous HY catalysts. All samples showed good activity in the cyclisation of citronellal to form isopulegols with $> 97\%$ selectivity. A high diastereoselectivity for (±)-isopulegol of $\sim 93\%$ was observed over Zr-zeolite beta, whereas Al-MSU-S_{FAU} and HY showed a lower selectivity of $\sim 65\%$. Zr-zeolite beta was synthesised in a range of Si/Zr of 75–200 with the use of fluoride and zeolite beta seeds. Zeolite beta with Al and Ti substitution was less active and selective than Zr-zeolite beta. The rate of reaction strongly depended on the type of solvent used, but the reaction could also be carried out without any solvent. A hydroxylated surface is important for good activity. This is consistent with the proposed mechanism, where both Lewis and Brønsted acid sites are essential for the reaction.

Keywords: Zr-zeolite beta; Fluoride-assisted synthesis; Al-MSU-S_{FAU}; Diastereomers; (±)-Isopulegol; Solvent effect

1. Introduction

Citronellal can be cyclised to form isopulegol, which is an intermediate in the synthesis of menthols. All three chemicals are used in the fragrance industry [1]. Because of the presence of three asymmetrical centers, there are actually four stereoisomers of isopulegol, each of which occurs as a pair of enantiomers: (±)-isopulegol, (±)-neo-isopulegol, (±)-iso-isopulegol, and (±)-neoiso-isopulegol (Scheme 1). Hydrogenation of these isopulegols leads to four pairs of enantiomers: (±)-menthol, (±)-neomenthol, (±)-isomenthol, and (±)-neoisomenthol. Of these, the most useful isomer is (−)-menthol, which has a peppermint odour and exerts a cooling effect. The latter property is peculiar to this isomer, as none of the other isomers possesses this "refreshing" property. The cyclisation of citronellal proceeds readily over various homogeneous and heterogeneous catalysts. Scandium trifluoromethanesulfonate [2]; Lewis acids like $ZnCl_2$, $ZnBr_2$, and ZnI_2 [3]; and molybdenum and tungsten complexes [4] were reported to be active in the reaction. In particular, zinc bromide shows a high selectivity



Scheme 1. Cyclisation of (+)-citronellal to isopulegol isomers.

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for (−)-isopulegol, 94%, and is used industrially. A recent patent by Takasago International Corporation [5] reports that using a substituted tris(2,6-diarylphenoxy)aluminium catalyst gave close to 100% selectivity for isopulegol. However, the use of homogeneous catalyst requires extensive workup, and hence the catalyst frequently cannot be recovered and reused. A number of heterogeneous catalysts have also been found to be active, including metallic Cu–Cr; zeolite beta; MCM-41; HY; mordenite; MCM-22; alumina; mixed oxides of SiO_2–TiO_2, SiO_2–ZrO_2, and SiO_2–Al_2O_3 with and without copper; sulfated zirconia; and metal cation-exchanged montmorillonites [6–10]. The activity over zeolites such as clinoptilolite, mordenite, and faujasite was shown to be related to the total number of Brønsted acid sites [11]. Generally, over heterogeneous catalysts, all four isopulegol isomers are formed and the diastereoselectivity for (±)-isopulegol, 52–75%, is lower than for homogeneous catalysts. An exception to these results was reported by Arata and Matsuura for SiO_2–Al_2O_3, $FeSO_4$, $NiSO_4$, $Zr(SO_4)_2$, and alumina, in which the selectivity for isopulegol was higher than 91% [12]. However, it is not clear from the report whether selectivity is for all of the isopulegol isomers or only for (±)-isopulegol. A recent report by Corma and Renz [13] showed that Sn-beta zeolite catalyses the cyclisation of citronellal in acetonitrile with a high diastereoselectivity for (±)-isopulegol of 85%. However, in other solvents such as dioxane, *tert*-butanol, and nitromethane, the diastereoselectivity was only between 78 and 82%. In the absence of any solvent, the conversion was lower and the diastereoselectivity was only $\sim 72\%$.

We have synthesised aluminum-free Zr-zeolite beta and found that it is a very good catalyst for the Meerwein–Ponndorf–Verley (MPV) reduction of ketones and aldehydes [14]. Because of the microporous channels of zeolite beta, shape selectivity was manifested in the stereoselectivity of the products. We have also found that hydrous zirconia showed very good activity and selectivity in the reaction [15]. Phosphated zirconia formed by phosphating of the hydroxides was also highly active, with a selectivity for cyclisation of $> 99\%$. The diastereoselectivity for (±)-isopulegol was 68–72%. In a study of a number of catalysts, using ammonia TPD and pyridine IR spectroscopy, we showed that all catalytically active samples contained a combination of strong Lewis and weak Brønsted acidity. In view of the good activity of zirconium and the high diastereoselectivity observed over Sn-zeolite beta [13], we evaluated Zr-zeolite beta as a catalyst for the cyclisation of citronellal. For comparison, larger-pored materials like mesostructured Al-MSU-S_{FAU} and HY were also tested as catalysts. The former sample is made via the use of nanoclustered zeolite Y seeds as framework precursors [16,17]. With the addition of a micellar template, the zeolite seeds assemble into an ordered mesostructure around the templating structure. In these materials, the channels have mesoporous dimensions, whereas the walls have microporosity.

2. Experimental

2.1. Preparation and characterisation

The synthesis of aluminium-free Zr-zeolite beta has been described in [14]. The catalyst was prepared in a fluoride-assisted hydrothermal synthesis with the addition of seeds from dealuminated zeolite beta, similar to the procedure described by Corma et al. [18] for the preparation of Al-free Sn-beta. Typically, tetraethylorthosilicate (TEOS) was hydrolysed in a solution of tetraethylammonium hydroxide (TEAOH) with stirring. A solution of $ZrOCl_2 \cdot 8H_2O$ in water was added, and the mixture was stirred until all ethanol formed by hydrolysis of the TEOS was evaporated. Hydrogen fluoride and an aqueous suspension of seeds of dealuminated nanocrystalline zeolite beta (ca. 50 nm diameter as determined by TEM) were added. Samples with a Si/Zr ratio of 50–200 were prepared. The final gel had the composition 1 SiO_2:0.005–0.02 ZrO_2:0.56 TEAOH: 0.56 HF:7.5 H_2O. Crystallisation was carried out in a static Teflon-lined stainless-steel autoclave at 140–170 °C for 5–30 days. The longer crystallisation times were necessary for higher zirconium substitution. The solid product obtained was filtered, washed with deionised water, dried at 100 °C, and activated at 580 °C for 4 h. The samples are designated Zr-beta-n, where $n =$ Si/Zr ratio of 75, 100, 150, or 200. For comparison, the synthesis of Zr-beta was attempted without the use of seeds. These samples are designated Zr-beta-nWS, where $n =$ Si/Zr ratio of 75, 100, or 200 and WS stands for “without seeds.” The Si/Zr ratios in the calcined samples were determined by ICP after dissolution of the samples. In addition to Zr-zeolite beta, Sn-beta (Si/Sn $\approx$ 125) zeolite was synthesised in a way similar to the synthesis of Al-free Zr-beta, with $SnCl_4 \cdot 5H_2O$ (Merck, 99%) as the tin source. Ti-beta (Si/Ti $\approx$ 100) was prepared with the use of titanium ethoxide, following the procedure described by Blasco et al. [19].

