Mesoporous Silica Applications

*L. F. Giraldo, B. L. López, L. Pérez, S. Urrego, L. Sierra, M. Mesa**

Summary: The mesoporous silica have been considered fascinating materials for many techonological applications due to their porous and morphological characteristics. This review focuses on their use as stationary phases for liquid chromatography, supports for immobilizing biomolecules, catalysts, agent for polymer reinforcement and hard templates for the preparation of mesoporous carbons.

Keywords: catalyst; delivery systems; fillers; HPLC; inorganic materials

Introduction

Mesoporous silicas are inorganic materials synthesized in the presence of surfactants as templates for the polycondensation of silic species, originating from different sources of silica (sodium silicate, alkoxydes like tetraethylortosilicate, TEOS and tetramethylortosilicate, TMOS). Synthesis conditions such as: source of silica, type of surfactant, ionic strength, pH and composition of the reaction mixture, temperature and duration of synthesis affect the surfactant micellar conformation, the silica – surfactant interactions and the degree of silica polycondensation.[1,2] These conditions determine the characteristics of the porous structure (type of mesostructure, diameter and volume of the pores, wall thickness) and the macroscopic morphology.[3–5]

A wide variety of ionic and non-ionic surfactants has been used for obtaining materials with different porous and morphological characteristics. MCM-41, MCM-48 and MCM-50 mesoporous silica (MCM: Mobile Crystalline Material) with hexagonal, cubic and lamellar mesostructures respectively and different morphologies have been synthesized by using alkyl ammonium surfactants and TEOS or sodium silicate in a basic medium.[6] Their pore size and wall thickness do not go beyond 4.0 nm and 2.0 nm, respectively. By using cationic surfactants in acidic medium the first SBA type materials with different mesostructures were obtained, with porous characteristics similar to the MCM-X type materials.[7] SBA-15 and SBA-16 silica (SBA: Santa Barbara University) with larger pore sizes and thicker walls are prepared by using non-ionic surfactants derived of poly (propylene oxide) and poly (ethylene oxide) in acidic medium.[8] Other materials named MSU-X (Michigan State University) are synthesized with non – ionic surfactants at neutral pH, but their structures are more unorganized and their pore diameter and wall thickness are around 2.1–8.0 nm and 1.5–4.0 nm.[9] Replacing TEOS by sodium silicate in presence of non-ionic surfactant is also possible to obtain silica with controlled morphology.[10]

The pore size can be modulated during the synthesis by controlling the reaction time[11] and temperature,[11–14] by using swelling organic molecules([6,15–18]) like aromatic hydrocarbons[6,7,19–24] and trialkylamines,[12] by adjusting the surfactant and co-cation concentration[11] or by post-synthesis treatment[25] like water-amine treatment[25] or changing the calcination conditions.[6,13]

The control of the morphology by the synthesis conditions has been explained by the influence of defects during the nucleation and growth process[26–28] or by the formation mechanism.[3,29]

Grupo Ciencia de los Materiales, Sede de Investigación Universitaria SIU, Instituto de Química, Universidad de Antioquia, Medellín – Colombia
E-mail: mmesacad@gmail.com

Different types of silanol groups (single (a), hydrogen-bonded (b) and geminal (c)) are present on the surface of a mesoporous silica (Figure 1) Their content depends on the way by which the surfactants were removed and can be modulated by post-synthesis treatments.[30] Their quantification can be made by Fourier Transform Infrared analysis (FTIR),^{29}Si Nuclear Magnetic Resonance (NMR) and temperature-programmed desorption (TPD).[31] Ramirez et al[30] combined termogravimetryc analysis (TGA) and Diffused Reflectance Infrared Fourier Transform (DRIFT) measurements to characterize the silanol content in mesoporous silica prepared in acidic medium, by using pyridine desorption. They found a highest silanol group concentration (6.5 groups/nm^2) when the silica was rehydroxilated during 24 h.

The presence of geminal and single silanol groups in the surface allows the modification of the chemical nature of the silica after synthesis by grafting different functionalities through covalent linkages. For example they can react with alkylchlorosilanes in order to obtain an hydrophobic surface.[32] Other methods for modifying the chemical nature of mesoporous silica during the synthesis by using alkoxysilanes are reviewed by Vinu et al.[33]

Due to their highly organized porosity, high surface area, high pore volume, tailorable pore size, wall thickness, chemical nature and morphology the mesoporous silica are attractive materials for applications in catalysis, adsorption, separation, sensing, drug delivering devices and nanotechnology. Since there are many reviews concerning with the synthesis, formation mechanism, modification and control of their characteristics[34–40] we only attempt to summarize the applications that we have explored in our research group: stationary phases for liquid chromatography, supports for immobilizing biomolecules, catalysts, agents for polymers reinforcement and templates for the synthesis of other materials.

