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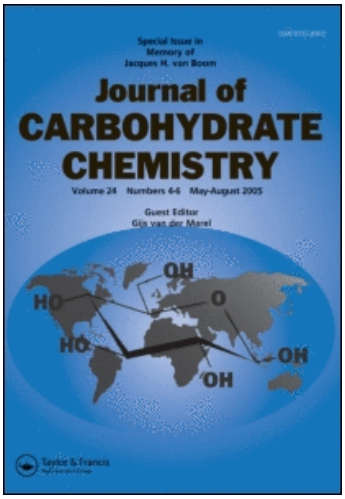

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MCM-41 MATERIALS AS CATALYSTS FOR THE SYNTHESIS OF ALKYL FRUCTOSIDES

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ABSTRACT

Alkylation of saccharides combines the essential characteristics of two major renewable classes, viz. triglycerides and carbohydrates, while leading to biofriendly surfactants and emulsifiers. The development of alkylated derivatives of fructose has lagged because no efficient synthesis was available. We have found that mesoporous materials of the MCM-41 type are active and selective catalysts for the alkylation of fructose. Quantitative yields were obtained in the reaction of fructose with lower alcohols, up to C4. For long chain alcohols yields were moderate but the alkyl fructopyranosides could be easily purified. The other isomers could be isolated by chromatography.

INTRODUCTION

The increasing costs of waste-water treatment and the growing consumer awareness of environmental considerations drive a trend towards surfactants that are readily biodegradable, produced using clean technology and derived from natural, renewable sources, such as carbohydrates and triglycerides.[1]

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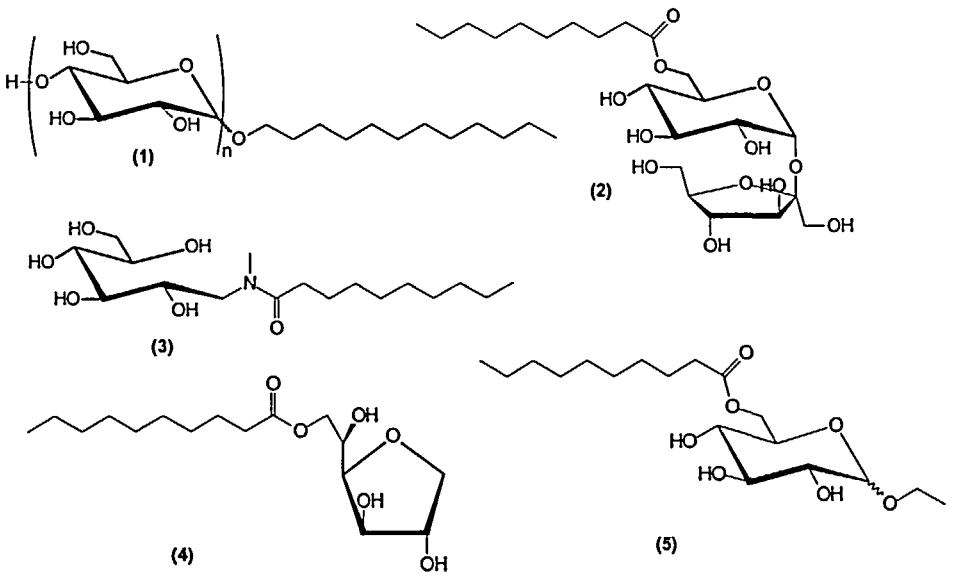

Figure 1. Commercial renewable-based surfactants.

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Several classes of surfactants are already manufactured in which the carbohydrate moiety (glucose, glucose-oligomer, sucrose, sorbitol) represents the hydrophilic part and a long chain hydrocarbon moiety (fatty acid, alcohol or amine) the hydrophobic part. These surfactants combine good cleaning properties with non-toxicity and ready biodegradability.

Examples (see Figure 1) include alkyl polyglucosides (APGs, e.g. **1**, n_{av}=1.5, Henkel), sucrose fatty acid esters (e.g. **2**, Sistema B.V.), *N*-methylglucamides (e.g. **3**, Proctor and Gamble/ Hoechst), sorbitan fatty acid esters (e.g. **4**, SEPPIC), and the recently developed ethyl glucoside esters (EGEs, e.g. **5**, Unichema). The respective conversion methods are acetalisation (**1**), (trans)esterification (**2** and **4**), reductive amination/acylation (**3**) and acetalisation/(trans) esterification (**5**).

The increasing production of inulin presumably will drive the price of fructose downwards. Hence, inulin and its monomer fructose may become economical chemical starting materials for surfactants, besides glucose and sucrose, provided that an efficient alkylation method becomes available. Moreover the fructofuranose headgroup may introduce other properties into the surfactant than exhibited by the glucopyranose group.

