ELSEVIER

Catalysis Today 81 (2003) 347–357

CATALYSIS TODAY

www.elsevier.com/locate/cattod

Application of combinatorial chemistry and high-speed experimentation concepts to the study of titanium-silsesquioxane catalysts

Paolo P. Pescarmona[a,*], Jan C. van der Waal[a,b], Thomas Maschmeyer[a]

[a] *Laboratory of Applied Organic Chemistry and Catalysis, DelftChemTech, TU Delft, Julianalaan 136, 2628 BL Delft, The Netherlands*
[b] *Avantium Technologies B.V., Zekeringstraat 29, 1014 BV, P.O. Box 2915, 1000 CX Amsterdam, The Netherlands*

Received 27 May 2002; received in revised form 16 January 2003; accepted 21 January 2003

Abstract

Combinatorial Chemistry and High-Speed Experimentation techniques find a growing number of applications in catalysis. Here, these techniques have been applied to the optimisation of the different steps in the preparation of active titanium silsesquioxane catalysts for the epoxidation of alkenes. First, the synthesis of the silsesquioxane precursors was optimised. The best precursor was obtained by the hydrolytic condensation of cyclopentyltrichlorosilane in acetonitrile. This lead was characterised by ^{29}Si NMR Spectroscopy and by Mass Spectrometry. Next, the effect of the nature of the titanium centres bound to the silsesquioxane structures on the catalytic activity was explored. The coordination of diols to the titanium centres resulted in an improvement of the activity when using H_2O_2 as the oxidant.

Keywords: Combinatorial chemistry; High-speed experimentation; Titanium-silsesquioxane catalysts

1. Introduction

Combinatorial chemistry and high-speed experimentation (HSE) techniques allow the preparation and the testing of large number of samples in a short time [1]. These techniques, initially developed for pharmaceutical research, are increasingly applied to various fields of chemical research and particularly to catalysis [2,3] and materials science [4]. The term combinatorial chemistry indicates the methodology of combining different experimental parameters and test the so-obtained combinations for selected properties. The term HSE, alternatively known as high-throughput experimentation (HTE), refers to the automated equipment that, allowing fast preparation and screening of samples, is often necessary to carry out a combinatorial approach.

These techniques are a powerful tool for industrial as well as for academic scientific research. To explain how and in which cases these techniques can be advantageously applied we will here consider the general case of the discovery/optimisation of a catalytic system. Given a chemical reaction for which a catalyst is wanted, the first step in *primary screening* consists of gathering all the knowledge already available in the literature about the subject. In many cases this search provides basic information about the characteristics of the most suitable catalytic system for the chosen

---

* Corresponding author. Tel.: +31-15-2782692; fax: +31-15-2784289.
E-mail address: p.p.pescarmona@tnw.tudelft.nl (P.P. Pescarmona).

0920-5861/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0920-5861(03)00133-0

chemical reaction (e.g. an acid rather than a basic catalyst, a homogenous rather than a heterogeneous catalyst). If this information is scarce or absent, the issue becomes how to find a way to get basic knowledge of the system under investigation. This could be achieved with an experimental approach and/or by means of computational modelling. If an experimental approach is chosen, this second step in *primary screening* should cover a broad range of parameters in order to gain very general information about the system. This usually requires a large number of experiments to be performed, for which purpose combinatorial chemistry and HSE techniques are particularly helpful.

Different combinatorial chemistry synthetic methods for *primary screening* have been developed. The *mix&split* method [1], mainly used in pharmaceutical research, and the *masking* strategies [4], developed for solid-state materials science, allow the fast synthesis and screening of very large libraries of compounds (thousands per week). *Parallel* methods [1] performed by means of HSE equipment allow the preparation and the testing of arrays of discrete samples in small-volume reaction vessels. These methods have a lower throughput (hundreds of samples per week) than *mix&split* and *masking* methods, but one that is still very high when compared with traditional serial methods. The lower throughput of HSE *parallel* techniques might be a drawback for a *primary screening*, which requires gathering a broad set of information in a short time. This problem can be overcome by using design of experiments (DOEs) methods and search algorithms, that allow to reduce the number of experiments to be performed by means of statistical data-handling [3,5–7]. Moreover, *parallel* methods are more versatile than *mix&split* and *masking* methods: with the latter, just the composition of a target compound can be optimised, while *parallel* methods also allow the variation of other synthetic parameters (solvent, pH, concentrations, temperature, etc.).

Typically, the *primary screening* provides a set of lead compounds and some basic correlation between the properties of the leads and their structural and synthetic characteristics. In the *secondary screening* one or more of these leads are further optimised: the information obtained from the *primary screening* is the basis to focus further research on a smaller experimental parameter space. Dealing with a more focussed parameter space means that more detailed and specific information can be obtained in this screening phase. The fact that the screened parameter space is smaller in the *secondary* than in the *primary screening* implies that the number of experiments performed in the *secondary screening* is lower while their accuracy should be higher. Therefore, HSE parallel techniques are specifically useful to speed up the *secondary screening*. Moreover, since they allow parallel testing of various samples, they can be used to gain insight in trends or even estimate reaction kinetics. The applicability of HSE techniques to *secondary screening* is determined by the technical limitations of the automated workstations employed. These limitations may range from the preparation of the samples (e.g. inefficient mixing of reaction mixtures in the small HSE vessels) to their analysis (e.g. equipment for high-throughput screening of the samples is not yet available for every spectroscopic technique). The quality of the HSE equipment is continuously improving, nevertheless at this stage not every chemical synthesis can be studied by means of HSE techniques.

