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Aqueous hydroformylation reaction mediated by randomly methylated β-cyclodextrin: How substitution degree influences catalytic activity and selectivity

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ABSTRACT

A crude mixture of randomly methylated β-cyclodextrin (RAME-β-CD) has been fractionated by chromatographic column to evaluate the influence of the methylation degree on activity and selectivity of a rhodium/tris(*m*-sulfonatophenyl)phosphane trisodium salt (TPPTS) catalytic system in hydroformylation of 1-decene. Each sample of methylated β-cyclodextrin (β-CD) was carefully analyzed by matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF-MS) and electrospray ionization mass spectrometry (ESI-MS). The catalytic activity was found to gradually increase with the number of methyl groups on the methylated β-CD whereas the chemoselectivity and regioselectivity remained unchanged.

1. Introduction

Hydroformylation reaction is one of the most important reactions in industrial scope that employs transition metal in solution. The worldwide production of aldehydes by this way exceeds 10 millions tonnes per year [1]. This reaction can be performed in aqueous media and therefore presents the advantages, not only to use a green solvent but also to allow the recycling of the catalyst at the end of the reaction. The industrial viability of the biphasic hydroformylation process has been demonstrated in the case of lower olefins such as propene and butene with a Rh/tris(*m*-sulfonatophenyl)phosphane trisodium salt (TPPTS) catalytic system [2]. Unfortunately, the olefins possessing more than five carbon atoms display a weak solubility in water that leads to a very low catalytic activity. In order to circumvent this crucial problem, some of us have proposed the use of modified cyclodextrins (CDs) as mass transfer promoter. Indeed, the hydroformylation of higher olefins in the presence of CDs can be achieved with high reaction rate and selectivity, while avoiding the formation of an emulsion and the partition of the rhodium catalyst between the organic and aqueous phases [3–8]. The efficiency of CDs was attributed to the formation of an inclusion complex between the highly hydrophobic olefin and the CD at the liquid/liquid interface which facilitates the reaction of the olefin with the water-soluble organometallic catalyst. After reaction, the inclusion complex is dissociated and the product is released in the organic phase (Fig. 1).

Among the numerous modified CDs used, the commercial methylated β-CD (Table 1) called RAndomly MEthylated-β-CD (RAME-β-CD) appears as the best mass transfer promoter. Indeed, this CD is water-soluble, weakly toxic, cheap, biodegradable, industrially available in large quantities and allows to perform hydroformylation of a large variety of olefins [9].

RAME-β-CD is a mixture of various β-CD partially *O*-methylated with statistically 11.8 OH groups modified per CD. The OH groups in C-6 position are fully methylated whereas those in C-2 and C-3 positions are partially methylated. To resume, RAME-β-CD is a complex mixture of several molecules which differ not only in the number of methyl groups, but also (for the same number of groups) in the position of these groups (regioisomers). So, a single degree of substitution corresponds to a very large number of possible methylation distributions. For these reasons, it was thus of great interest to know if among the different methylated

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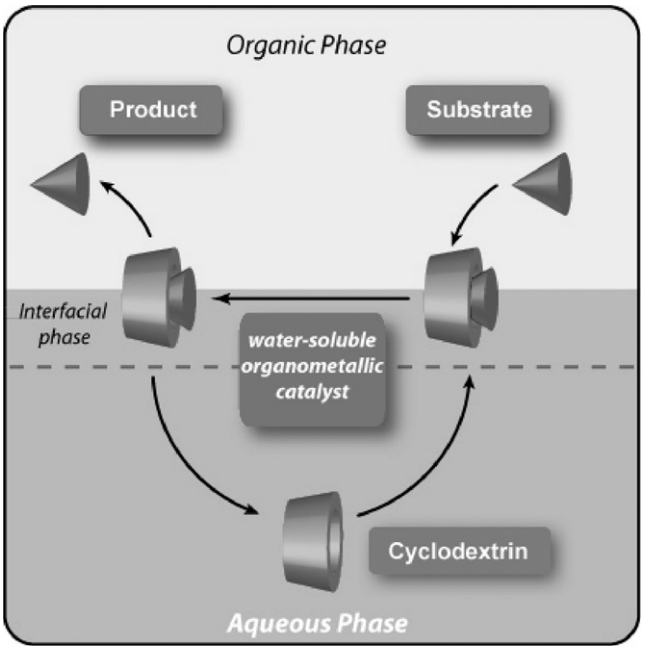


Fig. 1. Principle of interfacial catalysis in biphasic aqueous organometallic process promoted by CD.