A sample of ion-exchanged Zr-zeolite beta was also prepared by stirring, at room temperature, 50 ml of 0.5 M zirconium chloride solution with 1.0 g of Al-zeolite beta (Zeolyst, Si/Al 12.5) overnight. After drying at 100 °C, the sample, IE-Zr-beta, was calcined at 300 °C for 3 h, with a slow heating rate of 1 °C/min.

HY15 (Si/Al 15) was obtained from Zeolyst. Al-MSU-S_{FAU} with Si/Al 9, 35, 50, or 70 was prepared following Ref. [20]. An alumino-silicate gel was formed by dissolving NaOH, $NaAlO_2$, and sodium silicate solution in water. This gel was stirred at room temperature for 1 h and then heated under reflux with moderate stirring at 100 °C overnight to form the zeolite Y seed solution. The seed solution was added to a solution of cetyltrimethyl ammonium bromide (CTAB) template at room temperature, and the pH was lowered to about pH 9 with the addition of dilute sulfuric acid. The final gel composition can be represented as 0.09 NaOH:0.90 Na_2SiO_3:x $NaAlO_2$: 0.20 CTAB:0.65 H_2SO_4:100 H_2O. $x = 0.0128$–0.1. The final gels were aged for 1 h at room temperature and then heated at 100 °C for 48 h in a Teflon-lined autoclave under static conditions. The samples were calcined at 540 °C for 12 h to remove the template, ion exchanged with NH_4NO_3 solution, and recalcined to obtain the H^+ form.

The surface area and pore volumes were measured by nitrogen adsorption (Micromeritics Tristar). The samples were dried at 300 °C prior to measurement. The crystal phase was determined with a Siemens D5005 powder X-ray diffractometer equipped with a Cu anode and variable primary and secondary beam slits. Infrared adsorption spectroscopy of pyridine adsorbed to the samples was used to determine the type of acid sites present on the samples. Self-supporting wafers (8–10 mg) were mounted in an evacuable Pyrex IR cell with NaCl windows. After the sample was degassed at 300 °C in vacuum (10^{-3} mbar) for 2 h, the sample was cooled to room temperature, and pyridine at 22 mbar was introduced into the cell. The cell was again evacuated for another hour before an IR measurement was made. A Bio-Rad FTS 165 FT-IR spectrometer with a resolution of 2 cm^{-1} was used. Further measurements were made after the sample had been heated at 100 and 200 °C for 1 h at each temperature.

2.2. Catalytic testing

Racemic citronellal (Fluka) was used as received. It contained $\sim$ 94% citronellal together with 6% isopulegol. The reaction mixture, containing 0.62 g (4 mmol) of citronellal, 5 g of solvent, and 0.2 ml of nitrobenzene (internal standard), was placed in a round-bottomed flask equipped with a septum port, a reflux condenser, and a guard tube. For preparative synthesis, the batch was scaled up by a factor of 5, with the use of 3.1 g (20 mmol) of citronellal with or without 5 g of solvent. The mixture was heated to reaction temperature, following which 50 mg of catalyst was added. The reaction was carried out with stirring, typically at 80 °C, although lower temperatures were also studied. Samples were removed at different reaction times, and the products were analysed by gas chromatography (HP5 capillary column, FID). The products were identified by GC-MS, and the different isomers were confirmed with ^{1}H NMR (Bruker AMX 500). The overall selectivity is defined as the sum of all isopulegol isomers divided by the sum of all products formed (isopulegol isomers and etherification products of isopulegols). The diastereoselectivity is the selectivity for (±)-isopulegol with respect to all four isopulegol isomers.

3. Results

3.1. Synthesis and properties of Zr-zeolite beta

To study the effect of zirconium on the formation of Zr-zeolite beta in a fluoride medium, the crystallisation kinetics was determined for an initial Si/Zr ratio from 200 to 50. Fig. 1 shows that a longer crystallisation time is needed to obtain Zr-zeolite beta when the Si/Zr ratio in the synthesis mixture is decreased. The "induction period" or time before any crystallinity is observed increased as the Si/Zr ratio decreased. A similar dependence of the crystallisation time on the metal content is observed for Al-zeolite beta, whether it is synthesised in basic medium without alkali metals [21] or in fluoride medium [22].

From powder X-ray diffractometry, it is found that with the use of zeolite beta seeds, zirconium could be successfully incorporated into zeolite beta up to 2.4 wt% Zr (Si/Zr 75). The diffraction peaks were well developed and of high intensity, indicating the crystalline state of the samples. Only the zeolite beta phase was present, with no other competing phases detected (Fig. 2). Taking the peak intensity at 22.3° of 580 °C-calcined Zr-beta-200 as reference with 100% crystallinity, we made a comparison of the crystallinity of higher

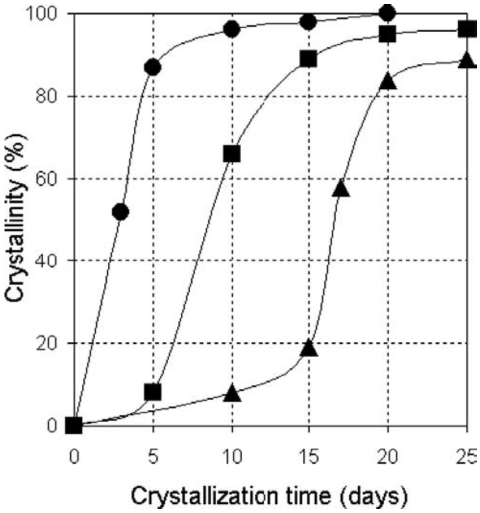


Fig. 1. Influence of Si/Zr ratio on the synthesis of Zr-beta. (●) Si/Zr = 200, (■) Si/Zr = 100, and (▲) Si/Zr = 75.