At the end of the *secondary screening* a restricted number of leads will be identified and the correlation between their properties and their structural and synthetic characteristics will be much more defined than at the end of the *primary screening*. It is at this point that the leads can be studied in detail at a conventional laboratory scale: this typically includes the characterisation of the lead with different spectroscopic techniques. If combinatorial chemistry and HSE techniques have been used during the earlier screening stages, repeating the experiment in a conventional manner is an important check of the reproducibility of the results on a larger-volume scale.

2. Results and discussion

As an example of some of the concepts described above, we report here the application of HSE techniques to the study of the synthesis of titanium silsesquioxanes as catalysts for the epoxidation of alkenes.

Silsesquioxanes [8] are compounds of general formula $(RSiO_{1.5})_a(H_2O)_{0.5b}$, where R is a hydrogen atom or an organic group and *a* and *b* are integer

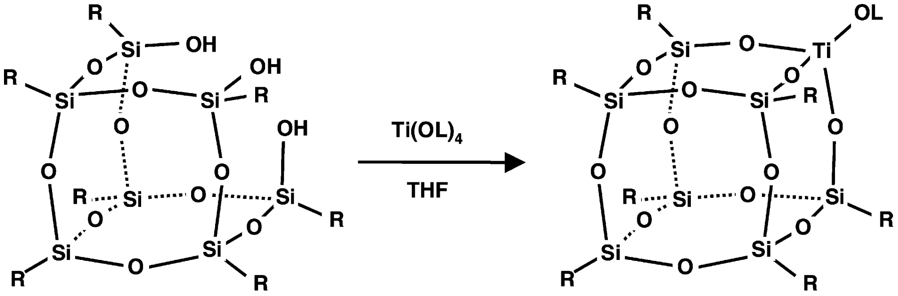

Fig. 1. Insertion of a titanium centre on silsesquioxane *a*7*b*3 [$R_7Si_7O_9(OH)_3$].

numbers ($a = 1, 2, 3, \ldots; b = 0, 1, 2, 3, \ldots$) linked to each other by the following relations:

$$a + b = 2n, \text{ where } n \text{ is an integer } (n = 1, 2, 3, \ldots),$$
$$b \leq a + 2$$

They are usually subdivided into two categories: completely condensed silsesquioxanes, for which $b = 0$, and incompletely condensed silsesquioxanes, for which $b \neq 0$ and which therefore contain silanol groups (Si–OH). Silsesquioxanes have found applications in the areas of catalysis, materials science, coordination chemistry and in general as model compounds for silica.

The incompletely condensed silsesquioxane *a*7*b*3 has found applications as ligand for a number of metal centres [8]. Particularly, titanium complexes of silsesquioxane *a*7*b*3 resulted in very active catalysts for the epoxidation of alkenes (Fig. 1) [9,10]. There is considerable interest in these catalysts, but commercial introduction is severely hindered by the long and expensive preparation method of the silsesquioxane precursor [11,12]. Therefore, we set as our first goal the identification of a new and efficient way to synthesise silsesquioxane precursors for titanium catalysts active in the epoxidation of alkenes.

During the initial step in *primary screening*, a survey of the literature concerning silsesquioxanes together with our chemical knowledge of the subject lead us to some general considerations:

- Silsesquioxanes are usually synthesised by the hydrolytic condensation of organosilanes ($RSiX_3$) [8]: this is a multiple-step reaction for which an overall mechanism is not available.
- Many parameters influence the hydrolytic condensation and determine which silsesquioxane species are formed and in which amounts.
- The hydrolytic condensation of organosilanes usually produces a mixture of completely and incompletely condensed silsesquioxanes.
- Incompletely condensed silsesquioxanes different from *a*7*b*3 may also complexate titanium centres and produce active epoxidation catalysts.

Given all this information and considering the amount of variables involved in the problem, we decided no experimental *primary screening* was necessary and applied HSE parallel techniques, as *secondary screening*, to the optimisation of the synthesis of silsesquioxanes as a function of the activity of the catalysts obtained after titanium insertion in the silsesquioxane structures. The epoxidation of 1-octene with *tert*-butyl hydroperoxide (TBHP) as oxidant was chosen as test reaction for the catalysts. The first step of this *secondary screening* was to decide which parameter space had to been screened. It is known that the parameters influencing the hydrolytic condensation are the nature of the R group and of the X group in the organosilane and its concentration in the reaction mixture, the solvent in which the synthesis is performed, the rate of addition and amount of H_2O, the pH, the temperature and the reaction time. On the basis of our chemical knowledge and intuition, we assumed that the solvent and the R group were likely to have the strongest influence on the hydrolytic condensation. Therefore, our approach was to study a parameter space defined by the combination of these two parameters. The choice of extensively studying a small set of parameters rather than investigating a more varied parameter space also gives the possibility