Stationary Phases for High Performance Liquid Chromatography (HPLC)

Mesoporous silicas are interesting materials as stationary phases for HPLC due to their high surface area and their organized porous structure. Moreover their content of silanol groups as well as their chemical and mechanical stability under the chromatographic operation conditions is similar to those of the precipitated silica. Mesoporous silica constituted by loose particles agglomerates selected by sedimentation was the first material used in HPLC.[41,42] Since that many groups have studied this application (Table 1)

Generally, silicas used for RP-HPLC are modified after synthesis with alkylchorosilanes (C8 y C18).[54]

The chemical nature of the surface and the morphologic and porous properties determine the efficiency of a given separation. In order to avoid pressure drop and facilitate the flow of the mobile phase through the column, the particle size of the

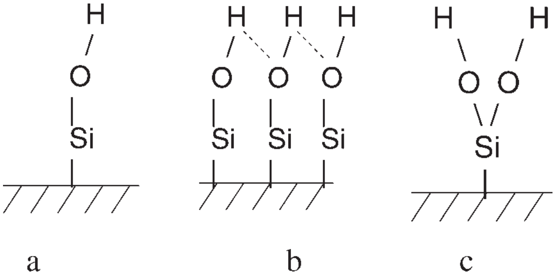


Figure 1.
Schematic representation of single (a), hydrogen-bonded (b) and geminal (c) silanol groups present on the surface of mesoporous silica.

Table 1.
Some examples of application of mesoporous silica as normal or reverse HPLC stationary phases.

Mesoporous material	Chromatographic applications [(a)] (analytes)	Ref.
MCM-41 constituted by loose particles agglomerates	NP-HPLC (aromatic polycyclic hydrocarbons)	[41]
Solid obtained in acidic medium by using cationic surfactant and TMOS. It was grinded and separated in aggregates of 15μm	NP-HPLC (phtalic esthers and aromatic compounds)	[42]
SBA-3 type spherical particles	NP-HPLC (ferrocene and acetylferrocene) y RP-HPLC (aromatic hydrocarbon and racemic mixtures)	[43]
MSU-X type spherical particles (diameter ~7.6 μm)	NP-HPLC and RP-HPLC (aromatic hydrocarbon)	[44]
SBA-15 or SBA-16 type spherical o polyhedral particles (diamter 3–10 μm)	NP-HPLC and RP-HPLC (aromatic hydrocarbon)	[45–47]
MSU-X type sílica constituid by agglomarates of nanometric particles	NP-HPLC (hydrocarbon)	[48]
MCM-41 type spherical particles (diameter 5 μm) obtained by pseudomorphic synthesis from macroporous silica gel	RP-HPLC (alkylbenzenes)	[49]
SBA-15 type spheroidal particles (diameter ~1 μm)	Capillary RP-HPLC (biomolecules)	[50]
MCM-41 type silica with pore diameter ~3.38 nm	Exclusion size HPLC (low molecular weight polystyrene compounds)	[51]
MCM-41 type silica with pore diameter ~2.5 nm	Separation of three aluminun species (cationic, tridecameric and polynuclear)	[52]
Chiral stationary phases supported on MCM-48 or SBA-3 type silica	α-methylbenzylamine enantiomers	[43]
Bifunctionalized mesoporous organosilica spheres (diameter 5 μm) with trans-(1R,2R)-diaminocyclohexane	Resolution of DL-valine by chiral HPLC	[53]

stationary phase must be between 3–10 μm. The first reports did not consider the morphology[41,55] but in order to improve the performance of these materials, isometric particles (>3 μm) and "core-shell" type particles from several surfactants systems has been reported by our group: a) Neutral surfactant Triton X-100 and sodium silicate (MSU-X type silica).[10,56] b) Cationic surfactant cetyl trimethyl ammonium bromide (SBA-3 silica).[45] c Non-ionic triblock copolymer (Pluronic P123 or F127) and a cationic co-surfactant (SBA-15 y SBA-16 silica).[46,57] (Figure 2)