β-CDs composing RAME-β-CD, some of them would differently behave during hydroformylation catalytic process. In this paper, commercial RAME-β-CD has been fractioned in various samples with different degree of methylation and the catalytic properties of these methylated β-CDs have been evaluated in the hydroformylation reaction.

2. Experimental

2.1. Materials and apparatus

Organic solvents, dicarbonylacetylacetonato rhodium (I), 1-decene and 2,5 dihydroxybenzoic acid (DHB) were purchased, respectively from Acros Organics, Strem Chemicals, Sigma–Aldrich and Fluka in their highest purity and used without further purification. RAME-β-CD was purchased from Wacker Chemie GmbH and was used as received. RAMEB was of pharmaceutical grade (Cavasol® W7M Pharma) and its degree of substitution was equal to 1.7.

Tris(3-sodium sulfonatophenyl)phosphane (TPPTS, P(*m*-$C_6H_4SO_3Na)_3$) was synthesized as reported by Gärtner et al. [10]. The purity of TPPTS was carefully controlled. In particular, ^1H and $^{31}P\{^1H\}$ NMR analysis indicated that TPPTS was only sulfonated in meta-position and less than 1% of its oxide was present. Carbon monoxide/hydrogen mixture (1:1) were used directly from cylinders (>99.9% pure; Air Liquide). Distilled deionized water was used in all experiments. All catalytic reactions were performed under argon using standard Schlenk techniques. All solvents and liquid reagents were degassed by bubbling argon for 15 min before each use or by two freeze–pump–thaw cycles before use. TLC plates (TLC Silica gel 60 F254 Aluminium) and silica (Geduran® Si60, 0.063–0.200 mm) for preparative column chromatography were purchased from Merck. Ultrapure water was used in surface tension measurements (Fresenius Kabi, France; $\gamma = 72.0\ mN\ m^{-1}$ at 298 K). All the high-pressure hydroformylation experiments were carried out in a 25 mL stainless steel autoclave supplied by Parr. Gas chromatographic analyses were carried out on a Shimadzu GC-17A gas chromatograph equipped with a methyl silicone capillary column (30 m × 0.32 mm) and a flame ionization detector (GC:FID).

2.2. Thin-layer chromatography (TLC)

Commercial RAME-β-CD was dissolved in dichloromethane and a spot was deposited on a thin-layer chromatography (TLC) plate. Dichloromethane–methanol (80:20) was used as eluent. Detection was performed by brief immersion of the plate into methanol containing 5% of H_2SO_4. The plate was further placed on a hot plate until the blue staining appears developed.

2.3. Preparative column chromatography

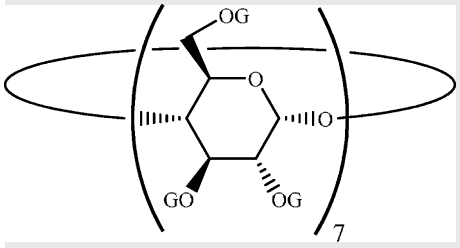
In order to isolate various samples, 5.6 g of commercial RAME-β-CD was dissolved in dichloromethane (7 mL). This preparation was loaded on the top of silica gel (200 g) column (i.d. 3 cm), which was eluted using a mixture dichloromethane–methanol.

2.4. Mass spectrometry

2.4.1. MALDI-TOF mass spectrometry

MALDI mass spectrometry experiments were performed in reflectron mode on a matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF-TOF) mass spectrometer equipped with a smart beam laser (Ultraflex II, Bruker Daltonics, Bremen, Germany). Molecular mass measurements were carried out with FlexControl™ 3.0 software (Bruker Daltonics) using an acceleration voltage of 25 keV and a delayed extraction time of 10 ns. External calibration was performed using the peptide calibration standard kit (Bruker Daltonics). Typically, 200 spectra were summed over a 750–4200 mass range and the mass lists were generated from MS spectra using FlexAnalysis™ 3.0 software (Bruker Daltonics). The methylated β-CD samples were dissolved

Table 1
Structures of β-CD and commercial RAME-β-CD.



