PREPARATION OF TETRAMETHYLGUANIDINE-FUNCTIONALIZED MESOPOROUS SILICA AS A CATALYST FOR THE EPOXIDATION OF ELECTRON DEFICIENT ALKENES

JEG Mdoe
Chemistry Department, University of Dar es Salaam, P. O. Box 35061,
Dar es Salaam, Tanzania
E-mail: mdoe@chem.udsm.ac.tz

ABSTRACT

A heterogeneous guanidine catalyst, based on 1,1,3,3-tetramethylguanidine was prepared by functionalisation of a glycidylpropyl group previously attached to hexagonal mesoporous silica. The catalyst was characterized by various techniques including Diffuse Reflectance FTIR, ^{13}C NMR, elemental analysis and simultaneous thermogravimetric and differential scanning calorimetry analyses. It was then screened in the epoxidation of electron deficient alkenes. The results obtained show that indeed the intended moiety was attached onto silica surface at a loading of 0.4 mmol per g silica. The parent silica had a surface area of 1511 m^2 g^{-1} which decreased to 1275 m^2 g^{-1} upon functionalisation. The catalyst was active and highly selective in epoxidation of electron deficient alkenes, giving yields up to 60% within 12 hours. The reusability of the catalyst was however limited, calling for further investigation.

INTRODUCTION

Guanidines are one of the most common strong organic bases that are used as homogeneous catalysts for base-catalysed reactions (Simoni *et al.* 1997, Simoni *et al.* 1998, Pahadi *et al.* 2007) add few recent references if any). Supported guanidines onto organic polymers and their use in transesterification reactions, among other applications have been reported (Gerbald and Vielfaure-Joly 1998). Unfortunately organic polymers lack mechanical and chemical stability usually demonstrated by inorganic counterparts. Among the various inorganic supports that are used for supporting homogeneous catalysts, silica has been used widely. This is because silica offers advantages such as high surface area, insolubility in organic and aqueous solvents, thermal and mechanical stabilities, and non-swelling behaviour.

Various authors have reported the heterogenization of guanidines onto silica supports (Subba Rao *et al.* 1997, Derrien *et al.* 1998, Macquarrie *et al.* 2001, Macquarrie *et al.* 2002, DeOliveira *et al.* 2006, Likhar *et al.* 2008). Whereas some authors accomplished the process of heterogenization through a nucleophilic replacement of chlorine by the guanidine on a 3-chloropropylsilane chain previously grafted onto the silica surface, others coupled the moiety via a previously silica-supported glycidylpropyl group. The resultant materials were used with variable successes in various base catalysed reactions such as transesterification (Subba Rao *et al.* 1997), epoxidation of α,β-unsaturated carbonyl compounds, Knoevenagel (Macquarrie *et al.* 2001, Macquarrie *et al.* 2002) and Aldol type reactions (Likhar *et al.* 2008). Most systems however, were constrained by limited reusability, the maximum reported runs being two (Macquarrie *et al.* 2001). Subsequent runs produced insignificant amounts of products. Nevertheless, these interesting results encourage further research into heterogenisation of polynitrogen strong bases. In this direction, the present work reports on a methodology for the heterogenisation of 1,1,3,3-tetramethylguanidine onto hexagonal mesoporous silica (HMS) by a co-

condensation process and its application in the epoxidation of electron deficient olefins.