Long chain alkyl fructosides have been prepared from fructose using a number of protecting and deprotecting steps.[2] The direct, acid catalysed reaction of fructose (or inulin) with an alcohol, according to the Fischer method, is undoubtedly the most attractive method from an industrial point of view. The acid catalysed reaction of fructose with short chain alcohols has been described in the literature[3] but the conditions applied are not sufficient to effect reaction of fructose with higher alcohols. The use of strong acids and high temperatures as used in the production of alkyl glucosides, causes dehydration and degradation reactions leading to products like 5-hydroxymethylfurfural (HMF) and levulinic acid. Obviously, efficient alkylation of fructose requires less drastic reaction conditions. Alternative routes from sucrose using thermal[4,5] or acid catalysed alcoholysis[6] resulted in low yields of fructosides for similar reasons. Enzyme-catalysed alcoholysis of sucrose also gave moderate yields of lower alkyl fructosides and is ineffective for fatty alcohols.[7]

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We have shown that Fischer alkylation of fructose can be performed by moderately strong acid catalysts such as oxalic acid[8] and amorphous silica-alumina catalysts, as well as acid clays.[9] The use of the silica-alumina catalysts already resulted in a reasonably effective alkylation method (45 % conversion to dodecyl fructosides) but the catalysts are deactivated by deposition of fructose and its anhydrides. We reasoned that this problem could be overcome by the use of a catalyst with a less polar surface and we now report that MCM-41 material type catalysts are much more efficient than silica-alumina in the alkylation of fructose.

RESULTS AND DISCUSSION

Synthesis of the catalyst. MCM-41 is a mesoporous molecular sieve which contains parallel tubular pores.[10] During the synthesis of the catalyst cylindrical micelles of surfactants serve as organic templates for the crystallisation of the mesoporous silica-alumina. We used cetyltrimethylammonium hydroxide as the template and obtained an average pore diameter of 29 Å. The pore surface has cation-exchange properties due to the aluminium atoms.[11] Catalysts with different Si/Al ratios (30, 40, 60 and 100) and, consequently, different surface concentrations of exchange sites have been synthesised.

Table 1. Characterisation of MCM-41 materials

	Si/Al ratio	Surface analysis		
	ICP analysis	area[a]	d_p[b]	V_{ads}[c]
Sample code	(-)	(m^2/g)	(nm)	(mL/g)
MCM-41/30	34	n.d.	n.d.	n.d.
MCM-41/40	42	n.d.	n.d.	n.d.
MCM-41/60	66	1222	2.85	0.775
MCM-41/100	107	1131	2.85	0.714

a. area is calculated using the BET method[12]
b. d_p is mean pore diameter
c. V_{ads} is the adsorption volume

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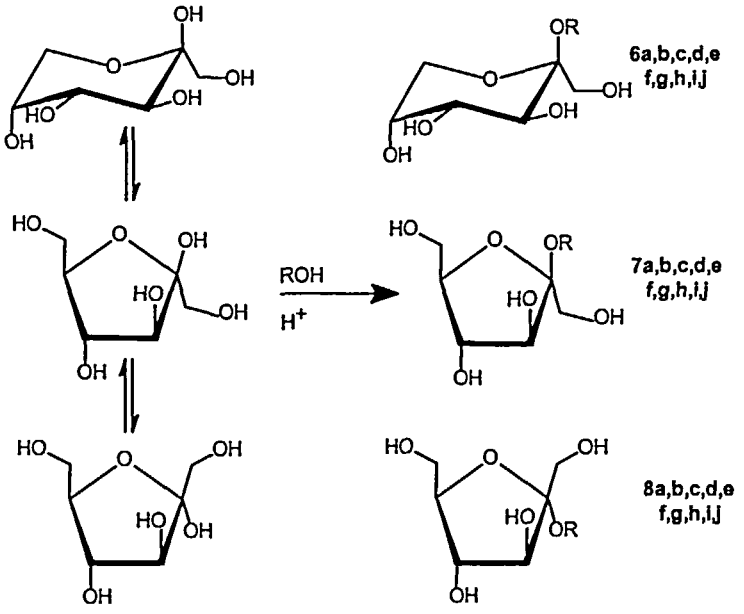
By NH_4^+ exchange followed by NH_3 removal these materials were transformed into Brønsted acidic catalysts (H-MCM-41). Table 1 shows some characteristics.

From ^{29}Si MAS NMR it became clear that a substantial amount of silicon was trigonally coordinated in the lattice, which led to the conclusion that the inner pore wall structure contains many Si-OH groups,in agreement with the results of Hitz.[13]

Alkylation of D-fructose with short chain alcohols. The alkylation of fructose with methanol or ethanol resulted in total conversion; in the case of ethyl fructosides only 5 h reaction time (reflux) were required. Analysis of the reaction mixture showed that only the corresponding fructofuranosides **7b** and **8b** (Figure 2), the kinetically favoured products,[8,9] had been formed.

The alkylation of fructose with 1-butanol also resulted in quantitative conversion. Besides the two furanosides, butyl β-fructopyranoside (**6g**) was formed (no α-pyranoside was found). Reaction in butanol took place at a slightly higher temperature (80 °C) and required more time than in ethanol, allowing the isomerisation to the pyranoside form to proceed at a measurable rate. These results are comparable with those obtained with the amorphous silica-alumina catalyst.[9] However, in that case 100 wt% of the catalyst (based on fructose) was used, and with MCM-41 only 10 wt% was applied.



a R= CH_3 **d** R= $CH_2CH{=}CH_2$ **g** R= $CH_2CH_2CH_2CH_3$ **j** R= $CH_2(CH_2)_{10}CH_3$
b R= CH_2CH_3 **e** R= $CH_2CHOHCH_2OH$ **h** R= $CH_2(CH_2)_6CH_3$
c R= CH_2CH_2OH **f** R= $CH(CH_2OH)_2$ **i** R= $CH_2(CH_2)_8CH_3$

Figure 2. The alkylation of fructose by the Fischer reaction.