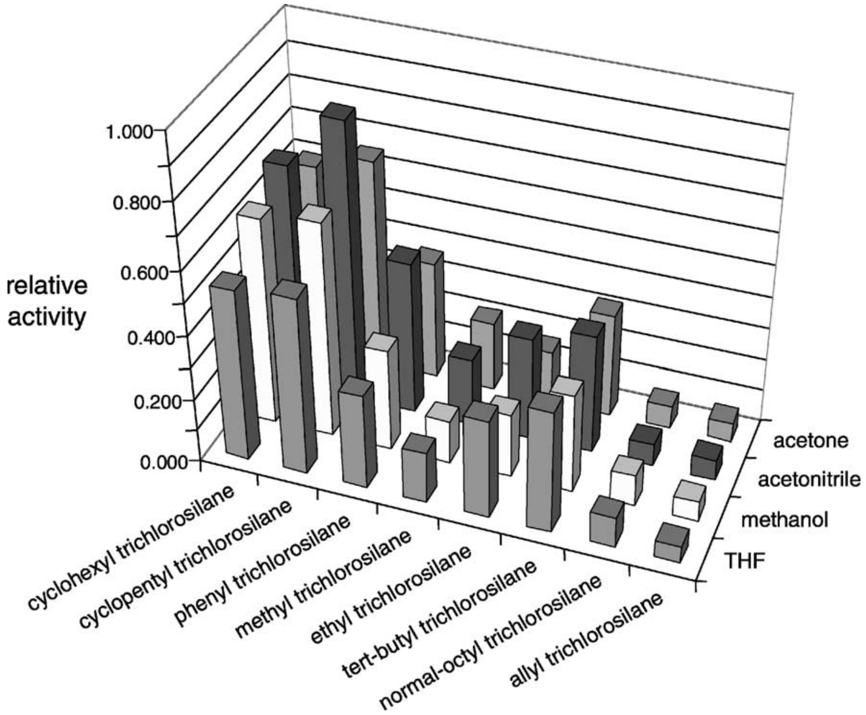

Fig. 2. HSE screening of the epoxidation activity of Ti-silsesquioxanes as a function of the parameters varied in the synthesis of the silsesquioxane precursors.

of identifying some trends concerning the effects of these parameters on the reaction. It is important that each of the parameters is sufficiently varied within the parameter space in order to minimise the risk of identifying a local maximum or missing local trends. Here, we studied a parameter space defined by the combination of four solvents and eight R groups. The set of R groups should be wide enough and varied. The set of solvents is smaller and more defined: just water-miscible solvents were selected, since the reaction includes water among the reagents. The solvents were chosen on a scale of polarity to check the influence of this property on the synthesis of silsesquioxanes. In Fig. 2 is reported the activity of the titanium catalysts as a function of the solvents and R groups varied in the hydrolytic condensation.[1] Experimental information and a detailed discussion of these HSE results are reported elsewhere [13,14]. Summarising these results, the following information was identified:

- A trend indicating that more polar solvents favour the formation of incompletely condensed silsesquioxane precursors for active titanium catalysts.
- A trend that suggests that more sterically hindered R groups favour the formation of incompletely condensed silsesquioxane ligands for active titanium catalysts.
- A lead displaying the highest activity in the screened parameter space, given by the combination of R = cyclopentyl and acetonitrile as solvent.

From a methodological point of view, the fact that different points in the screened parameter space show very different activities confirms the hypothesis that the chosen parameters have a relevant influence on the hydrolytic condensation: this means that a representative parameter space was studied. An important question that arose from this experiment was whether the

---

[1] The values are normalised to the activity of the complex obtained by reacting $Ti(OPr^i)_4$ with the pure cyclopentyl silsesquioxane *a*7*b*3 (the activity of which is set at 1).

parameter space was narrowed too much using literature and experience as the starting point, rather than an experiment in a wider parameter space. In this respect, the coincidence of finding only cyclopentyl and cyclohexyl as good candidates while they are also the only ones reported in the literature for the synthesis of silsesquioxane *a*7*b*3 [11,12], might be due to bias for the synthesis condition particularly suited for these silanes. This remark together with the trend indicating a beneficial effect of polarity suggest that it could be interesting in future research to broaden the screened parameter space to other polar solvents.

The identified lead shows 87% of the activity of the titanium catalyst obtained from pure silsesquioxane *a*7*b*3. This is a relevant result since the synthesis of the HSE-developed silsesquioxane precursors is faster and more straight-forward [13]. It is then interesting to characterise this lead on a conventional laboratory scale. First, the experiment was repeated in a 125 ml scale (50 times up-scaling) giving a comparable activity and, therefore, confirming the applicability of HSE techniques to the synthesis of silsesquioxanes. Then, the silsesquioxane precursor was characterised prior to reaction with the titanium centre. The reaction of cyclopentyl trichlorosilane with water in acetonitrile, for 18 h at 50 °C, yields two silsesquioxane fractions: one as a precipitate (A) and the other that is soluble in the reaction mixture (B). Fraction B was dried under vacuum and redissolved in tetrahydrofuran. The drying of fraction B induces an increase in the level of condensation of the silsesquioxane species, as proved by the fact that the gel obtained is not anymore soluble in acetonitrile. Both fractions were characterised by NMR spectroscopy and mass spectrometry. Fraction A mainly consists of silsesquioxane *a*7*b*3 [12], as determined by means of ^{29}Si NMR (Fig. 3) and MS analysis. Fraction B is a mixture of different silsesquioxane species, as indicated by MS analysis. The region in which most of the peaks in the ^{29}Si NMR spectrum of fraction B are found is that of silanol groups belonging to incompletely condensed silsesquioxanes (Fig. 4) [8,12]. It is equally difficult to assign all the species present in the mixture or separate them. However, on the basis of both NMR and MS data, we suggest that the main species is the silsesquioxane structure *a*6*b*2 reported in Fig. 5; this structure is in agreement with the three ^{29}Si NMR peaks marked in Fig. 4 and with the main set of MS peaks, corresponding to silsesquioxanes with six Si atoms. This assignment is supported by the similarity of the ^{29}Si NMR spectrum with that of cyclohexyl silsesquioxane *a*6*b*2, which can be obtained by cleavage of the completely condensed *a*6*b*0 structure [15]. Finally, both fractions were reacted with titanium butoxide. The insertion of the titanium centre in the silsesquioxane structures was confirmed by ^{29}Si NMR (Figs. 3 and 4). The catalytic activity in the epoxidation of 1-octene of the HSE lead and of the two fractions in which the latter can be divided were studied as a function of the reaction time (Fig. 6). The activity of fraction A is comparable to that of the Ti-catalyst obtained with pure silsesquioxane *a*7*b*3, whose activity is set as 1. Fraction B shows a much lower, but still significant, activity: this result confirms the validity of our initial assumption that incompletely condensed silsesquioxanes other than *a*7*b*3 can be precursors for active titanium catalysts. It is interesting to notice that for fraction A, the activity reaches a maximum after 30 min while for fraction B the activity slowly increases along the 4 h and does not reach a plateau. The behaviour of the HSE lead is an average of that of the two fractions: a plateau is reached after 2 h of reaction.