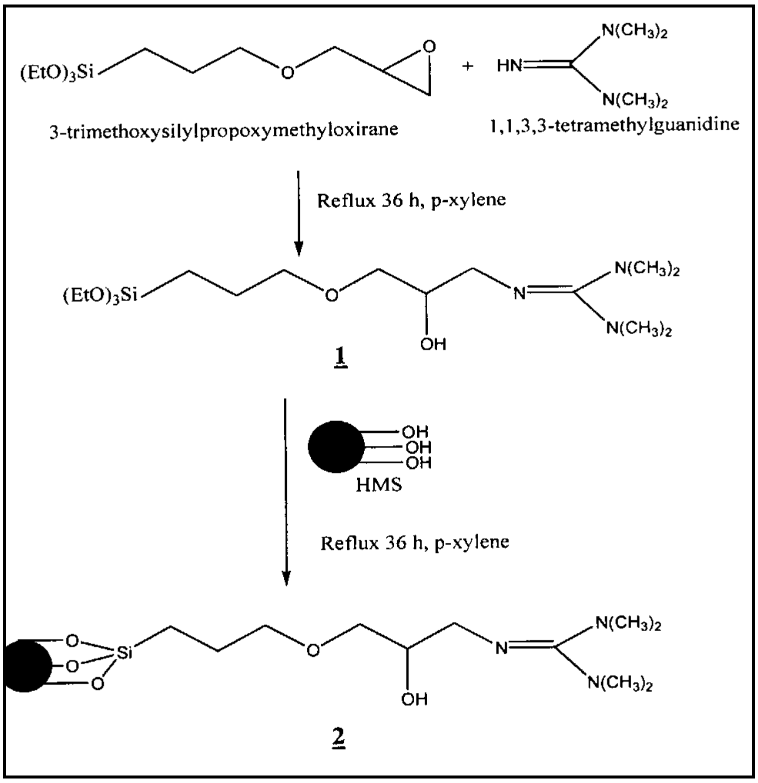
MATERIALS AND METHODS

Reagents and Chemicals

Tetraethylorthosilicate (98%) and *n*-dodecylamine were all purchased from Fluka whereas 1,1,3,3-tetramethylguanidine (99%) and 3-trimethoxysilylpropoxymethyloxirane (98%) were supplied by Sigma Aldrich. Ethanol and *p*-xylene were all supplied by BDH laboratory supplies, England. Distilled water was obtained from the chemistry laboratory, University of Dar es salaam. All chemicals were used as received without further purification except for the removal of water using sodium wire in the case of *p*-xylene.

Synthesis of Hexagonal Mesoporous Silica (HMS)

A co-condensation method was used to synthesize HMS using *n*-dodecylamine as a surfactant. The synthesis was done as described elsewhere (Tanev and Pinnavaia 1995) whereby to a stirred solution of *n*-dodecylamine in aqueous ethanol (46 ml of absolute ethanol and 53 ml of distilled water) at ambient conditions of temperature and pressure, tetraethylorthosilicate (8.3 g) was added rapidly. The formed white solution mixture which starts to thicken after three minutes was stirred for 18 hours. Thereafter, the thick solution was vacuum filtered, and a white solid was collected after being thoroughly washed with ethanol. The wet solid product was refluxed with ethanol in a Soxhlet apparatus for 10 hours so as to extract the template. After the removal of the template the obtained solid was dried in an oven at 100ºC for 8 hours and then stored in sealed bottles.



Scheme 1: Preparation of TMG-HMS

Functionalisation of HMS by 1,1,3,3-Tetramethylguanidine

The procedure used in anchoring tetramethylguanidine onto HMS was adapted from a recipe reported by Subba Rao *et al*. (1997). In a typical procedure, 4.5 mmol of 3-trimethoxysilylpropoxymethyloxirane were mixed with 6.5 mmol of 1,1,3,3-tetramethylguanidine (TMG) in 30 cm^3 of *p*-xylene. The mixture was refluxed for 36 hours followed by removal of the solvent under reduced pressure to give a crude product containing compound **1** (Scheme 1). The crude product obtained was then used without further purification. The crude product was introduced into a reaction flask containing 3.0 g of vacuum dried HMS and 30 cm^3 of dry *p*-xylene. The mixture was refluxed for 36 hours producing a solid substance identified as compound **2** (hereinafter TMG- HMS), that was further washed thoroughly with *p*-xylene and dried at room temperature. The remaining physisorbed materials in compound **2** were extracted for several hours by a Soxhlet apparatus using dichloromethane.

Characterization of the Materials

The HMS and TMG-HMS materials were characterised by a variety of standard techniques. The physical structures of the materials were studied by nitrogen physisorption on NOVA 1200E porosimeter at 77.4 K. Infrared (IR) spectra were measured on a Perkin-Elmer 2000 Fourier Transform Infrared (FTIR) spectrometer fitted with a diffuse reflectance unit. The samples were initially dried at 100°C prior to analysis and then run at room temperature as mixtures with KBr. On the other hand, simultaneous thermogravimetric (TG) and differential scanning calorimetry (DSC) analyses were performed on a Stanton Redcroft STA 625 instrument under a flow of nitrogen gas using 10 mg of sample. Neutral alumina was used as a reference material. Solid state ^{13}C NMR spectra were obtained on a Bruker MSL 300 spectrometer operating at 75 MHz. The samples were inclined at an angle of 54.7° to the magnetic field and the magic angle rotor spinning rate was typically 5 kHz. The samples were referenced to adamantine (^{13}C: 37.6 ppm).