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The alkylation of fructose with allyl alcohol did not proceed as was expected. The reaction started very fast and after only two hours there was already a conversion of 50 %. Then the allyl fructopyranoside (**6d**) started to precipitate and presumably also "coated" the catalyst. After 24 h, the yield of allyl fructosides in solution was only 40 %. Raaijmakers *et al.* prepared allyl fructosides using acetyl chloride as catalyst and previously noted the low solubility of the allyl fructopyranoside in allyl alcohol.[14]

The alkylation of fructose with ethylene glycol and glycerol was also attempted; the reaction was carried out at 80 °C under vacuum for 24 h. Because of the high polarity of these alcohols a good conversion was expected. However, the combined yield for the ethylene glycol derivatives **6c**,**7c**, and **8c** was 60 % after 24 h. In the reaction of fructose with glycerol the combined yield was also only 60 % and a complex mixture with at least six different products was formed according to GC analysis. Theoretically nine different

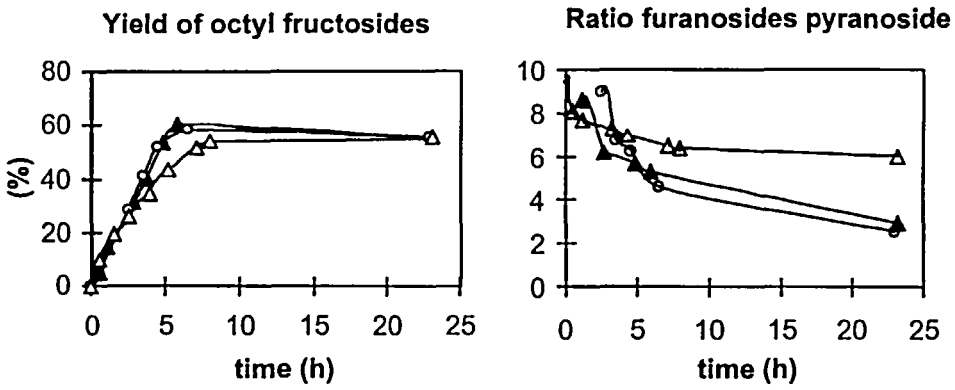

Figure 3. Course of the H-MCM-41 catalysed reaction of D-fructose with 1-octanol. ▲ MCM-41/30, o MCM-41/40, Δ MCM-41/100. Reaction conditions: D-fructose (3.0 g, 16.7 mmol), catalyst (activated at 400 °C for 24 h, stored for one week, 0.3 g), 1-octanol (42 mL, 0.267 mol), 80 °C at 15 torr (2 10^3 Pa).

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products may be formed (**6e,f**, **7e,f**, and **8e,f** where the **e** compounds represent two diastereomers since glycerol is a prochiral compound). However, the differences between them are small, and their complete separation is not to be expected. The allyl fructosides may be good starting compounds for selective oxidation to obtain a less complex mixture of glyceryl fructosides.

Recirculation of the catalyst. The activity of the catalyst in the synthesis of short chain alkyl fructosides is relatively high and it seemed promising to re-use the catalyst without calcination. Some experiments with the synthesis of ethyl fructosides showed a deactivation of 50 % after the first reaction cycle but no further loss of activity took place in subsequent cycles. After calcination (and storage for at least a week) the activity of the catalyst was essentially the same as in the first experiment.

Alkylation of D-fructose with long chain alcohols. Octanol was fructosylated less readily than the lower alcohols, as has been noted previously, and gave rise to competing breakdown of fructose. The effect of varying the Si/Al ratio of the catalyst is shown in Figure 3. From these results we concluded that there is no significant difference in initial rate between the catalysts, which is in agreement with the results of Climent *et al.* obtained during acetalisation of heptanal over MCM-41.[15] It may be noted that upon

enhancing the Si/Al ratio two properties change: the number of acid sites decreases and the materials become less hydrophilic which has a bearing on the adsorption of the reactants.[16]

It would seem that the initial reaction rate (7.2 mmol h^{-1} g^{-1} catalyst) is limited by the rate of dissolution of D-fructose in octanol.[17] However, measurements of the rate of dissolution of D-fructose in octanol at 80 °C (see Table 3) showed a rate of 180 mg mL^{-1} h^{-1} (42 mmol h^{-1} under reaction conditions), and we concluded that this step was not rate limiting.