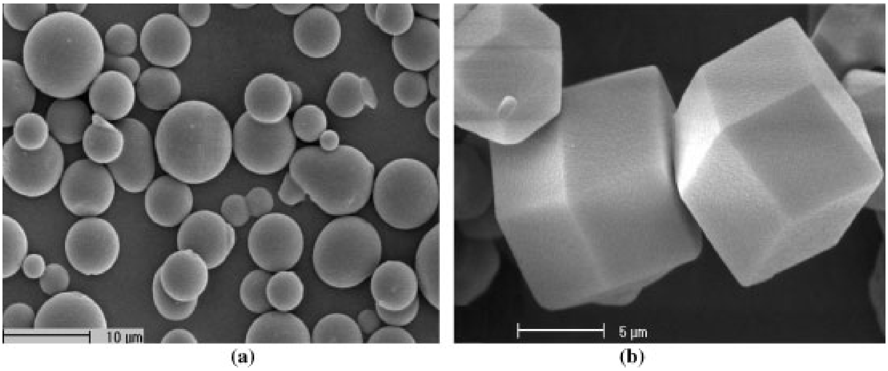


Figure 2.
Mesoporous silica with different morphologies: (a) SBA-15 and SBA-16 (b).

Some selected chromatograms for normal RP-HPLC and NP-HPLC are shown in Figure 3.

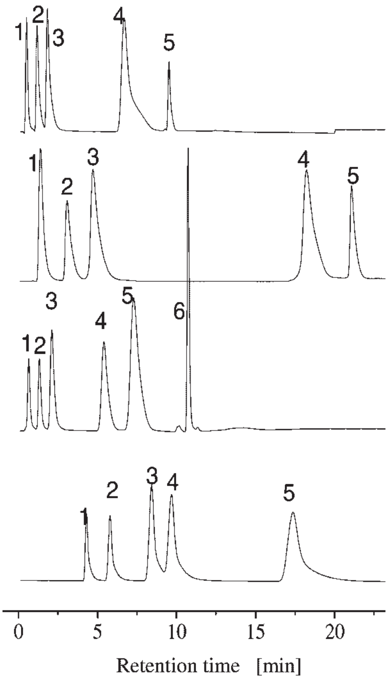
Prouzet et al.[58] summarized the chromatographic application of MSU-X silica particles with controlled morphology. Monolithic materials are also interesting materials for HPLC.[59] A novel macro–mesoporous organosilica monolith with phenylene bridged in the framework exhibits good characteristics for its potential application as a stationary phase for (HPLC) due to its hierarchical porosity and the integrity of the phenylene group in the hybrid structure,[60] confirmed by solid ^{13}C CP MAS and ^{29}Si MAS NMR techniques.

In order to use the mesoporous silica for reverse chromatography (RP-HPLC), they are usually modified by silylation.[45,47] The hydrophobic materials are characterized by ^{29}Si NMR, DRIFT, TGA, elemental analysis and a new FTIR/elemental carbon analysis method.[61] Also a post-synthesis modification by using Grignard reactants has been published.[62]

Recently the synthesis of mesoporous organosilicas by co-condensation of different types of chiral organosilane precursors in the presence of surfactant allowing the obtention of hybrid materials with high surface area was reported. The distribution of chiral groups on the surface was homogeneous. They exhibit higher retention, better selectivity and resolution for the amino acids than silica prepared by conventional grafting method.[53]

Mesoporous Silica as Support for Immobilization of Bioactive Molecules

The immobilization of bioactive molecules, such as enzymes and drugs, in a porous support is one of the strategies for increasing their activity, stability and selectivity, which facilitates their use.[63] The most common mechanisms for immobilization are adsorption, covalent binding, encapsulation, cross-linking and entrapment.[64]



SBA-15$_{C8C1}$
Mobil phase: 1.0 ml/min, 70% methanol : 30% H_2O. Analytes: 1) Phenol, 2) Benzene, 3) Toluene, 4) Anthracene, 5) Benzopyrene, Column: 150 x 4.6 mm

SBA-16*$_{C8C1}$
Mobil phase: 0.8 ml/min 60% methanol : 40% water 4 min, lineal increase until 90% methanol : 10% in 3 min. Analytes: 1) Phenol, 2) Benzene, 3) Toluene, 4) Anthracene, 5) Benzopyrene Column: 150 x 1.5 mm

SBA-16$_{C8C1}$
Mobil phase: 0.8ml/min 60% methanol-40% 4 min. After 100 % methanol. Analytes : 1) Phenol, 2) Benzene, 3) Toluene, 4) Naphtalene, 5) Anthracene, 6) Benzopyrene. Column: 150 x 1.5mm

SBA-16
Mobil phase: 100% hexane. Analytes: 1) Toluene, 2) Naphtalene, 3) Biphenyl, 4) Anthracene, 5) o-Terphenyl. Column: 150 x 4.6 mm

Figure 3.
Reverse (a–c) and Normal (d) HPLC chromatograms obtained by using mesoporous silica as stationary phases.