Catalytic Activity Tests

The activity of the prepared material as a catalyst was tested in the epoxidation of electron deficient olefins. The procedure involved addition of 0.25 g TMG-HMS to a mixture of methanol (15 cm^3) and 10 mmol of α,β,-unsaturated carbonyl compound in 100 cm^3 two-necked round-bottomed flask. This was followed by a drop-wise addition of 5 cm^3 of 30% wt/wt H_2O_2 at a rate of 0.05 cm^3 per minute. The reaction mixture was stirred at room temperature and monitored by gas chromatography (GC). The various α,β,-unsaturated carbonyl compounds that were used in this study are given in Table 1. In a few experiments the product was isolated at the end of the reaction by filtering off the catalyst, adding 25 cm^3 of water to the filtrate and extracting the product using 50 cm^3 dichloromethane. The extract was then dried with anhydrous Na_2SO_4 and evaporated under reduced pressure using a rotary evaporator. The identities of the products were confirmed by gas chromatography-mass spectrometry (GC-MS).

RESULTS AND DISCUSSION

The Physicochemical Properties of the Prepared Materials

The success of the functionalization process was confirmed by elemental analysis, diffuse reflectance FTIR and solid state ^{13}C NMR. Results from elemental analysis showed that the TMG-HMS material had a carbon to nitrogen ratio of 4:2 consistent with an organic group loading of 0.4 mmol per g silica (Table 1). In addition, the tetramethylguanidine functional groups were evident on the HMS surface as proved by the presence of aliphatic N=C vibrations at 1610 cm^{-1} and C-H bending and stretching modes at 1446 cm^{-1}, 1407 cm^{-1} and 2966 cm^{-1}, 2925 cm^{-1}, respectively (Fig. 1). These were in addition to other vibration modes consistent with the silica lattice structure. On the other hand, the solid state ^{13}C NMR spectrum (Fig. 2) also showed that all expected carbons were available in the material. A closer look at the spectrum reveals that the peak at 38.2 ppm has two shoulders on both sides. This implies that there are two or more overlapping peaks, one being very sharp. The sharp peak is believed to result from physisorbed TMG, while the others come from chemisorbed TMG. The two methyl groups on the supported TMG are potentially different due to possible restricted rotation. Their peaks are therefore likely to be the two shoulders on each side of the broad peak at 38.2 ppm. However, despite having some physisorbed TMG on the silica surface, still the results confirm the presence of chemically bound TMG as well.

Table 1: Physicochemical properties of the prepared materials.

Material	**Specific surface area (S_{BET}) /m^2 g^{-1}**	**Pore diameter /nm**	**Total pore vol. /cm^3 g^{-1}**	**Loading* /mmol g^{-1}**
HMS	1511	2.4	0.91	-
TMG-HMS	1275	2.1	0.66	0.4