The initial composition of the reaction mixture reflects the stability of the corresponding furanosidic and pyranosidic oxocarbenium ions rather than the anomeric composition of fructose in solution.[9] Subsequently the furanosides isomerise to the more stable β-pyranoside isomers presumably via protonation of the ring oxygen.[16] The difference in isomerisation rate is an effect of the concentration of protonic sites in the catalyst: on MCM-41/100 the isomerisation is very slow. With homogeneous HCl-catalysis the isomerisation could be carried out during the crystallisation of the pyranoside. In this way 85 % of the formed octyl fructosides could be obtained as octyl pyranoside.

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The conversion of fructose with 1-octanol to octyl fructosides was 60 % (see Figure 3), but with longer chain alcohols such as 1-decanol and 1-dodecanol the conversion dropped to about 40 %, presumably because of the very low solubility of fructose in these alcohols. This problem could partially be overcome by performing the reaction in two steps, first synthesis of butyl fructoside - which is quantitative - followed by transglycosylation to decyl or dodecyl fructoside in one pot.[9] This procedure resulted in a 60 % yield of dodecyl fructosides. The use of an inert solvent would provide an alternative solution.

Use of a solvent. *N,N*-dimethylformamide and dimethyl sulfoxide dissolve fructose and the alcohol readily,[18] but are incompatible with the intended application of the alkyl fructosides in food and personal care products. It has been reported in the literature that *tert*-butyl alcohol and 1,2-dimethoxyethane can be used as solvents for the transacylation of saccharides with fatty acid esters.[19,20] *tert*-Butyl alcohol is a weakly polar non-toxic solvent, but dehydration to isobutene is known to occur under acidic

Table 2. Effect of solvent on the alkylation of fructose with 1-dodecanol.[a]

Solvent	Initial reaction rate		Maximum yield
	($g \cdot g_{cat}^{-1} \cdot h$)	($mg \cdot mL^{-1} \cdot h^{-1}$)	(%)
none	0.17	0.82	40[b]
tert-butyl alcohol	7.5	15	60[c]
1,2-dimethoxyethane	11	22	60[d]

a. formulation see eperimental part
b. yield after 24 h, 80 °C
c. yield after 6 h, reflux (83 °C)
d. yield after 1.5 h, reflux (83 °C)

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Table 3. Dissolution rate and solubility of D-fructose

Solvent	Dissolution rate ($mg \cdot mL^{-1} \cdot h^{-1}$)	Solubility ($mg \cdot mL^{-1}$)
1-octanol (80 °C)	180	12.7
1,2-dimethoxyethane (83 °C)	476	8.1
1-octanol and 1,2-dimethoxyethane[a]	271	16.8

a. See experimental part for ratio

conditions. Fortunately, the catalysts used are mildly acidic and did not dehydrate *tert*-butyl alcohol at the temperatures applied. In this way a 57 % conversion of fructose to dodecyl fructosides could be obtained in only 6 h. Dimethoxyethane is more polar than *tert*-butyl alcohol and is more stable towards acid catalysis than *tert*-butyl alcohol. Accordingly, the initial reaction rate was higher (see Table 2) but the yield of dodecyl fructosides passed through a maximum value of about 60 %. The reaction in *tert*-butyl alcohol showed the same effect. Analysis with GC showed that the formation of difructosides, which are thermodynamically favoured, started to dominate the formation of dodecyl fructosides as the reaction proceeded.

Table 4. Energy contents of the alcohols and the corresponding alkyl fructosides

Alcohol	Energy content of molecule		Difference (kcal/mol)
	Alcohol (kcal/mol)	Alkyl fructoside (kcal/mol)	
allyl alcohol	1.31	2.88	1.57
1-butanol	1.44	2.80	1.36
1-octanol	2.29	3.66	1.37
1-decanol	2.72	4.28	1.56
1-dodecanol	3.13	4.74	1.61

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When 1,2-dimethoxyethane was used as solvent in the reaction of fructose with 1-octanol and allyl alcohol respectively, the same yields and reaction rates were obtained as in the case of the reaction with 1-dodecanol. We reasoned that the dissolution rate of fructose perhaps was the rate limiting step, but the results (Table 3) show that this is not the case.

Apparently a parallel reaction took place. It is assumed that during the reaction the fructose molecule is protonated and dehydrated to a fructosyl cation which is subsequently alkylated by the alcohol to the alkyl fructoside. The product can be dealkylated to the fructosyl cation but it will not be rehydrated to fructose. The fructosyl cation can react, however, with fructose or an alkyl fructoside; in these cases a difructose dianhydride will be irreversibly formed. Some modelling results (Alchemy, Table 4) show that from 1-butanol to 1-dodecanol the energy levels of the alcohols and the corresponding products increase.

The energy difference between the product and the corresponding alcohol also increases in this sequence, which means that the difference between the product and the reaction intermediate decreases and the rate of the reverse reaction - dealkylation to fructosyl cation - will increase. Of course the energy contents are not absolute and many intermediates are possible for each molecule, but they are in agreement with the practical work and with the results of Panintrarux *et al.*[21] in the case of alkyl glucosides.

Allyl alcohol and the allyl fructoside (Table 4) show an energy difference of 1.57 kcal/mol which is on the order of 1-decanol and 1-dodecanol and might explain the problems which arise during the synthesis of allyl fructosides.