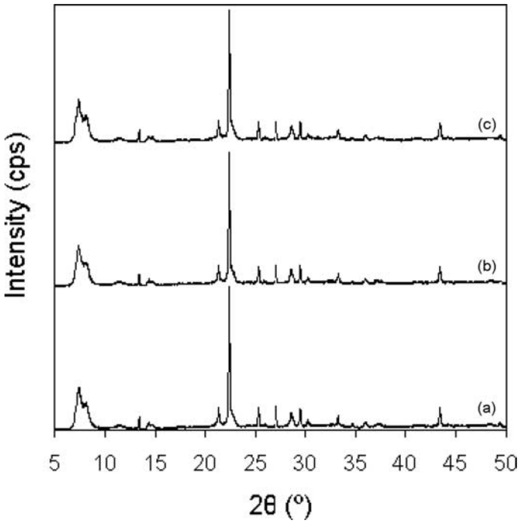


Fig. 2. X-ray diffraction patterns of Zr-beta-100 calcined at: (a) 580, (b) 750, and (c) 900 °C.

Table 1
Synthesis of Zr-zeolite beta in fluoride medium

Sample	Seeding[a] (wt%)	Time (days)	Temperature (°C)	Yield[b] (%)	Crystallinity (%)	Si/Zr molar ratio Gel	Si/Zr molar ratio product
Zr-beta-200	3.5	20	140	96	100[c]	200	194
Zr-beta-150	3.5	20	140	97	98	150	155
Zr-beta-100	3.5	20	140	95	95	100	107
Zr-beta-75	3.5	25	140	95	89	75	84
Zr-beta-50	3.5	30	140	–	Amorphous	50	–
Zr-beta-200WS	–	25	140	99	87	200	202
Zr-beta-100WS	–	30	140	100	81	100	105
Zr-beta-75WS	–	40	140	–	Amorphous	75	–

[a] Dealuminated zeolite beta as seeds.
[b] Calculated in calcined samples with respect to $SiO_2 + ZrO_2$ in the starting mixture.
[c] Reference.

Zr-containing zeolite beta samples (Table 1). Good crystallinity can be obtained up to a Si/Zr ratio of 75; higher Zr content resulted in an amorphous phase. The broadening of X-ray reflexes with Zr content is due to a lowering of the lattice order, as the bond length of Zr–O (2.00 Å) differs from that of tetrahedral Si–O (1.59 Å). Without the use of seeds, it was still possible to form Zr-zeolite beta up to a Si/Zr ratio of 100, although a longer crystallisation time was required. The yield was good, but the crystallinity was lower than that obtained with the seeded synthesis.

The samples also showed good thermal stability. Even after Zr-beta-100 was calcined to 900 °C for 2 h, the peak intensity of the sample remained as high as the one calcined at 580 °C (Fig. 2). It is well known that connectivity defects such as $Si–O^-$ or Si–OH groups exist in zeolite beta synthesised in hydroxide media [23]. The presence of connectivity defects can affect the sorption and hydrophilic/hydrophobic properties of zeolites, while usually causing a relatively poor thermal stability. However, zeolite beta synthesised in fluoride medium is almost free of connectivity defects because the organic cations are counterbalanced by occluded F^-. Therefore, we can conclude that the high thermal stability of Zr-beta synthesised in fluoride medium is due to the absence of connectivity defects.

The infrared spectrum of adsorbed pyridine remaining on Zr-beta-100 after heating at 100 °C is given in Fig. 3. The spectrum showed medium strong bands at 1608 cm^{-1} and 1450 cm^{-1} due to pyridine bonded to Lewis acid sites [24]. The band of medium intensity at 1490 cm^{-1} is due to both coordinated pyridine and pyridine chemisorbed at Brønsted acid sites. A very weak band at 1545 cm^{-1} is assigned to the pyridine adsorbed to Brønsted acid sites.

SEM images of Zr-beta-100 synthesised with and without seeding are shown in Fig. 4. The crystals show the truncated square bipyramidal morphology typical of zeolite beta. The crystal size is quite uniform and, for the unseeded sample, is > 10 µm. For zeolite beta seeds of around 50 nm, the resulting sample has a smaller crystal size of around 1 µm. From a catalytic point of view, small crystal sizes are usually preferred for the elimination of internal diffusion limitations. Moreover, by seeding, the synthesis time needed to crystallise Zr-beta zeolite is reduced.

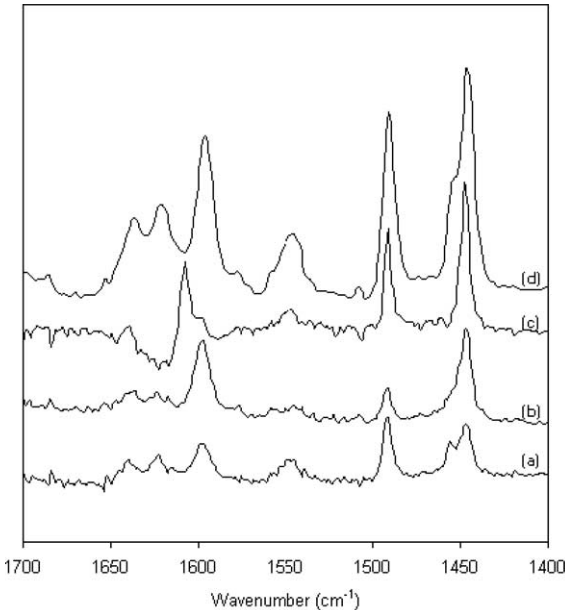


Fig. 3. Pyridine IR after heating the sample to 100 °C for 1 h (a) Al-MSU-9, (b) Al-MSU-50, (c) Zr-beta-100, and (d) HY15.

The BET surface area and total pore volume were found to be quite similar for all Zr-beta samples, within experimental error (Table 2). The external surface area constitutes less than 6% of the total, with the bulk located in the micropores. The micropore volume in zeolites, as calculated from the *t* plot, was in the range of 0.21–0.23 ml/g.