After the optimisation of the synthesis of the silsesquioxane precursors, it is interesting to further study the titanium-silsesquioxane epoxidation catalysts by varying the nature of the active titanium centre. Different ligands on the titanium can influence the activity of the catalyst both through steric and electronic effects [16,17]. It would be particularly useful to identify a titanium silsesquioxane that could be used with aqueous hydrogen peroxide (H_2O_2) as oxidant. The advantage of using hydrogen peroxide rather than TBHP or another organic peroxide, is that hydrogen peroxide would yield H_2O as the by-product, with evident environmental and economical benefits for the process. So far, the use of H_2O_2 as the oxidant with homogeneous titanium catalysts has been hindered either by strong adsorption of H_2O on the titanium centre or by the rapid deactivation of the catalyst due to the leaching of the titanium centre and formation of inactive TiO_2 species, caused by hydrolysis.

Here, we used HSE techniques for a further *secondary screening* of the titanium silsesquioxanes. As silsesquioxane precursors, both the pure cyclopentyl silsesquioxane *a*7*b*3 and the lead mixture obtained

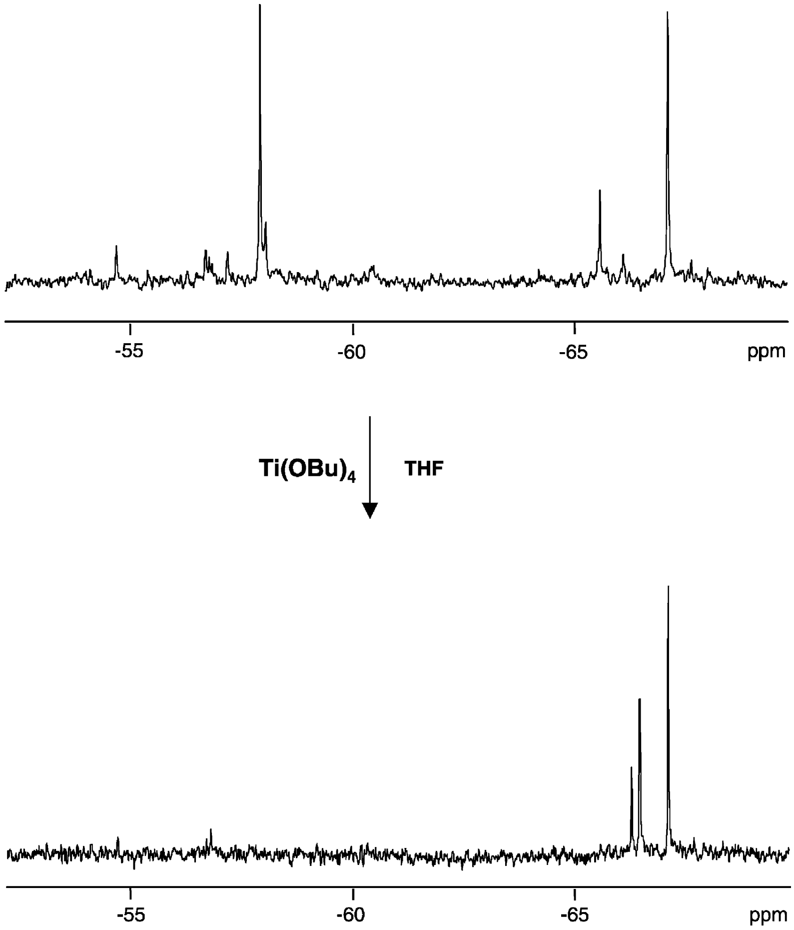

Fig. 3. ^{29}Si NMR analysis of fraction A, previous to (top) and after (bottom) titanium insertion.

from the previous HSE screening (cyclopentyl trichlorosilane hydrolysed for 18 h in acetonitrile) were used. As oxidants, TBHP and H_2O_2 were used. As titanium precursors, five different titanium alkoxides Ti(OL)$_4$ (L = Me, Et, Pr, Pr^i, Bu) and cyclopentadienyltitanium trichloride were chosen. Besides, a series of diols (ethylene glycol, 2,3-butanediol, cyclohexanediol, pinacol and benzopinacol) were used as ligands for the Ti-centre, in this case Ti(OBu)$_4$. The purpose of having a diol coordinating to the Ti-centre is to reduce its accessibility for polar molecules by increasing the hydrophobicity around the catalytic centre (Fig. 7); this may prevent the reaction with water and consequent catalyst deactivation when using H_2O_2 as oxidant. The resulting 44-elements parameter space was screened for the epoxidation of 1-octene (Fig. 8) (see footnote 1). The experimental results of the six titanium centres and of the five diols are discussed separately:

- For what concerns the six titanium centres, the first general observation is that all the catalysts are very active with TBHP as oxidant while they show low activities when H_2O_2 is the oxidising agent. This suggests that these catalysts still undergo deactivation due to the reaction with water, as confirmed by the formation of a white precipitate (probably TiO_2) in the reaction vessels. When TBHP is used as oxidant, the pure silsesquioxane *a*7*b*3 turns out being a slightly better precursor than our HSE mixture for any Ti-centre. In average, the ratio between the activities of the HSE mixture and the pure *a*7*b*3

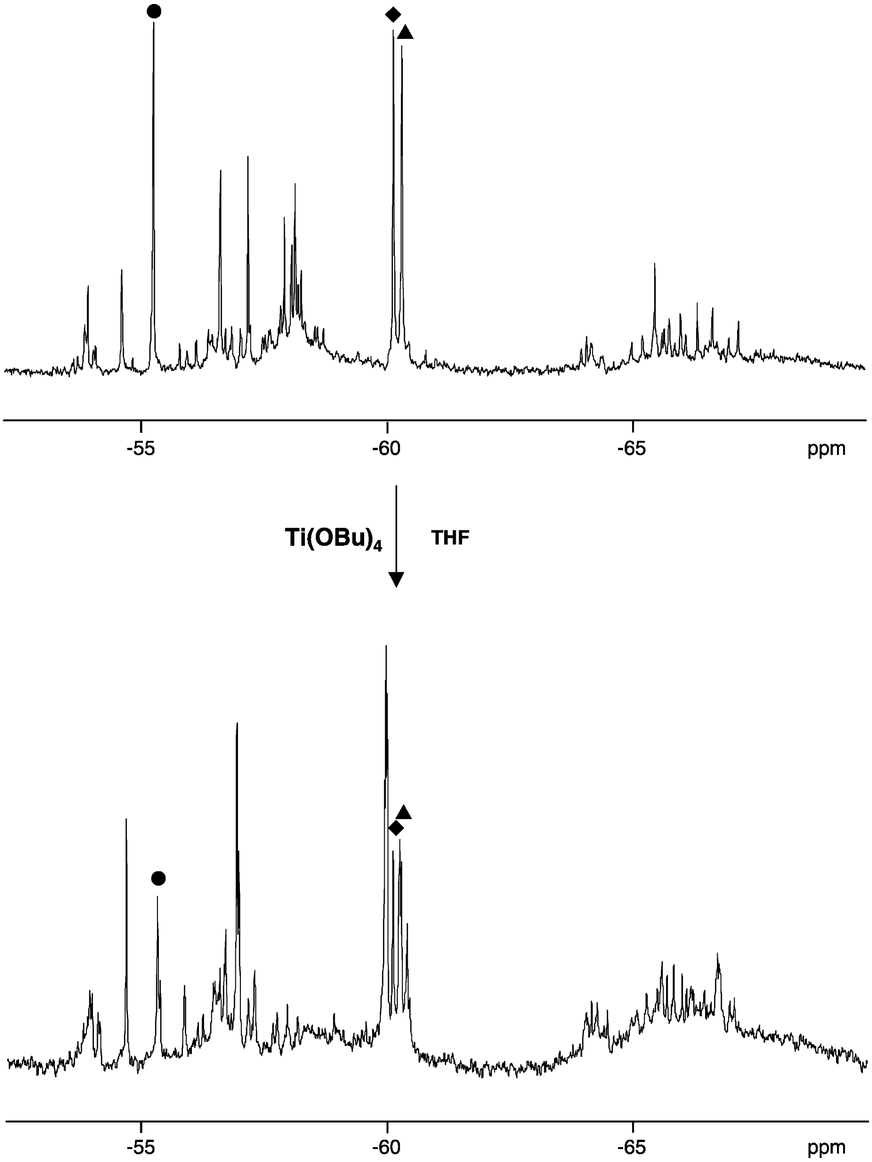

Fig. 4. ^{29}Si NMR analysis of fraction B, previous to (top) and after (bottom) titanium insertion.

catalysts is 0.87. Considering the various Ti-centres, no big variation in activity can be observed among the titanium alkoxides with L = Me, Et, Pr, Bu; most of the differences fall within the same range, given that the experimental error of these HSE data is ±3%. The activity with $Ti(OPr^i)_4$ and cyclopentadienyltitanium trichloride are slightly, but noticeably, lower. This trend can be explained by considering that the isopropoxy and cyclopentadienyl groups are bulkier compared to the linear alkoxides. Therefore, the accessibility to the titanium site is reduced, causing a decrease in catalytic activity [9]. On the basis of literature data [9], it would be also expected to have a trend in activity among the linear alkoxides. This trend cannot be confirmed nor denied by our experimental data, due to the

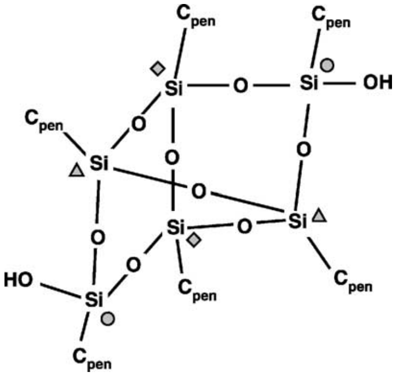

Fig. 5. Schematic representation of cyclopentyl silsesquioxane *a*6*b*2 $[R_6Si_6O_8OH)_2]$.

level of inaccuracy of the HSE techniques. From a methodological point of view, this indicates a limit of HSE techniques which may not be able to discern between activities within a narrow range of values.