CONCLUSIONS

It is shown that MCM-41 is an excellent catalyst for the alkylation of fructose with short chain alcohols at the anomeric position. With fatty alcohols the conversion dropped but no deactivation of the catalyst was observed. The conversion increased when *tert*-butyl alcohol was used as an inert solvent without formation of isobutene. When 1,2-dimethoxyethane was used as solvent the initial rate of the reaction was even higher but a rapid formation of difructosides also occurred.

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EXPERIMENTAL

Chemicals. Dowex® 1X8-200 ion-exchange resin, 1,2-dimethoxyethane, allyl alcohol and 1-decanol were purchased from Acros Chemicals, sodium aluminate ($NaAlO_2$ 54 % Al_2O_3, 41 % Na_2O) from Riedel de Haen, Ludox® HS-40 (40 wt% colloidal SiO_2 in water) from Du Pont de Nemours, tetraethylammonium hydroxide (35 wt% in water) and cetyltrimethyl ammonium chloride (25 wt% in water) from Aldrich, ammonium nitrate (NH_4NO_3) p.a., D-Fructose and 1-dodecanol from Merck, and methanol, ethanol, ethylene glycol, glycerol 1-butanol, 1-octanol and *tert*-butyl alcohol from J.T. Baker Chemicals.

Analysis. X-ray powder diffraction was carried out on a Philips PW 1840 diffractometer with a Cu LFF 40 kV 50 mA X-ray tube. The samples were scanned in the 2-theta range of 0.980-45.000 in steps of 0.020 with a count time of 2.00 seconds at each point.

Element analysis of the catalyst was performed using a Perkin-Elmer 1100 Flame AAS (Si determination) and a Perkin-Elmer Plasma-40 ICP-OES (for Al). All samples were prepared by dissolving 15 mg in a mixture of 750 μL 25 wt% H_2SO_4, 15 mL water and 150 μL 40 wt% HF. N_2-adsorption porosimetry was carried out using a Micromeretics ASAP-2400 and a Gemini-2360.

GC analysis was performed on a Hewlett-Packard 5890 Series II gas chromatograph equipped with a 7673 auto injector and a Chrompack 50 m x 0.32 mm

CP-Sil 5 CB, 0.12 μ column. Peaks were detected using FID and were integrated on a HP 3396A integrator. Samples were derivatised by reaction with a stock solution consisting of pyridine (104 mL), *N,N*-bis(trimethylsilyl)trifluoroacetamide (26 mL), and trimethylsilyl chloride (13 mL).

HPLC analysis was carried out on a system equipped with a Waters 590 programmable HPLC-pump, a Waters 8 x 100 mm 7 μ Symmetry C18 cartridge contained in a Waters 8 x 10 Radial Compression unit and a Waters 410 differential refractometer. For octyl fructosides a methanol-water mixture 70:30 v/v at 1.0 mL/min was used as the eluent, for the decyl and dodecyl fructosides a methanol-water mixture 80:20 v/v was used, also at 1 mL/min. Peaks were integrated using Millenium 2010 Chromatography Manager version 2.15.

Preparative scale HPLC was performed using a Millipore-Waters Delta Prep 4000 preparative chromatography system equipped with two 25 x 100 mm 6 μ Nova-Pak C18 cartridges in a 25 x 10 Radial Compression unit and an extension tube, a Waters differential refractometer R401 and a Waters fraction collector.

NMR spectra were recorded using a 300 MHz Varian Unity Inova spectrometer or a 400 MHz Varian-VXR 400S spectrometer.

Synthesis of the Catalysts. 200 g of the ion exchanging resin Dowex® 1X8-200 in its Cl^--form were rinsed with 1 L of an aqueous 1 M NaOH solution. A cetyltrimethylammonium hydroxide solution was prepared by ion exchanging 70 g (0.055 mol) cetyltrimethylammonium chloride solution (CTMACl) and 12.5 g of the exchanged Dowex® resin. The ion exchange resin was filtered off, and the filtrate was collected in a polypropylene flask of 500 mL and 48 g (0.32 mol SiO_2) of Ludox® HS-40, 27.1 g (0.06 mol) tetraethylammonium hydroxide solution, 1.00 g $NaAlO_2$ (Si/Al ratio 30) and 9.0 g water were added, bringing the total water amount to 6.0 mol. This mixture was vigorously stirred in the closed flask for two h at ambient temperature. Subsequently, the stirring was continued for two weeks at 100 °C using an oil bath. After this period, examination of the mixture under a polarisation microscope revealed that the gel material had disappeared and a finely divided material was formed.

The resulting solid was collected by centrifugation and washed with demineralised water until neutrality. The solid obtained was dried in air at room temperature and calcined in an oven at 540 °C (temperature gradient: 1 °C/min; 16 h at 540 °C; temperature gradient: -3 °C/min).

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The calcined product was refluxed in 250 mL 1 M NH_4NO_3 for three h. The solid product obtained was filtered off, washed with water to a neutral pH, followed by drying. The H-MCM-41 material obtained was calcined at 450 °C (1 °C/min; 16 h at 450 °C; -3 °C/min). The product obtained was characterised by X-ray powder diffraction and ICP analysis. The overall yield of the material (Si/Al ratio 30) was 15 g, which is 78 % based on SiO_2.