*Loading based on N% wt/wt as determined by elemental analysis

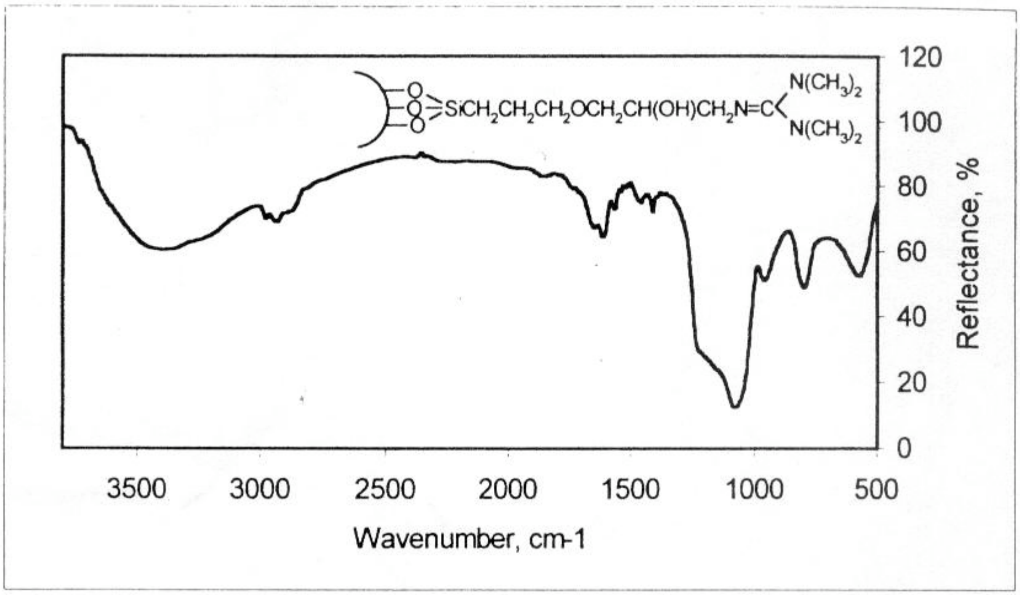


Figure 1: An FTIR spectrum for TGM-HMS

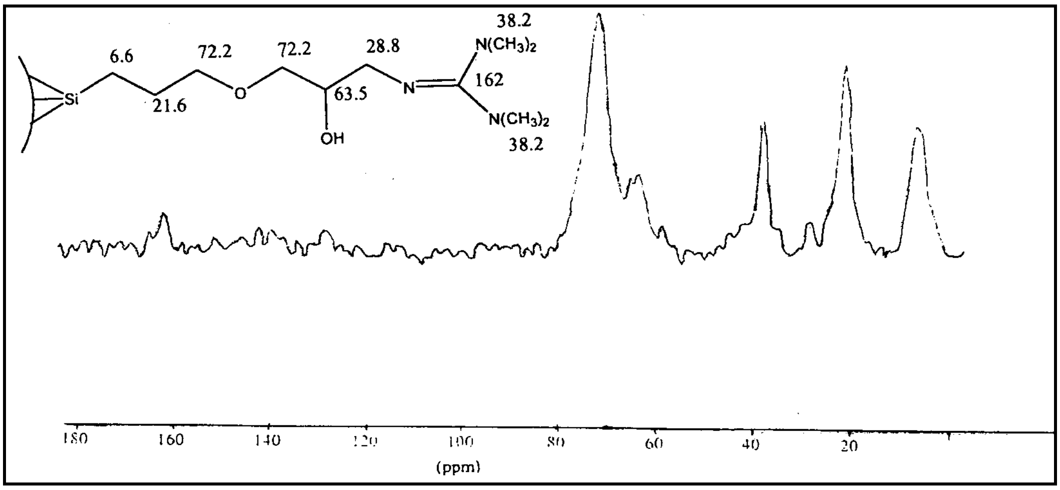


Figure 2: 13C NMR spectrum for TGM-HMS

Thermal analysis studies were also conducted on the prepared materials. Fig. 3 shows the simultaneous thermal analysis (STA) profile of the TMG-HMS. From the figure, three different weight losses are revealed. The first loss (1.5%) which is gradual with an endothermic effect centered at 70°C, starts at ambient temperature and finishes at 260°C. This is probably due to a loss of physisorbed TMG and residual solvent. It is followed by a relatively faster weight loss (12.5%) at temperatures between 260 and 430°C. This loss is consistent with the loading of *ca.* 0.4 mmol per g silica, suggesting that the chemisorbed TMG is desorbed at this stage.