- For what concerns the addition of a diol to the Ti-centre, the expected effect should be a lower catalytic activity when using TBHP as oxidant due to the lower accessibility of the site (similarly to what described above for isopropoxy and cyclopentadienyl groups). On the other hand, a higher activity with H_2O_2 may occur if the diol ligand were protecting the titanium site from reaction with water. The data reported in Fig. 7 show the expected decrease in activity with TBHP when ethylene glycol, 2,3-butanediol and cyclohexanediol are used, while the effect is less relevant with the two bulkiest diols, pinacol and benzopinacol. This indicates that the coordination of pinacol and benzopinacol to the titanium centres on the silsesquioxanes is probably sterically hindered, particularly for the Ti-centre on the pure silsesquioxane *a*7*b*3. The same effect in a minor extent can explain the intermediate activity obtained with cyclohexanediol. The fact that the presence of a diol causes a much higher decrease in activity with the HSE mixture of silsesquioxanes than with pure silsesquioxane *a*7*b*3 points to the different nature of the Ti-complexes present in the HSE mixture, some of which probably become

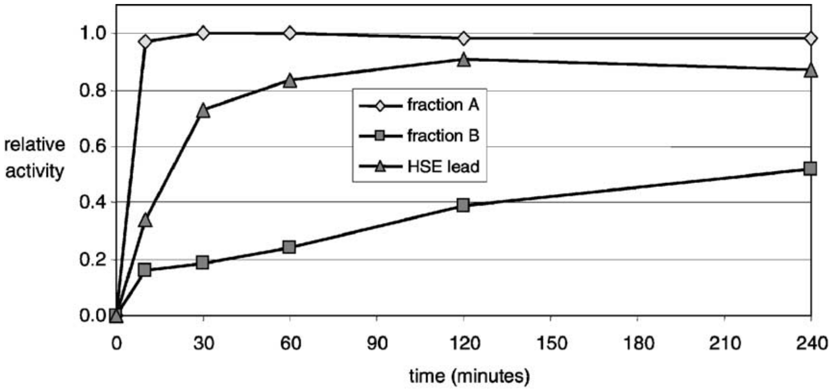

Fig. 6. Activity in the epoxidation of 1-octene with TBHP as a function of the reaction time.

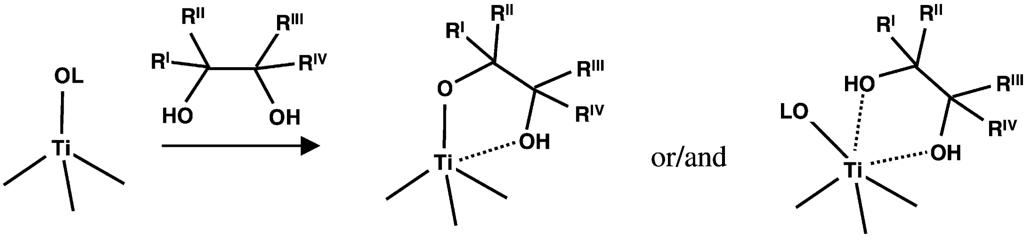

Fig. 7. Possible interactions between a diol and the Ti-centre on a silsesquioxane.