The catalysts with Si/Al ratios of 60 and 100 were synthesised using the same method, 0.5 and 0.3 g $NaAlO_2$ were added, respectively.

The catalyst with the Si/Al ratio of 40 was synthesised with precipitated SiO_2 (19.2 g, 0.32 mol). 0.5 g $NaAlO_2$ was added to obtain a Si/Al ratio of 60, but ICP-analysis showed a ratio of 40. The yield of the synthesis was 60 %, indicating that all the alumina was incorporated into the framework.

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Before use as a catalyst, the H^+ exchanged materials were subjected to another calcination at 400 °C (1 °C/min; 16 h at 400 °C; -3 °C/min). After this calcination the products were stored in a desiccator and aged for a week before use.

Activity of the Catalyst. The activities of the four catalysts were compared by testing them in a standard reaction. For this reaction 3.0 g (16.7 mmol) of D-fructose were added to 42 mL (266.7 mmol) 1-octanol and the suspension was stirred and heated to 80 °C under vacuum. 0.3 g MCM-41 catalyst was added and water was scavenged using zeolite KA (10 g) in a Soxhlet apparatus. The reaction was monitored using HPLC. After 24 h the reaction was stopped and the catalyst was removed by filtration. Depending on the reaction time and temperature and the Si/Al ratio of the catalyst, the composition of the reaction mixtures shifted from 50% α-furanoside and 50 % β-furanoside, for short reaction times, low tempeartures and a catalyst with a Si/Al ratio of 100, to mixtures of 35 % α-furanoside, 15 % β-furanoside and 50 % β-pyranoside, at prolonged reaction times, higher temperature and a catalyst with a Si/Al ratio of 30.

Synthesis of Methyl and Ethyl Fructosides. D-Fructose (3 g, 16.7 mmol) and alcohol (100 mL) were refluxed in a round-bottomed flask equipped with a Soxhlet apparatus containing zeolite KA. 0.3 g MCM-41/100 material was added. After 24 h for the reaction with methanol and 5 h for the reaction with ethanol, respectively, the reaction was stopped, and the reaction mixture was filtered. The alcohol was removed by evaporation *in vacuo* and the residue was dried *in vacuo* at 50 °C. Methyl fructosides (3.2

g, 100%, **6a, 7a, 8a**) and ethyl fructosides (3.5 g, 100%, **7b, 8b**) were obtained in this way. ^{13}C NMR data of the mixtures were in agreement with those reported in the literature.[9,22]

Recirculation of the Catalyst. Ethyl fructosides were synthesised as described above. After 5 h the catalyst was removed by filtration and directly reused in another reaction mixture. During these experiments the reactions were monitored using GC.

Reaction of Fructose with Allyl Alcohol. D-Fructose (3 g, 16.7 mmol) and allyl alcohol (75 mL) were refluxed over zeolite KA in a Soxhlet apparatus. Catalyst (0.3 g) was added and the reaction was monitored using GC. After 24 h the catalyst was removed by filtration. The alcohol was evaporated under vacuum, then 200 mL diethyl ether was added and the mixture was stored at 0 °C for one night. The allyl fructopyranoside (**6d**) crystallised from this mixture in a 0.56 g yield. ^{13}C NMR data were in agreement with those reported in the literature.[14]

Reaction of Fructose with Ethylene Glycol and Glycerol. D-Fructose (3 g, 16.7 mmol) was added to 15 mL of ethylene glycol and 20 mL of glycerol respectively (16 equivalents). The reaction mixture was heated under vacuum to 80 °C. 0.3 g of MCM-41/60 was added as catalyst and the reactions were monitored by GC. Very complex reaction mixtures were obtained.

Synthesis of Butyl Fructosides. D-Fructose (3 g, 16.7 mmol) and 1-butanol (100 mL) were refluxed in a round-bottomed flask which was connected to a Soxhlet apparatus, containing zeolite KA. The mixture was brought to 80 °C at such a pressure that a constant reflux of 1-butanol was obtained. 0.3 g MCM-41/40 material was added. After 24 h the reaction was stopped, the reaction mixture was filtered and the alcohol was removed by evaporation *in vacuo*. The yield of butyl fructosides was 3.8 g (97 %). The ^{13}C NMR data and melting point were in agreement with those reported earlier [9] and showed the presence of the butyl fructofuranosides **7g** and **8g** and the butyl fructopyranoside **6g**.