3.2. Properties of Al-MSU-S_{FAU} samples

The Al-MSU-S_{FAU} samples all showed high surface areas, 757–976 m^2/g, with pore volumes of 0.53–0.95 ml/g (Table 2). The mesoporous structure of these samples was confirmed by X-ray diffraction and by nitrogen porosimetry measurements (Fig. 5). Three well-defined *hk*0 reflections were observed in the XRD diffractograms. These could be indexed to the p6m hexagonal lattice. The N_2 sorption

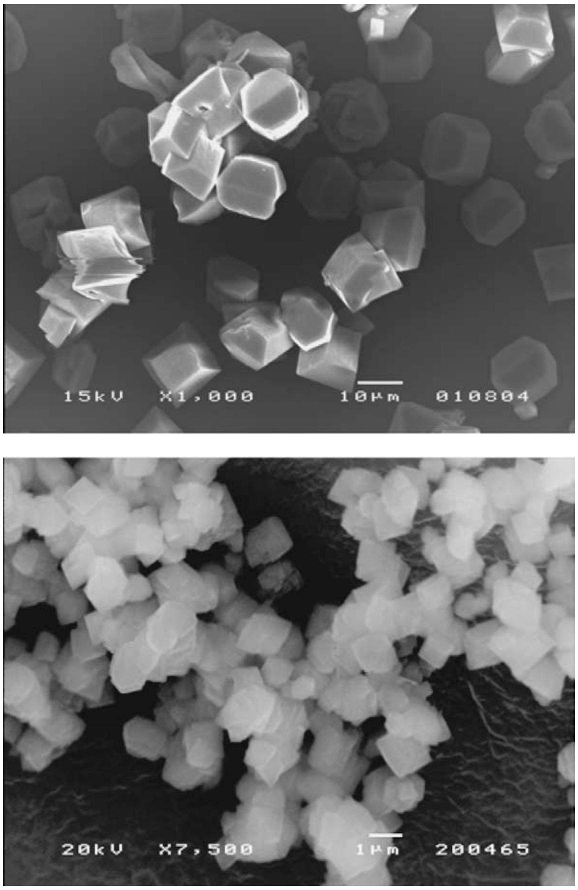


Fig. 4. SEM micrographs of Zr-beta-100 produced (a) without seeds, and (b) with seeds.

Table 2
Textural properties of catalysts

Catalyst	Surface area (m^2/g)	Total pore volume (ml/g)	Micropore volume (ml/g)	Zr content (wt%)
Zr-beta-75	499	0.26	0.23	2.39
Zr-beta-100	490	0.27	0.22	1.88
Zr-beta-200	474	0.27	0.21	1.04
Sn-beta-125	500	0.31	0.23	–
Ti-beta-100	468	0.25	0.22	–
Al-beta-12.5	559	0.99	0.17	–
IE-Zr-beta	489	0.94	0.15	–
HY15	650	0.55	0.26	–
Al-MSU-9	757	0.95		–
Al-MSU-35	839	0.71		–
Al-MSU-50	952	0.95		–
Al-MSU-70	976	0.91		–
Al-MSU-140	826	0.53		–

isotherms showed type IV isotherms with rectangular type H4 hysteresis loops at $P/P_0 > 0.4$ and capillary condensation steps at P/P_0 of 0.2–0.4. At the low-pressure end, t-plot analyses showed a very small microporosity of < 0.02 ml/g in some samples and no microporosity in others. From the pyridine adsorption IR spectra, the Al-MSU samples had predominantly Lewis acidity with some Brønsted acidity.

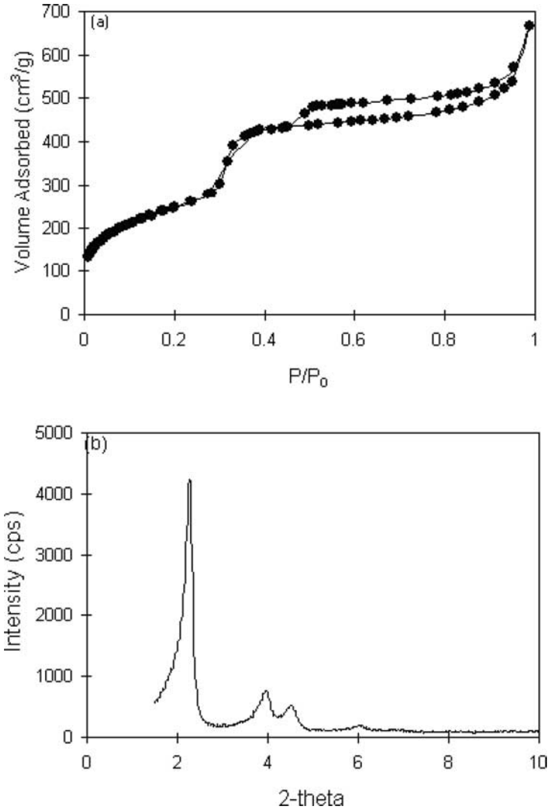


Fig. 5. (a) Nitrogen porosimetry, and (b) powder X-ray of Al-MSU-50.

3.3. *Cyclisation of citronellal over HY and Al-MSU-S_{FAU} catalysts*

The cyclisation of citronellal is a reaction that occurs easily over mildly acidic sites. Al-MSU-S_{FAU} samples were very active in the reaction, giving good selectivities of > 98% for the various isopulegol isomers. A comparison of the MSU samples with different Al content shows that a Si/Al ratio of 50–70 is optimal. Al-MSU-140, which had fewer acid sites, was, not surprisingly, less active than samples with higher Al-content. Irrespective of the Al content, the product distribution over all samples was similar, with (±)-isopulegol as the main isomer (65–68%), followed by (±)-neo-isopulegol (25–27%), (±)-iso-isopulegol (5–6%), and (±)-neoiso-isopulegol (1–2%) (Table 3).

The activity, overall selectivity, and isomer distribution were affected by the solvent used (Table 4). The reaction rate was higher in nonpolar solvents and slower in polar solvents. After 60 min, the conversion was less than 6% when acetonitrile was used as the solvent but > 96% in toluene. Lower selectivity to cyclisation was observed in polar solvents like acetonitrile and *tert*-butanol than in nonpolar solvents. In 2-propanol, the selectivity was only 28% because of the reduction of citronellal to citronellol in the Meerwein–Ponndorf–Verley reaction and subsequent dehydration of the products. The overall selectivity was 95–98% in nonpolar solvents like cyclohexane and toluene. Irrespective of the

Table 3
Conversion and selectivity to isopulegol isomers over various catalysts[a]

Catalyst	Solvent	Conversion[b] (%)	Overall selectivity[c] (%)	Isomeric ratio[d]
Zr-beta-100	*tert*-Butanol	82.8	98	93:5:2:0
Sn-beta-125	Acetonitrile	35.5	98	85:10:5:0
Ti-beta-100	Acetonitrile	8.5	84	59:37:4:0
Al-beta-12.5	*tert*-Butanol	56.7	85	71:24:4:1
IE-Zr-beta	*tert*-Butanol	64.0	88	73:22:4:1
HY15	Acetonitrile	25.1	59	62:26:5:6
HY15	*tert*-Butanol	94.3	87	54:37:7:2
HY15	Toluene	98.2	92	67:24:7:2
Al-MSU-9	Toluene	84.1	96	68:25:5:2
Al-MSU-50	Toluene	88.6	97	67:26:5:2
Al-MSU-70	Toluene	90.3	98	66:27:5:2
Al-MSU-140	Toluene	59.4	98	65:27:6:2

[a] Reaction conditions: 4 mmol (0.62 g) citronellal, 5 g solvent, 50 mg catalyst, 80 °C.