Abbreviations	Substituent (G)	Carbons bearing the CH_3 group	Number of CH_3 groups by cyclodextrin
β-CD	H	(–)	0
RAME-β-CD[a]	H or CH_3	2, 3 and 6	11.8

[a] Commercial compound obtained from Wacker-Chemie.

at 10 mM either in water, acetone or methanol and equally mixed with the DHB matrix solution (10 mg mL^{-1} of DHB in H_2O/0.1% trifloroacetic acid:acetonitrile, 70:30, v/v) and spotted onto a ground style MALDI target according to the dried droplet method.

2.4.2. Electrospray mass spectrometry (ESI)

Electrospray mass spectrometry (ESI) experiments were performed on a Quattro Ultima (Micromass Ltd., Manchester, UK) mass spectrometer operated in positive ion mode. Nitrogen was used as desolvation (500 L h^{-1}) and nebuliser (50 L h^{-1}) gas. The electrospray ion source was heated at 343 K and the desolvation temperature was set at 393 K. The ionspray voltage was +3500 V and cone tension +50 V. The solutions were infused in the electrospray source at a 20 μL min^{-1} flow rate via a Harvard Model 22 syringe pump (Instech Laboratories, Plymouth Meeting, PA, USA). Each infused solution contained approximatively 150 mg L^{-1} of analyte in water–acetonitrile (50:50, v/v) mixture containing 10 mM ammonium acetate.

Data acquisition was performed in the full scan mode from m/z 1220 to 1500. Data were acquired with MassLynx Version 4.0 (Waters, Manchester, UK).

2.5. Catalytic experiments

All catalytic reactions were performed under argon using standard Schlenk techniques. All solvents and liquid reagents were degassed by bubbling argon for 15 min before each use or by two freeze–pump–thaw cycles before use. Rh(acac)(CO)$_2$ (2.03×10^{-2} mmol), TPPTS (0.105 mmol) and RAME-β-CD (0.24 mmol) were dissolved in 5.75 mL of water. The resulting aqueous phase and an organic phase composed of olefin (10.17 mmol) were charged under an atmosphere of argon into the 25 mL reactor, which was heated at 353 K. Mechanical stirring equipped with a multipaddle unit was then started (1500 rpm) and the autoclave was pressurized with 50 atm of CO/H_2 (1/1) from a gas reservoir connected to the reactor through a high pressure regulator valve allowing to keep constant the pressure in the reactor throughout the whole reaction. The reaction medium was sampled after 6 h of reaction for GC analyses of the organic phase after decantation. For kinetic measurements the time corresponding to the addition of CO/H_2 was considered as the beginning of the reaction.

2.6. Surface tension measurements

The processor tensiometer Sigma 70 (KSV) and the Wilhelmy plate method for air–water interface have been used for the surface tension measurements at 298 K. A concentrated solution is installed in a syringe and the addition of small volumes to ultrapure water enhances the solution concentration. After each addition, the solution is gently stirred for 30 s. Equilibrium surface tension is measured for each concentration. All surface tension values were mean quantities of at least three measurements. The standard deviation of the mean never deviated ±1.5% of the mean. The precision of the force transducer of the surface tension apparatus was 0.1 mN m^{-1} and before each experiment, the platinum plate was cleaned in red/orange colour flame. The temperature stabilisation can be estimated as better than ±0.05 K with a thermoregulated bath Lauda RC6.

2.7. Calculation of the surface excess

The surface excess (i.e. the number of moles of CDs adsorbed at the air–water interface per unit area) is obtained from the interfacial tension data presented in supplementary data. The surface excess (Γ) at the air–water interface of the various methylated β-CDs has been determined by using the Gibbs adsorption equation (Eq. (1)):

$$\Gamma = \frac{1}{RT}\left(\frac{d\gamma}{d\ln C}\right) \quad (1)$$

γ is the interfacial tension, R the gas constant, T the temperature and C is the CD concentration. Although the modified CDs have a randomly molecular weight distribution, the calculation was made over all components in the solution, i.e. by using the mean molecular weight.

2.8. Calculation of association constants by UV–vis spectroscopy

The determination of the association constant (K) is based on a spectral displacement method with methyl orange (MO) in its basic form. Indeed, the addition of TPPTS to a solution containing RAME-β-CD and MO leads to the formation of the RAME-β-CD/TPPTS complex, thus decreasing the concentration of the RAME-β-CD/MO complex initially present. The resulting absorbance variation is directly linked to the added concentration of TPPTS, but also to the association constant of RAME-β-CD/TPPTS inclusion compound.