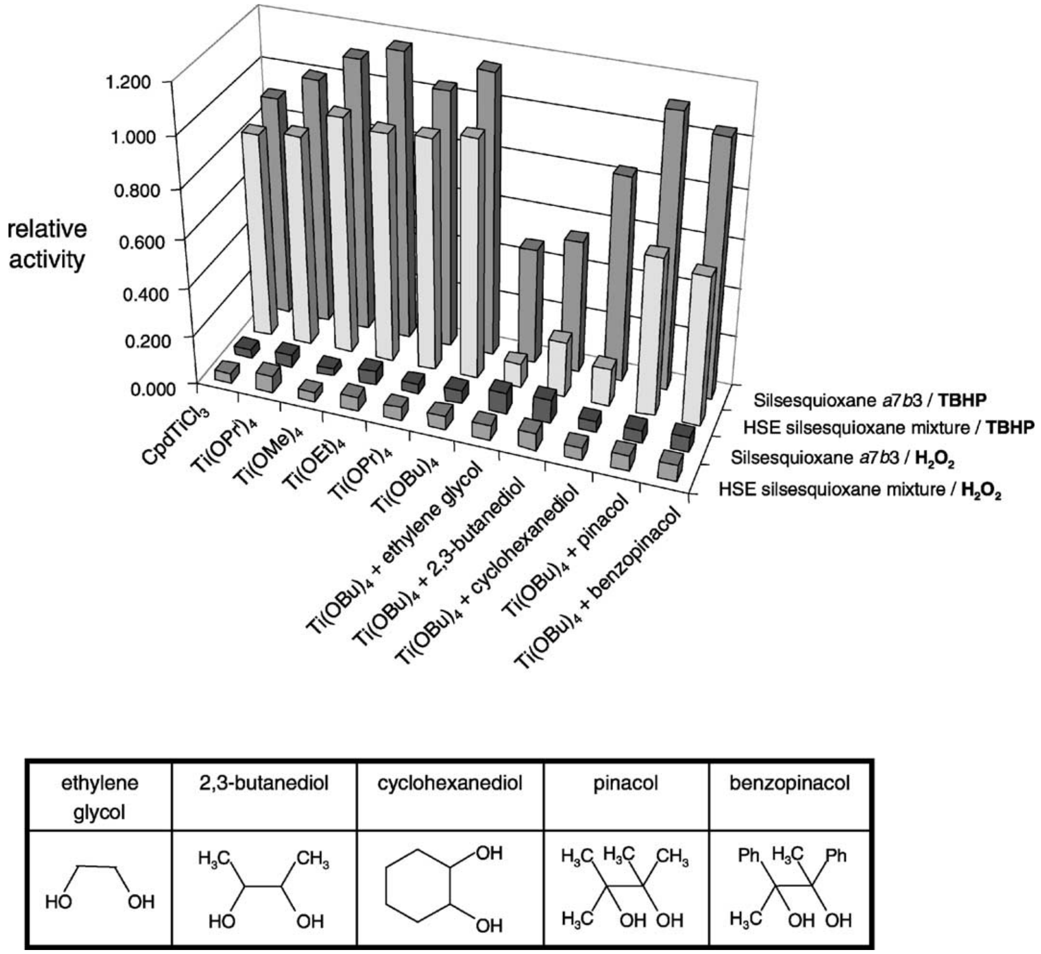

Fig. 8. HSE screening of the epoxidation activity of Ti-silsesquioxanes with two different oxidants (TBHP and H_2O_2) as a function of the nature of the Ti-centres.

completely inaccessible for catalysis in the presence of one or more diol ligands.

- When H_2O_2 is used as oxidant, a positive effect of the diols can be seen mainly with ethylene glycol and 2,3-butanediol, in agreement with the result for TBHP, where for these two diols the biggest decrease in activity is observed. Unfortunately, the activity is still rather low, with the best result being 8% of conversion of H_2O_2 into 1,2-epoxyoctane in the case of 2,3-butanediol with pure silsesquioxane *a*7*b*3.[2] This indicates that the effect of the diols, although detectable—thus, the concept works, is not relevant enough to produce a good and robust catalyst for the epoxidation of 1-octene with hydrogen peroxide.

3. Conclusions

HSE techniques proved to be a powerful tool for studying and optimising the synthesis of titanium-silsesquioxane catalysts. These techniques are rather versatile; they can be applied on different stages of the screening of the system under study and they can be useful for the identification of leads as well as investigating trends. For these reasons, HSE techniques can find application both in academic and

---

[2] As a reference, a blank reaction with 1-octene and H_2O_2 but no catalyst was performed, giving no epoxidation activity.

industrial research. At an academic level, HSE techniques can be fruitfully coupled with conventional characterisation techniques.

4. Experimental

Experimental details about the HSE optimisation of the synthesis of the silsesquioxane precursors can be found elsewhere [13,14].

125-ml scale synthesis of the HSE lead: 25 ml of deionised water were carefully added into a round-bottom flask containing a solution of 2.8 ml of cyclopentyltrichlorosilane (c-C_5H_9)$SiCl_3$ (97% purity), in 100 ml of acetonitrile (CH_3CN:H_2O = 4:1 in volume). The solution was then heated to 50 °C while stirring for 18 h; a white precipitate was formed (0.97 g, fraction A). The remaining solution (fraction B) was dried under reduced pressure to afford a dense gel, which was then dissolved in 10 ml of tetrahydrofuran: a non-soluble NH_4Cl residue (produced by the hydrolysis of CH_3CN) was removed. Consecutive drying of the solution afforded a silsesquioxane gel that was characterised by NMR and MS.

Titanium insertion was performed by dissolving each fraction in 50 ml of tetrahydrofuran, followed by the addition of 0.5 ml of titanium butoxide $Ti(OBu)_4$ to each solution. Both samples were then heated to 60 °C for 5 h and finally dried under vacuum. To test the catalytic activity in epoxidation reactions, the two solid samples were dissolved each in 56.5 ml of 1-octene (with 2 vol.% of decane as internal standard for GC analysis), followed by addition of 3 ml of TBHP (∼40 wt.% solution in cyclohexane), stirred and heated to 80 °C. Samples were taken at different times (see Fig. 6) and analysed with a UNICAM Pro GC using a CP-Sil-5B column. The activity data were obtained by normalising the 1,2-epoxyoctane GC peak area by means of the internal standard.

^{29}Si NMR spectra were measured on a Varian VXR-400S (79.5 MHz, ^{1}H decoupled, D-THF as solvent, 25 °C). Main peaks for fraction A, δ: −57.91, −65.70, −67.29 (3:1:3); fraction B, δ: −55.13, −60.16, −60.33 (1:1:1).

Mass spectrometry analysis was performed using a Micromass Quattro LC-MS with ESI+ as ionisation technique. The samples were prepared by dissolving ∼0.05 g of crude product in 4 ml tetrahydrofuran, 1 ml acetonitrile and 0.1 ml formic acid 0.1 M. From the MS data it is possible to determine the number of Si atoms (the value of a in $(RSiO_{1.5})_a(H_2O)_{0.5b}$) of the detected species but not the level of condensation (the value of b). The reason for this is that in the ionisation process silsesquioxanes can lose water molecules, as confirmed by the fact that the ratio among the peaks for a given value of a changes as a function of the cone voltage applied in the MS analysis.

Selected MS data:

Fraction A (cone voltage = 65 V). For $a = 7$, m/z: 875.04 (H^+, 100%), 839.00 (H^+, 41%), 897.08 (Na^+, 16%), 911.09 (H^+, 16%), 857.03 (H^+, 11%). For $a = 8$, m/z: 969.03 (H^+, 4%), 987.05 (H^+, 2%).