[b] After 30 min.

[c] Selectivity to all isopulegol isomers.

[d] Isopulegol:neo-isopulegol:iso-isopulegol:neoiso-isopulegol.

Table 4
Activity of Al-MSU-50 in different solvents[a]

Solvent	Relative polarity[b]	Conversion[c] (%)	Ratio of isomers[d]	Overall selectivity[e] (%)
Cyclohexane	0.006	93.8	64:28:6:2	98
Toluene	0.099	96.7	67:26:5:2	98
1,4-Dioxane	0.164	69.5	63:30:5:2	95
tert-Butanol	0.389	27.4	61:32:5:2	87
Acetonitrile	0.46	5.7	69:31:0:0	79
2-Propanol	0.546	39.1	63:32:5:0	28

[a] Reaction conditions: 4 mmol (0.62 g) citronellal, 5 g solvent, 50 mg catalyst, 80 °C.

[b] C. Reichardt, Solvents and Solvent Effects in Organic Chemistry, 2nd Ed., VCH, Weinheim, 1988.

[c] After 60 min.

[d] Isopulegol:neo-isopulegol:iso-isopulegol:neoiso-isopulegol.

[e] Selectivity to all isopulegol isomers.

solvents, the diastereoselectivity for (±)-isopulegol was between 61 and 69%.

The cyclisation of citronellal without any solvent was carried out over Al-MSU-50 (Fig. 6). The rate of reaction was higher without solvent than when toluene was used; this may be explained by a dilution effect. The diastereoselectivity for (±)-isopulegol was similar without solvent and in toluene, 65 and 68%, respectively. The used catalyst after the batch reaction had lower activity than the fresh catalyst, and the activity could not be restored by simply washing the catalyst with toluene (Table 5). However, if the catalyst was calcined at 540 °C for 4 h, almost full activity was restored. Extraction of the used catalyst with toluene showed that citronellal, isopulegols, and ether products of the isopulegols had been formed at the surface. The adsorption of these molecules blocks some of the active sites required for reaction.

The reaction was carried out from 25 to 80 °C, and the activation energy for the cyclisation reaction was calculated to be 55.6 kJ/mol (Table 6). The diastereoselectivity for (±)-isopulegol decreased slightly from 69 to 67% at higher temperatures, although the overall selectivity to cyclisation improved.

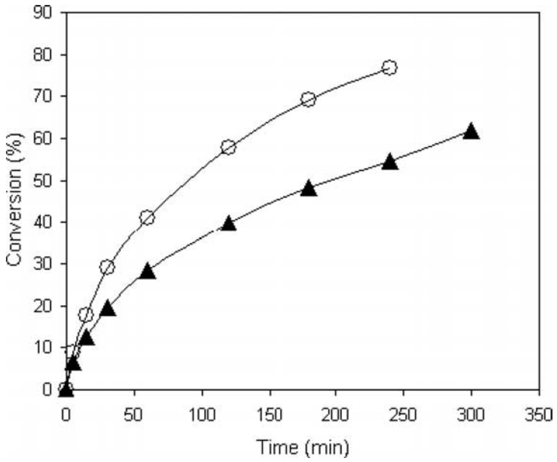


Fig. 6. Conversion of Al-MSU-50 without solvent (○) and in toluene (▲). Reaction conditions: 20 mmol (3.1 g) citronellal, (5 g toluene), 50 mg catalyst, 80 °C.

Table 5
Reuse of Al-MSU-50 catalyst[a]

Cycle	Conversion[b] (%)	Overall selectivity (%)	Treatment
1	96.7	98	Fresh catalyst
2	86.6	98	Wash with toluene
3	71.6	98	Wash with toluene
4	44.3	96	Wash with toluene
5	35.6	95	Wash with toluene
6	95.2	98	Calcined at 540 °C for 4 h

[a] Reaction conditions: 4 mmol (0.62 g) citronellal, 5 g toluene, 50 mg catalyst, 80 °C.

[b] After 60 min.

Table 6
Effect of reaction temperature over Al-MSU-50 and Zr-beta-100[a]

Sample	Temperature (°C)	Conversion[b] (%)	Overall selectivity[c] (%)	Diastereoselectivity[d] (%)
Al-MSU-50	25	4.4	> 90	69
	40	12.0	> 93	68
	60	40.2	> 95	67
	80	79.4	> 98	67
Zr-beta-100	25	8.1	> 92	92
	40	21.5	> 96	92
	60	43.7	> 98	92
	80	69.2	> 98	93

[a] Reaction conditions: 4 mmol (0.62 g) citronellal, 5 g toluene for Al-MSU-50 or *tert*-butanol for Zr-beta-100, 50 mg catalyst.

[b] Conversion after 15 min.

[c] Selectivity to isopulegol isomers.

[d] Selectivity to (±)-isopulegol with respect to the other diastereomers.

Like the Al-MSU samples, zeolite HY (Si/Al 15) was very active in the cyclisation of citronellal (Table 3). Again, a strong solvent dependence was observed. In acetonitrile, the reaction was slow and the selectivity for cyclisation was

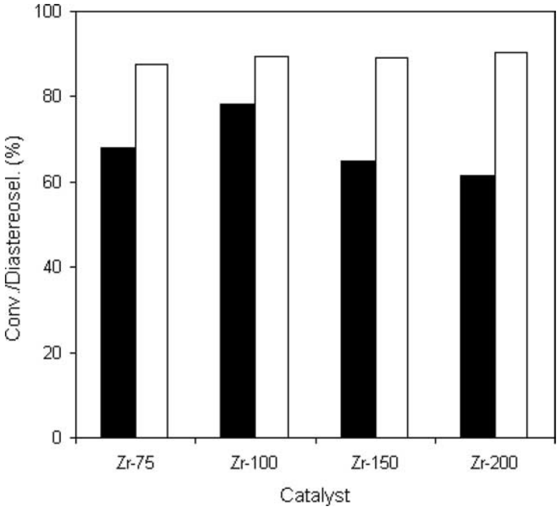


Fig. 7. Comparison of activity (■) and diastereoselectivity (□) to (±)-isopulegol over Zr-zeolite beta (measured after 15 min reaction, 0.62 g citronellal, 5 g acetonitrile, 50 mg catalyst, 80 °C).

only 59%, with (±)-isopulegol forming 62% of all isomers. In *tert*-butanol, the selectivity for cyclisation was higher, 87%, but the (±)-isopulegol constituted only 54% of the isomers formed. In toluene, the overall selectivity was 92%, with a diastereoselectivity of 67% for (±)-isopulegol.