In practice, spectra were recorded between 520 and 530 nm using a Perkin-Elmer Lambda 2 S double beam spectrometer and a quartz cell with optical path length of 1.00 cm at 298 K. The control of temperature was realised by the use of a thermostated bath linked to the cell holder (accuracy: ±0.1 K). All compounds were dissolved in phosphate buffer at pH 5.8. The concentrations for MO, RAME-β-CD and TPPTS were fixed at 0.1, 0.2 and 1 mM, respectively. The first derivatives of these spectra were used for quantitative analysis by an algorithmic treatment described elsewhere [11].

2.9. Calculation of percentages of complexed TPPTS and methylated CDs

The complex concentration can be easily calculated from Eq. (2) where K and $[\ ]_T$ stand for association constant and total concentration, respectively.

$$[\mathrm{COMPLEX}] = -1/2\{(1/K+[\mathrm{CD}]_T+[\mathrm{TPPTS}]_T)^2-4[\mathrm{CD}]_T[\mathrm{TPPTS}]_T\}^{1/2} + 1/2(1/K+[\mathrm{CD}]_T+[\mathrm{TPPTS}]_T) \quad (2)$$

The value for $[\mathrm{CD}]_T$ is the concentration of the catalytic experiments, i.e. 42 mM. The value of $[\mathrm{TPPTS}]_T$ has been calculated by considering the free TPPTS amount, i.e. two equivalents of TPPTS on the five introduced for one rhodium. Indeed, three equivalents of TPPTS are involved in the formation of the catalytic species HRh(CO)(TPPTS)$_3$. So, the $[\mathrm{TPPTS}]_T$ is equal to 7.2 mM (i.e. 2/5 of the concentration of the catalytic experiments which is equal to 18 mM).

3. Results and discussion

3.1. Fractionation of the crude mixture of commercial RAME-β-CD by chromatography and analysis of the collected fractions by mass spectroscopy

In order to find the optimal conditions to fractionate the crude mixture of commercial RAME-β-CD, various thin-layer chromatograms have been performed. The best chromatogram was depicted in Fig. 2 and revealed five individual spots which likely correspond to five different samples of methylated β-CDs.

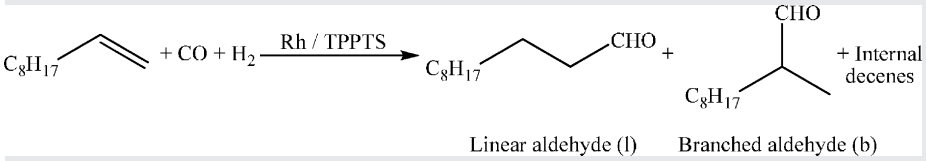
Further to this heterogeneity revealed by TLC, preparative separation of commercial RAME-β-CD on a silica gel column was successfully accomplished with dichloromethane–methanol solvent system. In order to isolate the compounds displaying different

Table 2
Composition of the commercial RAME-β-CD and of its related samples deduced from mass spectrometry spectra obtained by MALDI-TOF-MS and ESI-MS analyses: average number of methyl group by CD and calculated degree of substitution (DS).

Cyclodextrin	MALDI-TOF		ESI	
	Average number of methyl group by CD	DS	Average number of methyl group by CD	DS
RAME-β-CD[a]	11.7	1.7	11.8	1.7
Sample 1	13.6	1.9	13.6	1.9
Sample 2	12.4	1.8	12.4	1.8
Sample 3	11.5	1.6	11.5	1.6
Sample 4	10.5	1.5	10.5	1.5
Sample 5	9.7	1.4	9.6	1.4

[a] Commercial compound obtained from Wacker-Chemie.

Table 3
Biphasic rhodium-catalyzed hydroformylation of 1-decene in the presence of randomly methylated β-cyclodextrins with various degree of substitution (DS)[a].