Fraction B (cone voltage = 30 V). For $a = 4$, m/z: 543.60 (Na^+, 14%), 557.56 (H^+, $+H_2O$, 13%). For $a = 5$, m/z: 655.53 (Na^+, 30%), 633.61 (H^+, 28%). For $a = 6$, m/z: 763.41 (H^+, 100%), 785.39 (Na^+, 55%), 745.41 (H^+, 38%). For $a = 9$, m/z: 1157.23 (Na^+, 22%), 1175.24 (Na^+, 17%), 1135.12 (H^+, 18%). For $a = 10$, m/z: 1287.03 (Na^+, 29%), 1305.09 (Na^+, 27%), 1265.11 (H^+, 25%). For $a = 11$, m/z: 1417.97 (Na^+, 36%), 1396.11 (H^+, 26%). For $a = 12$, m/z: 1547.83 (Na^+, 39%), 1529.95 (Na^+, 26%).

The HSE study of the Ti-centres was performed by means of an automated parallel synthesis workstation[3] coupled with a personal computer supplied with software enabling to program the workstation. Titanium insertion was performed by dissolving either 4.7×10^{-5} mol of the pure cyclopentyl silsesquioxane $a7b3$ or a corresponding amount of the HSE-optimised cyclopentyl silsesquioxane mixture in 2 ml of THF, followed by the addition of 54 μmol of one of the titanium precursor as a solution in a an organic solvent (the corresponding alcohol for the titanium alkoxides, dichloromethane for cyclopentadienyltitanium trichloride). Samples were stirred in an orbital shaker for 5 h at 60 °C. In the case of the experiment with diols, THF solutions each containing 0.1 mmol of a diol were added to the appropriate vials. Samples were then stirred in the orbital shaker for 10 h at 50 °C. Finally, THF was removed by means of a vacuum centrifuge and the samples were stored under argon. The activity of the Ti-silsesquioxanes in the epoxidation of 1-octene was determined by adding to each dried sample 2.26 ml of 1-octene (with 2 vol.% of decane

---

[3] Kindly provided by Avantium Technologies.

as internal standard), that acted both as reactant and solvent, and 121 μl of TBHP (∼40 wt.% solution in cyclohexane) or 70 μl of H_2O_2 (35 wt.% solution in H_2O). H_2O_2 and 1-octene are not miscible; to obtain a monophasic system, the reaction was alternatively performed with 1-propanol as solvent (1.13 ml 1-propanol, 1.13 ml 1-octene and 70 μl of aqueous H_2O_2). However, the activities obtained in these conditions were lower than with the biphasic system, probably because of faster catalyst deactivation caused by reaction with water. Samples were taken after having been stirred in the orbital shaker for 4 h at 80 °C (TBHP) or for 6 h at 60 °C (H_2O_2) and analysed on the UNICAM Pro GC. The reported activities were obtained by normalising the 1,2-epoxyoctane GC peak area by means of the internal standard.

Acknowledgements

Anton Sinnema is kindly acknowledged for the measurement of the NMR spectra.

References

[1] P.P. Pescarmona, J.C. van der Waal, I.E. Maxwell, T. Maschmeyer, Catal. Lett. 63 (1999) 1.
[2] M.T. Reetz, Angew. Chem. Int. Ed. 40 (2001) 284.
[3] S. Senkan, Angew. Chem. Int. Ed. 40 (2001) 312.
[4] B. Jandeleit, D.J. Schaefer, T.S. Powers, H.W. Turner, W.H. Weinberg, Angew. Chem. Int. Ed. Engl. 38 (1999) 2494.
[5] D.C. Montgomery, Design and Analysis of Experiments, 4th ed., Wiley, New York, 1996.
[6] A. Holzwarth, P. Denton, H. Zanthoff, C. Mirodatos, Catal. Today 67 (2001) 309.
[7] J.M. Cawse, Acc. Chem. Res. 34 (2001) 213.
[8] P.P. Pescarmona, T. Maschmeyer, Aust. J. Chem. 54 (2001) 583.
[9] T. Maschmeyer, M.C. Klunduk, C.M. Martin, D.S. Shephard, J.M. Thomas, B.F.G. Johnson, Chem. Commun. (1997) 1847.
[10] M. Crocker, R.H.M. Herold, A. Guy Orpen, Chem. Commun. (1997) 241.
[11] F.J. Feher, D.A. Newman, J.F. Walzer, J. Am. Chem. Soc. 111 (1989) 1741.
[12] F.J. Feher, T.A. Budzichowski, R.L. Blanski, K.J. Weller, J.W. Ziller, Organometallics 10 (1991) 2526.
[13] P.P. Pescarmona, J.C. van der Waal, I.E. Maxwell, T. Maschmeyer, Angew. Chem. Int. Ed. Engl. 40 (2001) 740.
[14] P.P. Pescarmona, J.J.T. Rops, J.C. van der Waal, J.C. Jansen, T. Maschmeyer, J. Mol. Catal. A 182–183 (2002) 319.
[15] F.J. Feher, F. Nguyen, D. Soulivong, J.W. Ziller, Chem. Commun. (1999) 1705.
[16] M.C. Klunduk, T. Maschmeyer, J.M. Thomas, B.F.G. Johnson, Chem. Eur. J. 5 (1999) 1481.
[17] J.M. Thomas, G. Sankar, M.C. Klunduk, M.P. Attfield, T. Maschmeyer, B.F.G. Johnson, R.G. Bell, J. Phys. Chem. B 103 (1999) 8809.