3.4. Cyclisation of citronellal over Zr-zeolite beta: effect of Zr loading

A comparison of the activity of Zr-zeolite beta with different Zr loading was carried out with acetonitrile as a solvent (Fig. 7). The rate of reaction was highest with Zr-beta-100, whereas higher and lower Zr-containing samples were less active. In all cases, the selectivity for cyclisation was > 99%. The predominant product was (±)-isopulegol, which constituted about 90% of the isomers, followed by (±)-neo-isopulegol (7%) and (±)-iso-isopulegol (3%). No (±)-neoiso-isopulegol was detected.

3.5. Effect of solvents

Considering the pronounced effect of solvents on the activity and selectivity for cyclisation over Al-MSU-S_{FAU} and HY catalysts, studies of solvent effects were also carried out with Zr-zeolite beta. The conversion was higher in polar solvents than in nonpolar solvents (Table 7). The overall selectivity for cyclisation was generally > 97%, except for 2-propanol, where a parallel reaction, the Meerwein–Ponndorf–Verley reduction, can also take place between the solvent and citronellal. Irrespective of the solvent, the diastereoselectivity for (±)-isopulegol was high, between 87 and 93%. The highest selectivity for (±)-isopulegol, > 93%, was obtained with *tert*-butanol as a solvent.

Zr-beta-100 could be reused for several batch reactions when the used catalyst was washed after each reaction with *tert*-butanol (Table 8). Although the conversion decreased with each batch, the diastereoselectivity for (±)-isopulegol remained constant. Full activity of the catalyst could be restored by calcining of the catalyst at 550 °C for 4 h, followed by exposure to ambient conditions overnight. To test for leaching of Zr, the catalyst was filtered from the hot reaction mixture after 10 min, when the conversion had reached 47%. The filtrate was monitored for any additional conversion. The conversion remained unchanged with time, showing that no leaching of Zr had occurred.

The cyclisation of citronellal also proceeded smoothly without any solvent. However, unlike Al-MSU-50, the initial rate of reaction was very fast but was followed by a much slower reaction rate at longer times (Fig. 8). With 3.1 g of citronellal, the conversion over Zr-beta-100 was 50% after 10 min but reached 75% after 4 h. The rate dependence with time was similar to that when acetonitrile was used as a solvent. The rate dependence cannot be fitted with that of a first-order rate equation, as would be expected for cyclisation. The leveling at higher conversion is indicative of poisoning by the reaction products, in which adsorption sites may be blocked. With *tert*-butanol as a solvent, the initial rate of reaction was slower but the conversion continued to increase with time, following a first-order rate equation. This

Table 7
Activity of Zr-beta-100 in different solvents[a]

Solvent	Conversion[b] (%)	Ratio of isomers[c]	Overall selectivity[d] (%)
Cyclohexane	83.1	90:6:4:0	> 98
Toluene	59.7	87:9:4:0	> 98
1,4-Dioxane	93.5	90:8:2:0	> 98
tert-Butanol	93.8	93:5:2:0	> 97
Acetonitrile	95.9	91:6:3:0	> 99
2-Propanol	97.5	89:8:3:0	∼ 82

[a] Reaction conditions: 4 mmol (0.62 g) citronellal, 5 g solvent, 50 mg catalyst, 80 °C.

[b] After 60 min.

[c] (±)-isopulegol:(±)-neo-isopulegol:(±)-iso-isopulegol:(±)-neoiso-isopulegol.

[d] Selectivity to isopulegol isomers.

Table 8
Reuse of Zr-beta-100 catalyst[a]

Cycle	Conversion[b] (%)	Overall selectivity[c] (%)	Selectivity (±)-isopulegol (%)	Treatment
1	93.4	> 98	93	Fresh catalyst
2	92.1	> 98	93	Wash with *tert*-butanol
3	86.8	> 98	93	Wash with *tert*-butanol
4	79.3	> 98	93	Wash with *tert*-butanol
5	66.8	> 98	93	Wash with *tert*-butanol
6	94.2	> 98	93	Calcined at 550 °C for 4 h and exposed to ambient overnight

[a] Reaction conditions: 4 mmol (0.62 g) citronellal, 5 g *tert*-butanol, 50 mg catalyst, 80 °C.

[b] After 60 min.

[c] Selectivity to isopulegol isomers.

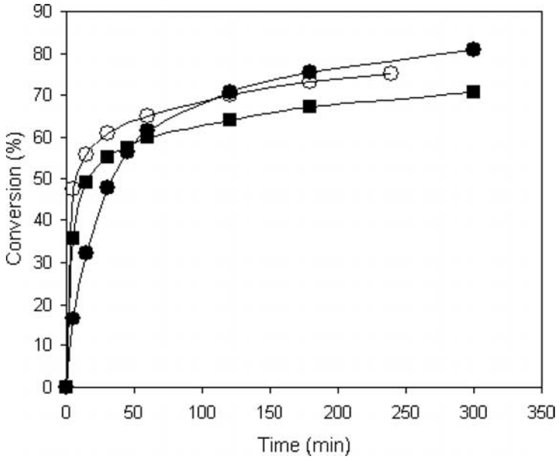


Fig. 8. Conversion over Zr-beta-100 without solvent and in (○) acetonitrile and (■) *tert*-butanol (●). Reaction conditions: 20 mmol (3.1 g) citronellal, (5 g solvent), 50 mg catalyst, 80 °C.

Table 9
Effect of pretreatment and of water in the reaction mixture on Zr-beta-100[a]

Conditions	Conversion[b] (%)	Overall selectivity[c] (%)	Selectivity (±)-isopulegol (%)
Pretreatment of catalyst			
Exposed to air	93.6	> 98	93
Dry at 100 °C for 4 h	60.9	> 93	90
Dry at 300 °C for 4 h	35.5	> 90	86
Reaction conditions			
1% H_2O	72.2	> 99	93
2% H_2O	62.8	> 99	93
3% H_2O	59.4	> 99	93

[a] Reaction conditions: 4 mmol citronellal, 5 g *tert*-butanol, 50 mg catalyst, 80 °C.
[b] Conversion after 1 h.
[c] Selectivity to isopulegol isomers.

may be due to the solubility of the isopulegols in the alcohol solvent. The diastereoselectivity for (±)-isopulegol without any solvent was 89%, which is slightly lower than that in *tert*-butanol, 93%.