Entry	CD (DS)	Conversion (%)[b]	Selectivity (%)[c]	*l*/*b* ratio[d]
1	(–)	10	60	2.8
2	RAME-β-CD (1.4)	62	96	1.8
3	RAME-β-CD (1.5)	72	96	1.8
4	RAME-β-CD (1.6)	77	96	1.8
5	RAME-β-CD (1.7)[e]	80	97	1.8
6	RAME-β-CD (1.8)	90	96	1.8
7	RAME-β-CD (1.9)	97	95	1.8

[a] Experimental conditions: $Rh(acac)(CO)_2$ (2.03×10^{-2} mmol), TPPTS (0.105 mmol), cyclodextrin (0.24 mmol), H_2O (5.75 mL), 1-decene (10.17 mmol), 1500 rpm, *T*: 353 K, $P(CO/H_2: 1/1) = 50$ atm, time = 6 h.
[b] Calculated with respect to the starting olefin.
[c] (Mol. of aldehydes)/(mol. of converted olefins) × 100. The side products were mainly isomeric olefins.
[d] Ratio of linear to branched aldehyde product.
[e] Commercial compound obtained from Wacker-Chemie.

degrees of methylation, 5.6 g of commercial RAME-β-CD was dissolved in dichloromethane (7 mL). The mixture thus obtained was added to the top of silica gel column, which was eluted using a mixture dichloromethane–methanol (98:2) at the rate of 10 mL min^{-1}. Sixty fractions of 40 mL were collected and monitored by TLC that revealed the presence of two different mixtures. The fractions containing similar constituents were combined and after evaporation of the solvent, two samples (0.52 and 1.56 g) of a white powder were obtained. In order to separate the rest of RAME-β-CD initially introduced on silica gel column, the fractionation has been going on with the same solvents but with a lower dichloromethane–methanol ratio (96:4). One hundred forty fractions of 40 mL were collected and the previously described procedure has been repeated. Three supplementary samples (1.52, 1.00 and 0.54 g) of a white powder were thus obtained.

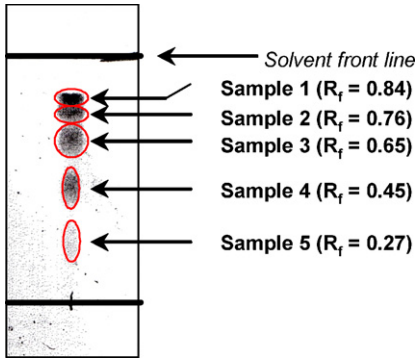


Fig. 2. Thin-layer chromatogram obtained from a commercially sample of RAME-β-CD (mobile phase: CH_2Cl_2–MeOH, 8:2, v/v; stationary phase: silica plate; developed by heating the TLC plate after immersion in methanol–sulphuric acid, 9.5:0.5, v/v).

In order to determine the composition of these five samples, each fraction was subjected to analysis by MALDI-TOF-MS and electrospray ionization mass spectrometry (ESI-MS) (all the spectra and their analysis are gathered in supplementary data). The heterogeneity of each sample was characterized from their DS, which represents the number of methyl group per glucose unit (Table 2), calculated using the mass peak area from both MALDI-TOF-MS and ESI-MS for each derivative in a given sample.

As previously observed in the case of RAME-β-CD analysis [12], whatever the mass spectrometry apparatus used, even if the ion sources (liquid versus solid ionization) and the molecular mass analyzer (quadrupole versus time-of-flight) were different, the MS spectra recorded by each kind of mass spectrometry provided an average number of methyl group per CD strictly identical, except for the sample 5 where the difference is only of 0.1 unit. As the same manner, the DS deduced from MS data are the same and decrease from sample 1 (1.9) to sample 5 (1.4).

3.2. Catalysis

The effect of these different samples of methylated β-CDs on the activity, chemoselectivity and regioselectivity has been evaluated in the rhodium-catalyzed hydroformylation reaction of 1-decene in an organic-aqueous biphasic system using $Rh(acac)(CO)_2$ as catalyst precursor and TPPTS as a water-soluble ligand. A CD/TPPTS ratio of 2.3 was used as we have previously described that this ratio

Table 4
Surface excess (Γ) for methylated β-CDs at 298 K[a].

Cyclodextrin	Γ (μmol/m^2)
RAME-β-CD (1.4)	0.304
RAME-β-CD (1.5)	0.403
RAME-β-CD (1.6)	0.530
RAME-β-CD (1.7)[b]	0.763
RAME-β-CD (1.8)	0.903
RAME-β-CD (1.9)	1.093

[a] Obtained the Wilhelmy plate method at the air–water interface and from Gibbs equation.
[b] Commercial compound obtained from Wacker-Chemie.

allowed reaching highly conversion of 1-decene in the presence of commercial RAME-β-CD [13]. For comparison, the results in the absence of CD and in the presence of commercial RAME-β-CD were also presented in Table 3.