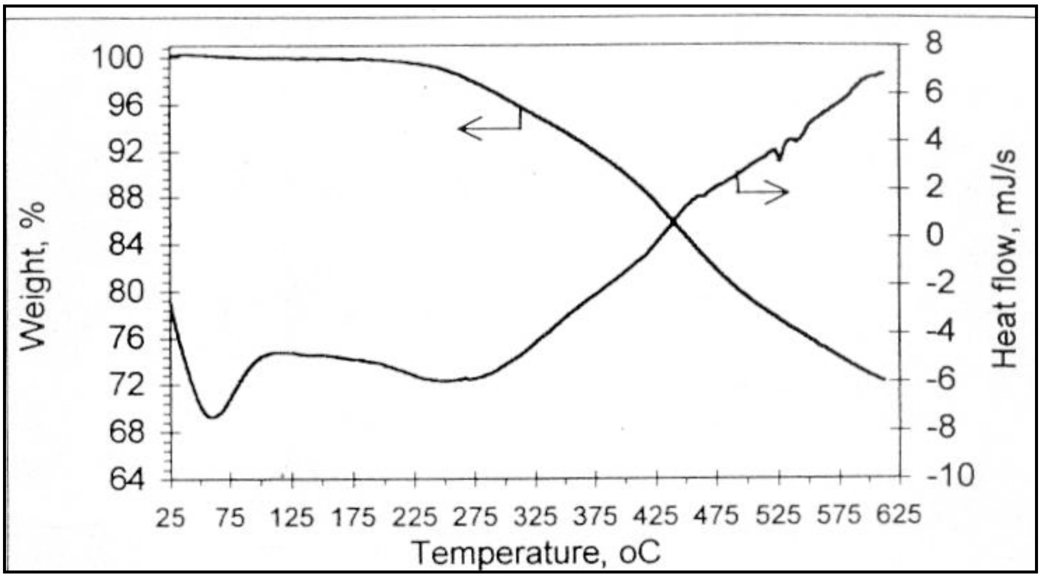


Figure 3: Simultaneous Thermal Analysis (STA) profile for TMG-HMS

As expected, the adsorption isotherms of the materials are type IV (Fig. 4) (Sing *et al.* 1985). The materials exhibit a characteristic inflection point at about relative pressure 0.2 consistent with the adsorption isotherms observed for MCM-type materials (Beck *et al.* 1992). The inflection point is an indication of capillary condensation in framework-confined mesopores, whereas the relative pressure position of the inflection point is related to the diameter of the pores being filled. As seen in the adsorption isotherms the inflection point appears at lower relative pressure and is less steep in the case of TMG-HMS, whereas in HMS the point appears at higher relative pressure and it is steep. The steepness is attributed to the uniformity of the framework-confined pores whereas the appearance of the inflection point at lower pressures indicates that the mesopore sizes are smaller in TMG-HMS than in HMS, as evidenced in Fig. 5.

The pore size distributions curves for the HMS and TMG-HMS show a monodisperse distribution (Fig. 5). The average pore diameters for the two curves are 2.4 nm and 2.1 nm for the HMS and TMG-HMS, respectively (Table 1). The decrease in the pore size is due to the attachment of the TMG functional groups which occupy a certain space in the pores. Results for Brunnauer-Emmet-Teller (BET) surface areas, pore sizes and pore volumes for the materials are given in Table 1. As can be seen, there is a decrease in surface area, pore diameter and pore volume resulting from the grafting of the organic moiety onto a clean HMS surface.