The advantages and disadvantages of these have been discussed by Kennedy.[65]

Different nanostructures have been used as supports.[66] The inorganic porous supports, such as mesoporous silica, can offer advantages over their organic counterparts in terms of mechanical strength, thermal and pH stability, handling, flow rates in continuous reactors and life time.[67]

Since the silicates and aluminosilicates are biocompatible,[68,69] do not react in the human body[70–72] and can be obtained in the form of nanoscopic particles, they are good candidates as supports for controlled drug delivery systems or for immobilizing enzymes, which are used as biosensors and in bioconversion processes. The glass matrix was the first inorganic materials used for encapsulating enzymes but its high cost, low surface area and wide pore size distribution have limited its use[73,74] Mesoporous silica have shown a better performance than commercial silica gel[75] for immobilization of molecules with different morphologies and chemical nature.[76,77] The general methodology for the immobilization of enzymes into mesoporous materials is exemplified by Hudson et al.[78]

It is shown that the immobilization conditions, such as pH,[79–81] type of solvent[33,79] and ionic strength[82] can modify the adsorption rate and load of immobilized substance as well as the release rate, because they affect the interaction of the bioactive molecules with the support.[80] These interactions depend either on the characteristics of the biomolecule (size, hydrophobic, basic o acidic nature and the superficial charge) and on the porosity of the support.[83,84] In the case of mesoporous silica it has been demonstrated that:

a) The immobilization process is very efficient if the support exhibits high surface area and the size of the pores is similar or slightly higher than the diameter of the biomolecule. The pore entrapment can improve the enzyme activity because the protein maintains its native structural integrity. By contrast, the free enzyme is more prone to misfolding.[85] The delivery rate of drugs or the leaching of the enzymes from the support (diffusion controlled process) is affected by the size, connectivity[86] and geometry of the pores.[87] In the case of enzymes, even if the bioactive load in the mesoporous supports can be high, the leaching must be controlled or avoided, especially when the adsorption or electrostatic interactions are responsible of the immobilization. Several advances in the development of stable enzyme - mesoporous silica systems include covalent attachment,[88] partial closure of mesopore inlets after adsorption of the enzyme,[89] encapsulation of the enzyme-loaded support by polyelectrolyte[90] or organic polymer shells[91,92] and crosslinking of the adsorbed enzyme by using glutaraldehyde.[93]

The mesopore size of materials MCM-41, SBA-15, SBA-16, MSU-X, synthesized with the common ionic and non ionic surfactants, does not go beyond 10 nm, even by applying the methodologies described in the introduction.[11,15–19,94] This forbids their use as supports for immobilization of molecules when their minimun dimension is higher than that size. Moreover, the pore size of the support must not hinder the transportation of substrates or products towards or from the enzyme.[95–98] Silica with large mesopores or bimodal pore size distribution have been obtained by aggregation of small particles[99] or by spinodal decomposition when the PEG or other water-soluble, hydrogen bonding polymers are added to the reaction mixture.[100] There are few reports about the use of the last kind of materials as supports.[101–103] We synthesized silica with large mesopores by the addition of salt to the reaction mixture before to the thermal treatment at 95 °C or by heating at 150 °C in absence of salt. These two materials have a higher capacity for immobilization of the globular hydrophilic enzyme lactase (β-galactosidase, EC 3.2.1.23, estimated size ~17,63 nm x ~13,85nm) than a normal SBA-16-type material and other inorganic supports reported in the literature.[104–106] The immobilization of lactase allows its reuse several times and may provide a better environment for catalytic activity.[107]

b) The presence of silanol groups in the surface favors the adsorption of the biomolecules.[108] Others functionalities attached to the surface by different in-situ o post-synthesis methods improve the affinity of the support for the biomolecules.[28,96,109] The type of chemical group attached to the surface, the covering degree and homogeneity of this surface determine the immobilization capability and the release rate of the biomolecules.[110–113] If the functionalization process affects the mesostructure and/or makes the pore entrances too narrow to allow the entry of the enzyme to the channels, immobilized enzyme loss activity very fast upon reuse, by leaching.[78]
c) By reducing particle sizes, the superficial area increases allowing a fast and high biomolecule loading.[13,114]