Whatever the CD used, the conversion was increased (between 6- and 10-fold) in comparison to the value obtained for the reaction performed without CD. In the presence of commercial RAME-β-CD, the conversion after 6 h was equal to 80%. As already published, the benefice effect of this RAME-β-CD on the conversion was attributed to its high capacity to adsorb at the liquid/liquid interface [14]. In fact, RAME-β-CD forms host/guest complex with the water-insoluble olefins at the liquid/liquid interface which facilitates the reaction between the water-soluble catalyst and the substrate included in the RAME-β-CD cavity. The results obtained in the presence of the five different samples of methylated β-CDs issued from fractionation showed that the conversions varied from 62 to 97. It must be noticed that the higher conversion was reached with the more methylated RAME-β-CD (DS = 1.9) probably translating an easier adsorption at the interface. In order to confirm this assertion, the surface excess (Γ) at the air–water interface of the various methylated β-CDs has been determined by using the Gibbs adsorption equation (Table 4).

These values of surface excess corroborate an easier adsorption at the interface for the more methylated β-CD. In order to clearly connect these data to catalytic results, the conversion as function of the surface excess (Γ) has been plotted and a good correlation was found as demonstrated by the R^2 value (Fig. 3; $R^2 = 0.94$). It can be concluded that the higher is the CD concentration at the interface, the higher is the catalytic activity. Indeed, the more methylated β-CD (DS = 1.9; the less polar) is preferentially located at the interface compared to the less methylated β-CD (DS = 1.4; the more polar).

Concerning the chemoselectivity (the selectivity in aldehydes versus isomerisation products), no marked difference among the

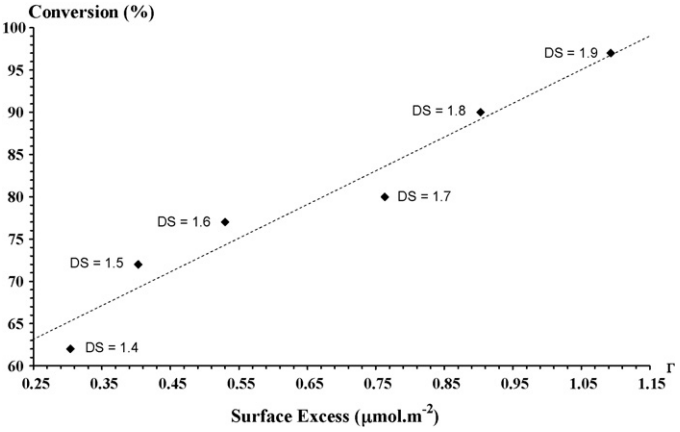


Fig. 3. Conversion in hydroformylation of 1-decene as a function of surface excess (Γ) [conversion (%) = 39.984 × Γ (μmol m^{-2}) + 53.038; $R^2 = 0.9499$].

Table 5
Value of association constant (K) between TPPTS and methylated β-CD in water at 298 K and percentages of complexed TPPTS and CD as a function of association constant.

CD	K (M^{-1})	Percentage of complexed TPPTS[a]	Percentage of complexed CD
RAME-β-CD (1.4)	1246	97.8	16.8
RAME-β-CD (1.5)	1044	97.3	16.7
RAME-β-CD (1.6)	811	96.6	16.6
RAME-β-CD (1.7)[b]	840	96.7	16.6
RAME-β-CD (1.8)	666	95.9	16.4
RAME-β-CD (1.9)	393	93.3	16.0

[a] The percentage of complexed TPPTS has been calculated by considering the free TPPTS species. Indeed, on the five equivalent of TPPTS initially introduced, three are involved in the formation of the catalytic species $HRh(CO)(TPPTS)_3$.
[b] Commercial compound obtained from Wacker-Chemie.

various methylated β-CDs is observed since in the presence of any CDs an increase of the value from 60% (without CD) to at least 95% is observed. In fact, a possible hydrogen bond interaction between the CD and the phosphane would be the cause of this improved chemoselectivity. No spectroscopic evidence has ever been found for the moment but Wipff et al. have demonstrated a possible hydrogen bond interaction between the secondary hydroxyl of methylated β-CD and the sulfonates of TPPTS by a molecular dynamics simulation [15,16].