When 0.3 g zeolite H-beta with a Si/Al ratio of 25 was used as catalyst, as reported by Corma *et al.* for the alkylation of glucose with 1-butanol,[23] an extensive browning of the reaction mixture occurred, indicating degradation of fructose. This was confirmed by GC-analysis

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Isolation of Octyl β-D-Fructopyranoside. To the filtrate of a reaction mixture obtained from a test reaction (formulation given above) with MCM-41/40, 400 mL diethyl ether was added. The mixture was kept 24 h at 0 °C, providing a precipitate of 0.5 g octyl β-D-fructopyranoside (85 % of the formed pyranoside). The furanosides remained in solution. Recrystallisation from water afforded 0.43 g (72%) of pure octyl β-D-fructopyranoside (**6h**): ^{13}C NMR (100 MHz, DMSO-d_6) δ 13.85 (CH_3), 21.99 (CH_2), 25.68 (CH_2), 28.59 (CH_2), 28.82 (CH_2), 29.62 (CH_2), 31.16 (CH_2), 59.61 (Cα), 62.00, 63.73 (C1, C6), 68.89, 69.09, 69.25 (C3, C4, C5) 100.00 (C2). These data are in agreement with those reported earlier.[9]

When both diethyl ether and distilled acetyl chloride (to catalyse the isomerisation) were added to the filtrate of a reaction mixture, 3.3 g of solids precipitated. GC analysis showed a mixture of 80 % octyl β-D-fructopyranoside and 20 % fructose; 85 % of the octyl fructosides formed were precipitated as pyranosides.

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Isolation of Octyl Fructofuranosides. A reaction mixture, as described above, was diluted with dichloromethane and subjected to silica gel column chromatography. Dichloromethane was continuously passed through the column to elute the 1-octanol.[9] When no more alcohol eluted, the column was flushed with methanol, and a solution of octyl fructosides in methanol was obtained. This mixture was separated by preparative HPLC. The octyl β-D-fructofuranoside (**7h**) was obtained as an essentially pure oil. $[\alpha]_D$ -14.8 ° (*c* 1.0, methanol): ^{13}C NMR (100 MHz, DMSO-d_6) δ 13.86 (CH_3), 22.00 (CH_2), 25.61 (CH_2), 28.83 (CH_2), 29.79 (CH_2), 30.58 (CH_2), 31.18 (CH_2), 60.43 (Cα), 61.06, 62.85 (C-1, C-6), 75.32, 76.30, 81.81 (C-3, C-4, C-5), 103.81 (C-2)

Anal. Calcd for $C_{14}H_{28}O_6$ (292.36): C, 57.51; H, 9.65; O, 32.83. Found: C, 56.95; H, 9.62; O, 33.4.

Decyl Fructosides. D-Fructose (3.0 g 16.7 mmol) was reacted with 1-decanol (42.1 g, 266.7 mmol) following the same procedure as for the reaction with 1-octanol. The maximum total conversion was 51 %. After filtration of the catalyst, 300 mL of diethyl ether was added and the mixture was cooled to -8 °C to precipitate the decyl fructopyranoside. After recrystallisation from methanol pure pyranoside was obtained.

Decyl β-D-Fructopyranoside (6i): ^{13}C NMR (100 MHz, DMSO-d_6) δ 13.85 (CH_3), 21.98 (CH_2), 25.66 (CH_2), 28.58 (CH_2), 28.86 (CH_2), 28.93 (2 x CH_2), 29.60

(CH_2), 31.18 (CH_2), 59.60 (Cα), 61.98, 63.72 (C-1, C-6), 68.88, 69.06, 69.25 (C-3, C-4, C-5), 100.00 (C-2). These data are in agreement with those reported earlier.[9]

Dodecyl Fructosides. D-Fructose (3.0 g 16.7 mmol) was reacted with 1-dodecanol (49.6 g 266.7 mmol) following the same procedure as for the reaction with 1-octanol. The maximum conversion was 42 %. After filtration of the catalyst 200 mL diethyl ether was added and the mixture was cooled to -8 °C to precipitate the dodecyl fructopyranosides. After recrystallisation from methanol pure pyranoside was obtained.

Dodecyl β-D-Fructopyranoside (6j): ^{13}C NMR (75 MHz, DMSO-d_6) δ 13.87 (CH_3), 22.05 (CH_2), 25.73 (CH_2), 28.67 (CH_2),28.93 (2 x CH_2), 28.98 (3 x CH_2), 29.67 (CH_2), 31.26 (CH_2), 59.65 (Cα) 62.05, 63.77 (C-1, C-6), 68.95, 69.16, 69.33 (C-3, C-4, C-5), 100.04 (C-2). These data are in agreement with those reported earlier.[9]

For isolation of dodecyl β-D-fructofuranoside (**7j**) the same procedure as described for the octyl fructofuranoside was used. The oil obtained was crystallised from acetonitrile: $[\alpha]_D$ -22.8 ° (*c* 1.0, methanol); ^{13}C NMR (75 MHz, DMSO) δ 13.86 (CH_3), 22.00 (CH_2), 25.62 (CH_2), 28.62 (CH_2), 28.95 (2 x CH_2), 28.99 (3 x CH_2), 29.78 (CH_2), 31.21 (CH_2), 60.45 (Cα), 61.06, 62.88 (C1, C6), 75.36, 76.33, 81.83 (C3, C4, C5) 103.80 (C2). These data are in agreement with those reported earlier.[9]

Anal. Calcd for $C_{18}H_{36}O_6$ (348.47): C, 62.04; H, 10.41; O, 27.55. Found: C, 61.64; H, 10.02; O, 28.0.