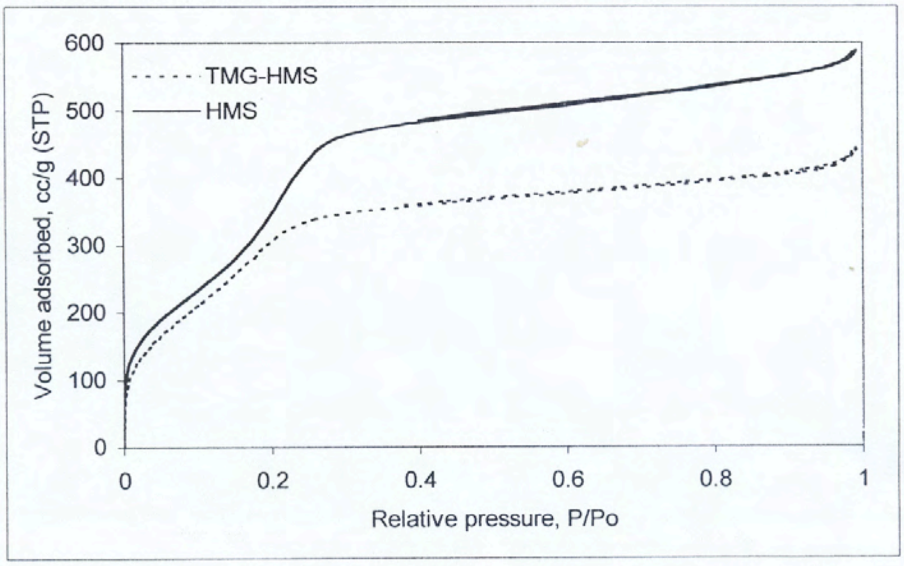


Figure 4: Adsoprtion-desorption isotherms for the prepared materials

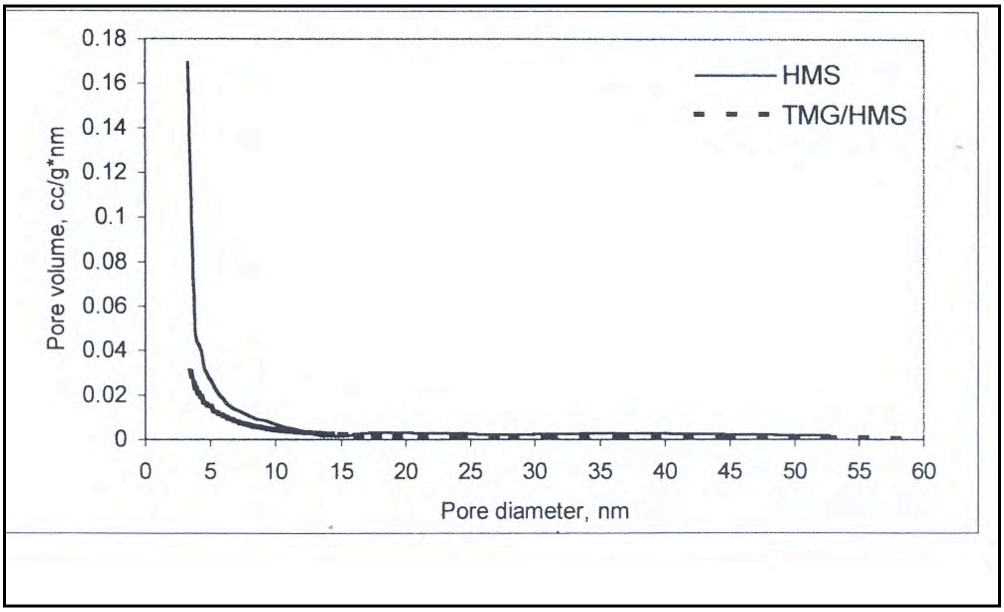


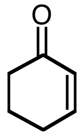
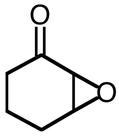
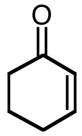
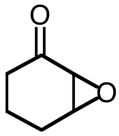
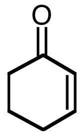
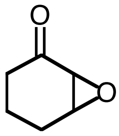
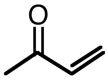
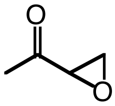
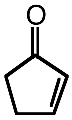
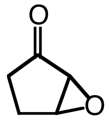
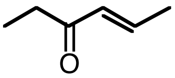
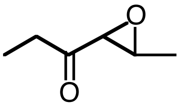
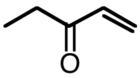
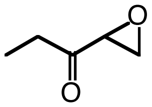
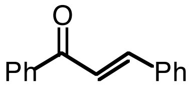
Figure 5: Pore size distribution curves for HMS and TMG-HMS

Epoxidation of Electron Deficient Olefins Using TMG-HMS Catalyst

The Catalytic Activity and Selectivity

Studies on the activity and selectivity of TMG-HMS as a catalyst were conducted in the epoxidation of 2-cyclohexen-1-one using dilute hydrogen peroxide solution as an oxidant. The reaction involved a drop-wise addition of the peroxide to a stirred reaction mixture of the substrate and catalyst in methanol at room temperature. A homogeneous TMG base and unmodified HMS materials were tested under the same conditions. Table 2 shows the obtained results. As seen from the table the reaction can give up to 10% of the desired product even on unmodified HMS. However, on using TMG-HMS as a catalyst moderate yields with very good selectivities (typically > 95%) are obtained. Unfortunately, the rate of the reaction and the ultimate yield are both lower than those obtained using homogeneous TMG. However, the homogeneous base has a setback that it can not be isolated easily from the reaction mixture. Moreover, it has a lower selectivity than its heterogeneous counterpart. The yields obtained with the TMG-HMS catalyst are however, significantly higher than those obtained by Subba Rao *et al.* (1997) using a similarly supported MCM-41 based 1,5,7-triazabicyclo[4.4.0]dec-5-ene (TBD). If the reaction is interrupted before completion by filtering off the catalyst, no increase in the product is observed. This suggests that indeed the catalyst plays a very significant role in the reaction process and the active group is unlikely to be homogeneous. Increase in reaction temperature leads to poor selectivity and no improvement in the yield is observed. It was also observed that drop-wise addition of H_2O_2 gives higher yields than adding it all at once. Titration of the H_2O_2 before and after the reaction does not reveal any significant loss of the peroxide other than that used in the substrate oxidation.

Table 2: Epoxidation of a,b-unsaturated ketones using TMG-HMS as a catalyst

Substrate	**Yield (%)**	**Time (h)**	**Product**
	10[a]	24	
	72[b]	12	
	69	12	
	40	10	
	59	13	
	58	14	
	52	12	
	0	36	None

[a]A yield obtained using unmodified HMS
[b]A yield obtained using homogeneous TMG

The activity of the TMG-HMS catalyst was further tested using a few more substrates and the results obtained are summarized in Table 2. From the results, it is seen that the catalyst has good activity and high selectivity on these substrates with the exception of chalcone which does not react in this system even after 36 hours of stirring. It has also been reported that chalcone does not react in toluene with a solution of NaOH in 30% H_2O_2 (Julia et al. 1980). The epoxidation of the substrate is however, possible with KF-alumina (with tert-butyl hydroperoxide) (Yadav and Kapoor 1994) and hydrotalcites (with H_2O_2) as catalysts (Yamaguchi *et al.* 2000).