Concerning the regioselectivity, the linear to branched aldehyde ratio (l/b) varies from 2.8 (without CD) to 1.8 (in the presence of commercial RAME-β-CD). As already described, this behavior is attributed to the formation of 1:1 inclusion complexes between TPPTS ligand and RAME-β-CD (commercial) [17,18]. Actually these inclusion complexes induced the formation of phosphane low-coordinated rhodium species responsible for the decrease in linear to branched ratio [19]. In the presence of any other methylated β-CDs, the value of the l/b ratio is also equal to 1.8. This result appears somewhat surprising since one could have expected that in the presence of the more methylated β-CDs, the affinity with TPPTS would be less important inasmuch as the cavity of these CDs is more encumbered. Indeed, the values of the association constants (K) for the complexes β-CD/TPPTS and RAME-β-CD (commercial)/TPPTS are equal to 1200 and 840 M^{-1}, respectively, showing the detrimental impact of the methyl groups onto the value of the association constant [20]. As no difference in regioselectivity has been observed with the various fractionated methylated β-CDs, we have determined the values of their association constants (K) with TPPTS by UV–vis spectroscopic studies in aqueous medium (Table 5).

As expected, a marked and linear decrease in the association constant is observed when the methylation degree increases suggesting that the steric hindrance resulting from the presence of more methyl groups on the methylated β-CDs would contribute to disfavour the inclusion of TPPTS inside the cavity. In order to understand the observed lack of effect on the regioselectivity, the percentages of complexed TPPTS and methylated β-CD (in the reaction condition) as a function of association constant have been calculated (Table 5). Interestingly, these percentages remained almost unchanged, explaining the invariability of the l/b ratio. Indeed, even with the lower value of association constant (RAME-β-CD; DS = 1.9; K = 393 M^{-1}), more than 93% of the free TPPTS remains complexed by this CD. These results suggest that for these values of association constant and for these concentrations, the CD methylation degree has no influence on the nature of the catalytic species explaining the invariability of the regioselectivity.

Finally, as the best catalytic result has been obtained in the presence of ramdomly methylated β-CD with a DS equal to 1.9, another experiment has been performed with the structurally well-defined 2,6-DIME-β-CD. This CD possesses a similar number of methyl groups (DS = 2) but this one is exactly methylated 14 times

on the positions 2 and 6. In the presence of this CD, only 25% of 1-decene was converted with a chemoselectivity and *l*/*b* ratio equal to 98 and 2, respectively. Interestingly, in comparison with RAME-β-CD (DS = 1.9; see Table 3, entry 7), 2,6-DIME-β-CD allows to reach equivalent chemoselectivity and *l*/*b* ratio but the conversion is four times lower (97% against 25%). This difference in conversion can be attributed to a variation of the CD physico-chemical properties such as tension surface, adsorption at the interface and solubility. For example, the water-solubility of this CD in hot water (80 °C; reaction temperature) is inferior at 1 g/L [21]. So, the positions of the methyl groups on the CD appear also as a crucial parameter to govern the efficiency of the mass transfer promoter. This aspect is currently under investigation and will be published in due course.

4. Conclusion

In this study, we have isolated by a column chromatography procedure five samples of methylated β-CDs from a crude mixture of commercially RAME-β-CD. The characterizations of these samples performed by MALDI-TOF-MS and ESI-MS show that these five methylated β-CDs possess an average number of methyl groups varying from 9.7 to 13.6 (DS from 1.4 to 1.9). The behavior of these five methylated β-CDs onto activity and selectivity has been evaluated in hydroformylation reaction. It appeared that the catalytic activity gradually increased with the number of methyl groups by CD whereas the chemoselectivity and regioselectivity remained unchanged. We have also demonstrated that a ramdomly methylated β-CD with an average substitution degree around 2 seems the best compromise for an application in aqueous hydroformylation reaction of higher olefins. Furthermore, another experiment conducted in the presence of 2,6-DIME-β-CD highlights that the positions of the methyl groups have a real impact on the activity of the catalytic experiments. As the catalytic activity is intimately related to the number and the position of methyl groups, it appears crucial to check the consistency of the commercially available methylated β-CD from batch to batch before the catalytic experiments.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.molcata.2008.12.017.

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