3.6. *Effect of sample pretreatment and reaction conditions*

Table 9 shows that the pretreatment conditions influence the activity of the catalyst. Careful drying of Zr-beta-100 under a flowing stream of nitrogen at 100 °C resulted in a catalyst that had a lower activity and less diastereoselectivity than the reference sample that had been exposed to ambient conditions. A higher drying temperature of 300 °C resulted in an even more inactive catalyst. The diastereoselectivity for (±)-isopulegol also decreased with higher drying temperatures. On the other hand, injection of additional water into the reaction medium had no effect on the diastereoselectivity, although the rate of reaction was decreased.

To study the influence of the reaction temperature, the cyclisation of citronellal was carried out at several temperatures between 25 and 80 °C (Table 6). With scandium trifluoromethanesulfonate, the diastereoselectivity for (±)-isopulegol increased at lower reaction temperatures [2]. However, with Zr-beta-100, no significant change in the diastereoselectivity was observed when the reaction temperature was lowered from 80 to 25 °C. From the decrease in the rate of reaction, the activation energy was determined to be 35.9 kJ/mol. This is lower than that measured for Al-MSU-S_{FAU} and could account for the faster reaction rate observed for Zr-beta-100. The lower activation energy also suggests that diffusion into the pores could be limiting for the Zr-zeolite beta.

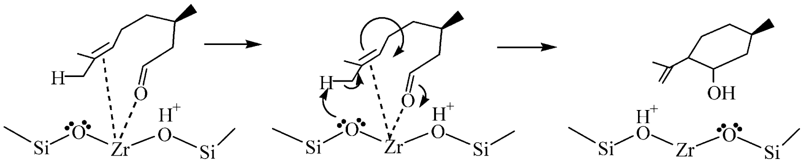
3.7. *Comparison with other metal-substituted zeolite beta*

In addition to Zr-zeolite beta, a number of other metal-substituted zeolite beta samples were synthesised and evaluated for the cyclisation reaction. Compared with Zr-beta-100, the conversion was lower for Sn-, Al-, and Ti-zeolite beta (Table 3). Only Sn-beta-125 showed a high selectivity for cyclisation, > 98%, whereas Ti-beta-100 and Al-beta-12.5 had lower selectivities of 84–85%. The diastereoselectivity for (±)-isopulegol over Sn-beta-100 was 85%, which is lower than that over Zr-beta-100. Ti-beta-100 was particularly inactive, with the conversion reaching only 8.5% after 30 min. Furthermore, the diastereoselectivity for (±)-isopulegol was only 59%. Over Al-beta-12.5, the diastereoselectivity for (±)-isopulegol was 71%. Ion exchange with Zr^{4+} improved the selectivity marginally to 73%.

4. Discussion

As (−)-isopulegol can be hydrogenated to form (−)-menthol, which is an industrially important product, a high selectivity for the isopulegol isomer is desired. Such high diastereoselectivity is found with homogeneous catalysts such as $ZnBr_2$, where the ratio of isopulegol to other isomers is as high as 94:6. Recently, another homogeneous catalyst, tris(2,6-diarylphenoxy)aluminium, was reported by Takasago International Corporation to bring about the almost exclusive formation of isopulegol (99.3%) compared with the other isomers. The reaction could be carried out with a range of dry solvents, but preferably at subambient temperatures. To obtain the product, workup with aqueous sodium hydroxide was necessary. Over heterogeneous catalysts, the diastereoselectivity for isopulegol is lower, usually < 70%. However, Corma and Renz [13] recently reported an industrially interesting diastereoselectivity of 85% for (±)-isopulegol, obtained with Sn-beta-125. This report shows that an active heterogeneous catalyst can be competitive with the best homogeneous catalyst in terms of selectivity for the desired isomer and yet offer the inherent advantages of ease of separation and regenerability.

The results of this study show that Zr-zeolite beta is an even more effective catalyst for the cyclisation of citronellal. The diastereoselectivity varies from 89 to 93%, depending



Scheme 2. Proposed mechanism for cyclisation of citronellal over Zr-zeolite beta.

on the solvent, with *tert*-butanol giving the highest selectivity. The high diastereoselectivity in Zr- and Sn-zeolite beta may be due to the size of the metal ion in the pore channels of zeolite beta. Although it is active, Al-zeolite beta has a diastereoselectivity of only 71%, far below the selectivity found for Zr- or Sn-zeolite beta. The selectivity for isopulegol isomers is also lower than that obtained over Zr-zeolite beta because substitution of Al^{3+} into the silica framework results in substantially increased Brønsted acidity. As a consequence, more dehydration products are formed. The presence of the bigger Zr^{4+} ion instead of Al^{3+} in the pore channels of zeolite beta restricts pore accessibility, in turn dictating the selectivity of the isomerisation products. Of all the diastereomers, isopulegol is the only one that can have all substituents—methyl, hydroxyl, and propene—in the equatorial positions. Neo-isopulegol, iso-isopulegol, and neoiso-isopulegol have at least one or two substituents in the axial position. The formation of these isomers is hindered if the pore size is restricted. In Al-beta-12.5, no pore constraint was encountered, as the isomeric ratio of the products was similar to that observed over Al-MSU-S_{FAU} or larger-pore zeolites such as HY. The preferred formation of isopulegol was also deduced from quantum mechanical calculations [9]. Isopulegol, with the three substituents in the equatorial positions, was calculated to be more stable by 15 kJ/mol than neo-isopulegol, with two groups at equatorial positions and one axial, neoiso-isopulegol (equatorial, axial, axial), and iso-isopulegol (equatorial, equatorial, axial).

Based on a study of a number of solid acids, we had earlier postulated that both strong Lewis acid sites and weak Brønsted sites are required for cyclisation. Citronellal coordinates through the aldehyde oxygen and the electron-rich double bond onto the zirconium ion (Scheme 2). The citronellal is brought into an orientation favourable for ring closure through an intramolecular carbonyl-ene reaction. The participation of a neighbouring (Brønsted) hydroxyl group is required for protonation of the oxygen. The abstraction of hydrogen from the 2-propyl group followed by ring closure gives the isopulegol. A hydroxylated surface is important in the activity of the Zr-zeolite beta. Carefully dried samples showed low activity. When Zr^{4+} is substituted for Si^{4+} in the silica framework, Brønsted acidity, in the conventional sense used when Al^{3+} is isomorphously substituted for Si^{4+}, is not present. However, differences in the electronegativity of Zr^{4+} and Si^{4+} could result in Brønsted acidity at the bridging oxygen if it is hydroxylated. Indeed, pyridine IR studies on Zr-zeolite beta showed the presence of Brønsted acid sites. Similarly, Wang et al. [25] found that the substitution of Zr into the silica lattice of MCM-41 resulted in both Lewis and Brønsted acid sites.