Synthesis of Dodecyl Fructosides Using a Solvent. 3.0 g (16.7 mmol) of D-fructose and 49.6 g (266.7 mmol) 1-dodecanol were added to 150 mL of *tert*-butyl alcohol or 150 mL of 1,2-dimethoxyethane. The reaction mixture was heated to reflux, 0.3 g MCM-41/60 was added and water was scavenged using zeolite 3A in a Soxhlet apparatus. The reaction was monitored using HPLC and GC. After 6 and 3 h, respectively, the reaction was stopped and the catalyst was removed. Analysis of the reaction mixtures showed the rapid formation of dodecyl fructosides to a maximum yield of 60 %. Then the yield of alkyl fructosides decreased and the formation of difructosides dominated as the reaction proceeded.

Dissolution rate. 50 mL of 1-octanol and 100 μL of tetradecane were heated to 80 °C and then 3.0 g of D-fructose were added. The concentration of fructose in solution was monitored by GC. For the dissolution rate in 1,2-dimethoxyethane, 50 mL of the solvent and 100 μL of tetradecane were heated to reflux (83 °C) and then 2 g of D-

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fructose were added. For the dissolution rate in a mixture of 1-octanol and 1,2-dimethoxyethane, 28 of mL 1-octanol and 67 mL of 1,2-dimethoxyethane were mixed and heated to reflux. 100 μL of tetradecane and 3 g of D-fructose were added, and the concentration of fructose in solution was monitored by GC.

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REFERENCES

1. H. Koch, R. Beck and H. Röper, *Starch/Stärke*, **45**, 2 (1993).
2. K. Noda, A. Nakagawa, Y. Haraguchi, K. Ueda, M. Hirano, I. Nishioka, A. Yagi, A. Koda and H. Ida (Hisamitsu Pharmaceutical Co., Inc.), Ger. Offen. 301199221 (1980), [*Chem. Abstr.*, **95**, 25551e (1981)].
3. Y. Haraguchi, A. Yagi, A. Koda, N. Inagi, K. Noda and I. Nishioka, *J. Med. Chem.*, **25**, 1495 (1945).
4. L. Pomchini and G. N. Richards, *Carbohydr. Res.*, **87**, 209 (1980).
5. W. Moody and G.N. Richards, *Carbohydr. Res.*, **97**, 247 (1981).
6. W. Moody and G.N. Richards, *Carbohydr. Res.*, **124**, 201 (1983).
7. A.J.J. Straathof, J.P. Vrijenhoef, E.P.A.T. Sprangers, H. van Bekkum and A.P.G. Kieboom, *J. Carbohydr. Chem.*, **7**, 223 (1988).
8. A.T.J.W. de Goede, F. van Rantwijk and H. van Bekkum, *Starch/Stärke*, **47**, 233 (1995).
9. A.T.J.W. de Goede, M.P.J. van Deurzen, I.G. van der Leij, A.M. van der Heijden, J.M.A. Baas, F. van Rantwijk and H. van Bekkum, *J. Carbohydr. Chem.*, **15**, 331 (1996).
10. J.S. Beck, J.C. Vartuli, W.J. Roth, M.E. Leonowicz, C.T. Kresge, K.D. Schmidt, C.T-W. Chu, D.H. Olson, E.W. Sheppard, S.B. McCullen, J.B. Higgins and J.L. Schenkler, *J. Am. Chem. Soc.*, **114**, 10834 (1992).
11. A. Sayari, *Stud. Surf. Sci. Catal.*, **102**, 1 (1996).
12. P.W. Atkins, Physical Chemistry 6th ed., Oxford University Press, Oxford, 1998
13. S. Hitz, PhD thesis ETH Zürich, 1997.
14. H.W.C. Raaijmakers, E.G. Arnouts, B. Zwanenburg and G.J.F. Chittenden, *Carbohydr. Res.*, **257**, 293 (1994).
15. M.J. Climent, A. Corma, S. Iborra, M.C. Navarro and J. Primo, *J. Catal.*, **161**, 783 (1996).

16. M.A. Camblor, A. Corma, S. Iborra, S. Miquel, J. Primo and S. Valencia, *J. Catal.*, **172**, 76 (1997).
17. A. Wolff, PhD thesis, Delft University of Technology, 1997, chapter 4.
18. L.I. Osipow, F.D. Snell, W.C. York and A. Finchler, *Ind. Eng. Chem.*, **48**, 1459 (1956).
19. M. Woudenberg-van Oosterom, F. van Rantwijk and R.A. Sheldon, *Biotechnol. Bioeng.*, **49**, 328 (1996).
20. A.M. van der Heijden, F.J. Zuijderduijn and F. van Rantwijk, *J. Mol. Catal. A,* in press.
21. C. Panintrarux, S. Adachi, Y. Araki, Y. Kimura and R. Matsuno, *Enzyme Microb. Technol.*, **17**, 32 (1995).
22. K. Bock and C. Pedersen, *Adv. Carbohydr. Chem. Biochem.*, **41**, 27 (1983).
23. A. Corma, S. Iborra, S. Miquel and J. Primo, *J. Catal.*, **161**, 713 (1996).

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