Catalyst Reusability

When the reaction reached completion, the catalyst was retrieved by filtration and washed thoroughly with methanol. The catalyst was then re-used without further treatment. The results obtained in the reusability studies show a significant decreased catalytic activity in the second and subsequent uses. The yields obtained are 69% (first use), 32% (second use) and 15% (third use) in the epoxidation of 2-cyclohexen-1-one. These results suggest that the active groups on the catalyst are either leaching or are poisoned at a very fast rate. An attempt to regenerate the catalyst by thermal treatment (at 90°C in vacuum) or washing it with methanol followed by drying in air at 110°C does not regenerate the catalyst either. The strongly decreased activity upon recycling has also been observed before with other supported guanidines (Lasperas *et al*. 1997).

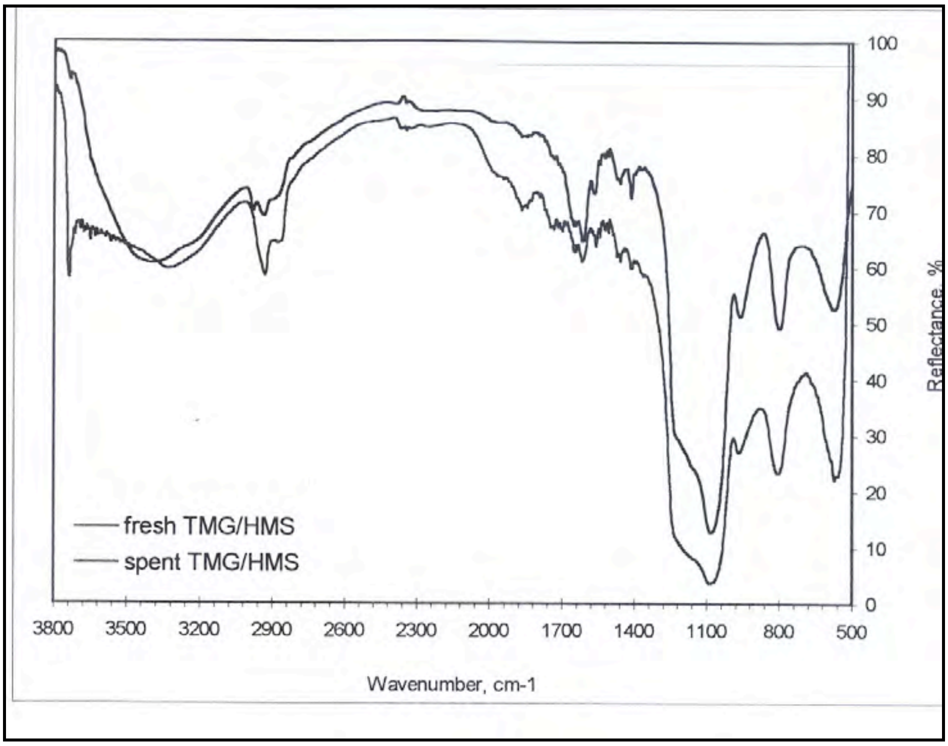


Figure 6: FTIR spectra of fresh TMG-HMS and spent TMG-HMS

Fig. 6 compares the spectra of the spent and fresh TMG-HMS catalysts. A notable difference in the two spectra is the decrease in intensity of the peak at 1620 cm^{-1} (attributed to C=N group) in the spent catalyst relative to that of the fresh catalyst. The intensity of the peaks attributed to C-H stretching at *ca*. 2900 cm^{-1} is, however, still strong in the spent catalyst. The loss in activity of the TMG-HMS catalyst is therefore likely to be associated with the disappearance of the imine group as inferred from the spectrum. The fact that the intensity of the peaks at *ca*. 2900 cm^{-1} is still strong suggests that only the guanidine group is lost in the course of the reaction whereas the spacer chain remains intact. Moreover, an FTIR spectrum of the TMG-HMS catalyst stirred with hydrogen peroxide (figure not shown) displays similar characteristics to those shown by the spectrum of a spent catalyst. It is likely therefore that hydrogen peroxide causes the deactivation of the catalyst. The lack of stability of this catalyst therefore needs to be investigated further.

CONCLUSION

Heterogeneous guanidine catalyst, based on 1,1,3,3-tetramethylguanidine has been prepared by a functionalisation of a glycidylpropyl group previously attached to hexagonal mesoporous silica. Characterisation of the catalyst proved that indeed the intended organic groups were anchored onto the silica surface. The catalyst was active and highly selective in the epoxidation of electron deficient alkenes. The reusability of the catalyst was however limited, calling for further investigation.

ACKNOWLEDGEMENTS

The author would like to thank NORAD through the University of Dar es Salaam for financial support.