In this study, Al-MSU-S_{FAU} samples were also found to be very active catalysts. These materials are mesoporous, and the walls are microporous. In particular, the sample with intermediate Al content (Si/Al 50) was the best catalyst. Despite the high activity and selectivity for cyclisation, the diastereoselectivity for (±)-isopulegol was about 65–69%. HY zeolite was also very active in the reaction, with an isomeric ratio of the isopulegols similar to that for the Al-MSU-S_{FAU} samples. The larger pore size of these samples as compared with Zr-zeolite beta is probably responsible for the lower diastereoselectivity.

The effects of various solvents on the activity and selectivity of the samples was very pronounced, and an optimal solvent had to be found for each of the samples. In microporous zeolites, the co-adsorption of the solvent into the microporous system of the catalyst greatly influences the intraporous citronellal concentration. The presence of solvent molecules may facilitate or retard the adsorption of the reactant to the catalytic active sites. The Zr-zeolite beta used in this study is hydrophobic because it was synthesised in a fluoride medium. When placed in a solution with molecules of different polarity, the preferential concentration of less polar molecules over more polar molecules occurs in the pore channels. Thus when a nonpolar solvent is used, there will be a low intraporous citronellal concentration and hence a low reaction rate. On the other hand, the concentration of citronellal in the pores should be higher with a polar solvent, so that a higher reaction rate is expected. This is seen in the different reaction rates over Zr-zeolite beta when acetonitrile or *tert*-butanol is used, as compared with toluene. However, in acetonitrile, the initial reaction rate was fast, but at longer times the leveling in activity indicates poisoning, which may be due to strong adsorption of citronellal, formed isopulegols, and acetonitrile at the active sites. For a less polar solvent like *tert*-butanol, no leveling in activity was observed at longer reaction times. The solvent effect was also very pronounced for Al-MSU-S_{FAU} and HY. The samples are hydrophilic in nature, and when nonpolar solvents are used, the intraporous concentration of citronellal (a polar molecule) is high. On the other hand, a polar solvent competes with citronellal, and the rate of reaction is slower.

5. Conclusion

Zirconium can be incorporated into zeolite beta up to 2.4 wt% Zr. The crystallisation time increased with zirconium content. Despite the low loadings of Zr, the Zr-zeolite beta samples were very active in the cyclisation of citronellal. High selectivity for (±)-isopulegol was found, ∼ 93%, together with small amounts of (±)-neo-isopulegol and (±)-iso-isopulegol. Neoiso-isopulegol was not observed over Zr-zeolite beta. In comparison, the selectivity for (±)-isopulegol was lower with Al- and Ti-zeolite beta. The presence of a hydroxylated surface is essential for good activity. Catalysts with larger pores, like micro/mesoporous Al-MSU-S_{FAU} and HY, were active in the cyclisation of citronellal, but their selectivity for (±)-isopulegol was lower. The choice of solvent is important, as it affects both the catalytic activity and the selectivity. The rate of reaction was faster in polar solvents than in nonpolar solvents over Zr-zeolite beta. However, for Al-MSU-S_{FAU}, a reversal of this order was observed.

References

[1] K. Bauer, D. Garbe, H. Surburg, in: W. Gerhertz (Ed.), Ullmann's Encyclopedia of Industrial Chemistry, vol. A11, VCH, Weinheim, 1988, p. 141.
[2] V.K. Aggarwal, G.P. Vennall, P.N. Davey, C. Newman, Tetrahedron Lett. 39 (1998) 1997.
[3] Y. Nakatani, K. Kawashima, Synthesis (1978) 147.
[4] P. Kočovský, G. Ahmed, J. Šrogl, A.V. Malkov, J. Steele, J. Org. Chem. 64 (1999) 2765.
[5] T. Iwata, Y. Okeda, Y. Hori, Eur. Pat. Appl. EP1225163 A2 (2002).
[6] K. Kogami, J. Kumanotani, Bull. Chem. Soc. Jpn. 41 (1968) 2530.
[7] N. Ravasio, M. Antenori, F. Babudri, M. Gargano, Stud. Surf. Sci. Catal. 108 (1997) 625.
[8] G.D. Yadav, J.J. Nair, Langmuir 16 (2000) 4072.
[9] P. Mäki-Arvela, N. Kumar, V. Nieminen, R. Sjöholm, T. Salmi, D.Y. Murzin, J. Catal. 225 (2004) 155.
[10] J. Tateiwa, A. Kimura, M. Takasuka, S. Uemura, J. Chem. Soc., Perkin Trans. 1 (1997) 2169.
[11] M. Fuentes, J. Magraner, C. de las Pozas, R. Rogque-Malherbe, Appl. Catal. 47 (1989) 367.
[12] K. Arata, C. Matsuura, Chem. Lett. (1989) 1788.
[13] A. Corma, M. Renz, Chem. Commun. (2004) 550.
[14] Y. Zhu, G. Chuah, S. Jaenicke, J. Catal. 227 (2004) 1.
[15] G.K. Chuah, S.H. Liu, S. Jaenicke, L.J. Harrison, J. Catal. 200 (2001) 352.
[16] Y. Liu, T.J. Pinnavaia, J. Mater. Chem. 12 (2002) 3179.
[17] S.A. Bagshaw, S. Jaenicke, G.K. Chuah, Ind. Eng. Chem. Res. 42 (2003) 3989.
[18] A. Corma, M.E. Domine, S. Valencia, J. Catal. 215 (2003) 294.
[19] T. Blasco, M.A. Camblor, A. Corma, P. Esteve, J.M. Guil, A. Martinez, J.A. Perdigón-Melón, S. Valencia, J. Phys. Chem. B 102 (1998) 75.
[20] Y. Liu, W. Zhang, T.J. Pinnavaia, J. Am. Chem. Soc. 122 (2000) 8791.
[21] M.A. Camblor, A. Corma, A. Mifsud, J. Pérez-Pariente, A. Valencia, Stud. Surf. Sci. Catal. 105 (1997) 341.
[22] M.A. Camblor, A. Corma, S. Valencia, J. Mater. Chem. 8 (1998) 2137.
[23] A. Corma, L.T. Nemeth, M. Renz, S. Valencia, Nature 412 (2001) 423.
[24] E.P. Parry, J. Catal. 2 (1963) 371.
[25] X.X. Wang, F. Lefebvre, J. Patarin, J.-M. Basset, Micropor. Mesopor. Mater. 42 (2001) 269.