REFERENCES

Beck JS, Vartuli JC, Roth WJ, Leonowicz ME, Kresge CT, Schmitt KD, Chu CTW, Olson DH and Sheppard EW 1992 A new family of mesoporous molecular sieves prepared with liquid crystal templates. *J. Am. Chem. Soc.* **114**: 10834–10843.

DeOliveira E, Torres JD, Silva CC, Luz AAM, Bakuzis P, Prado AGS 2006 Tetramethylguanidine covalently bonded onto silica gel as catalyst for the addition of nitromethane to cyclopentenone. *J. Braz. Chem. Soc.* **17**: 994–1000.

Derrien A, Renard G and Brunel D 1998 Guanidine linked to micelle-templated mesoporous silicates as base catalyst for transesterification. *Stud. Surf. Sci. Catal.* **117**: 445-452.

Gelbard G and Vielfaure-Joly F 1998 Polynitrogen strong bases: 1-new syntheses of biguanides and their catalytic properties in transesterification reactions. *Tetrahedron Lett.* **39**: 2743-2746.

Gelbard G and Vielfaure-Joly F 2001 Polynitrogen strong bases as immobilized catalysts. *React. Funct. Polym.* **48**: 65–74.

Juliá SJ, Masana J, and Vega JC 1980 Highly stereoselective epoxidation of chalcone in a triphasic toluene-water-poly[(S)-alanine] system. *Angew. Chem. Int. Ed. Engl.* **19**: 929–930.

Laspéras MT, Llorett T, Chaves LI, Rodriguez I, Cauvel A and Brunel D 1997 Amine functions linked to MCM-41-type silicas as a new class of solid base catalysts for condensation reactions. *Stud. Surf. Sci. Catal.* **108**: 75–82.

Likhar PR, Roy S, Roy M, Subhas MS and Lakshmi KM 2008 Silica supported tetramethylguanidine: An efficient solid base for Aldol type coupling of aldehydes with ethyl diazaoacetate. *Synlett* **9**: 1283–1286.

Macquarrie DJ, Brunel D, Renard G and Blanc AC 2001 29-P-10-Guanidine catalysts supported on silica and micelle templated silicas: new basic catalysts for organic chemistry. *Stud. Surf. Sci. Catal.* **135**: 312-316.

Macquarrie DJ, Jackson DB, Mdoe, JEG and Clark JH 1999 Organomodified hexagonal mesoporous silicates. *New J. Chem.* **23**: 539_544

Macquarrie DJ, Utting KA, Brunel D, Renard G and Blanc AC 2002 Guanidine catalysts supported on micelle templated silicas. New basic catalysts for organic chemistry. *Stud. Surf. Sci. Catal.* **142**: 1473–1480.

Pahadi NK, Ube H and Terada M 2007 Aza-Henry reaction ketimines catalysed by guanidine and phosphazene bases. *Tetrahedron Lett.* **48**: 8700-8703.

Simoni D, Invidiata FP, Manferdini M, Ferroni R, Lampronti I, Roberti M and Pollini GP 1997 Facile synthesis of 2-nitroalkanols by tetramethylguanidine (TMG)-catalyzed addition of primary nitroalkanes to aldehydes and alicyclic ketones. *Tetrahedron Lett.* **38**: 2749–2752.

Simoni D, Invidiata FP, Manferdini M, Lampronti I, Rondanin R, Roberti M and Pollini GP 1998

Tetramethylguanidine (TMG)-catalyzed addition of dialkyl phosphites to _,_-unsaturated carbonyl compounds, alkenenitriles, aldehydes, ketones and imines. *Tetrahedron Lett.* **39**: 7615–7618.

Sing KSW, Everett DH, Haul RAW, Moscou L, Pierotti RA, Rouquerol J and Siemieniewska T 1985 Reporting physisorption data for gas/solid systems with special reference to the determination of surface area and porosity. *Pure Appl. Chem.* **57:** 603-619.

Tanev PT and Pinnavaia TJ 1995 A neutral templating route to mesoporous molecular sieves. *Science* **267**: 865–867.

Yadav VK and Kapoor KK, 1994 Al_2O_3 Supported KF: An efficient mediator in the epoxidation of electron deficient alkenes with t-BuOOH. *Tetrahedron Lett.* **35**: 9481-9484.

Yamaguchi K, Mori K, Mizugaki T, Ebitani K, and Kaneda K 2000 Epoxidation of α,β-unsaturated ketones using hydrogen peroxide in the presence of basic hydrotalcite catalysts. *J. Org. Chem.* **65**: 6897–6903.