Recently the immobilization of Single Enzyme Nanoparticles (SEN) in mesoporous silica has been reported. These SENs are stable by themselves but the mesoporous silica offer a high surface area for a high load of them, allowing a better performance.[66]

Mesoporous Silica in Catalysis

The zeolites[115] and mesoporous aluminoslicates[116] have been widely used in heterogeneous catalysis as catalysts or as supports for the catalyst. The mesoporous materials are ones of the most promissory catalysts due to their high surface area and pore volume, besides of the possibility of surface modification and pore distribution control. The adequate diffusion of molecules through the catalyst pores allows the direct interaction with the acidic sites on the wall surface, promoting the conversions. The mesoporous catalysts provide a new possibility in relation with the zeolites due to its higher pore size range (2–100 nm), allowing a large number of molecules of higher size being transformed into the catalyst. Moreover, the formation of porosity in two or three different length scales in an ordered fashion with interconnectivity between the pores and with hierarchical structure would be advantageous for a variety of applications because the reactant molecules need to access readily inside of the pore structure. Commercial support pellets are usually prepared by compacting fine micro- or mesoporous particles[117] Macropores are formed between the agglomerated particles. These macropores allow a fast mass transfer to the surface of the primary particles. The active sites of a supported catalyst are mainly located inside the primary particles. Recently, bimodal silica gels have been used as catalysts supports.[118] Here, the macroporous pore structure is formed during the synthesis process.

These materials can be used as support for metallic clusters by impregnation and reduction or by direct incorporation of a metal precursor into the silica structure by sol-gel process. Also single and geminal silanol groups behave as weak Brønsted acidic sites.[11,31,119,120] In order to increase the catalytic activity of mesoporous silica it is possible to increase the strength of Brønsted type sites by direct incorporation of a trivalent metal like aluminum into the lattice during synthesis or by post-synthesis grafting.[121–124] The tetrahedral substitution of aluminum in the mesoporous structure generates strong Brønsted acid sites while the presence of tri-coordinated aluminum species in the framework can generate weak Lewis acid sites as it is illustrated in Figure 4. Other wise if the aluminum is not incorporated in the framework, strong Lewis acid sites are present. The characterization of the strength of the acidic sites is mainly done by TPD of probe molecules like pyridine and ammonia, FTIR and multinuclear NMR spectroscopy.[30,125–128] The acid sites exhibit different activation and desorption energies and thus can be differentiated.

The incorporation of Al and transition metal elements within the framework of

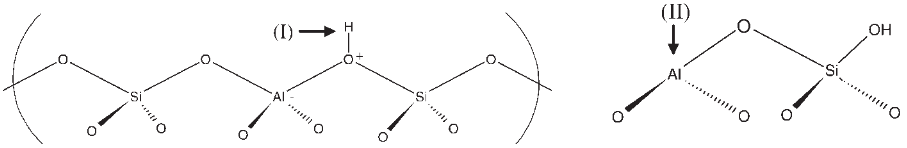


Figure 4.
Representation of Brønsted and Lewis sites in mesoporous silica generated by structural tetra- (I) and tri-coordinated (II) aluminum, respectively.

MCM-48,[129] MCM-41[130–133] and SBA-16[134] mesoporous silica has been broadly studied. It is well known that as the concentration of aluminum in the framework increases the structural regularity of silica decreases, but there is an increase in the pore wall thickness providing better stability in catalytic processes.

In a previous work we have incorporated aluminum in mesoporous silica MCM41 with different Si/Al ratios and without octahedral coordinated aluminum.[135]

The MCM-41 aluminosilicates show a sharp XRD signal at d_{100} spacing = 39.73 Å (d: interplanar space) and two minor peaks corresponding to d_{110} and d_{200} reflections (Figure 5). The aluminosilicate samples with Si/Al ratios ~ 41–112 also exhibit the same reflections, but the d spacing values decreasing slightly according to the aluminum content, indicating that the mesoporous hexagonal MCM-41 structure is preserved. The broader and less intense main peak for Si/Al ratio = 10 indicates a poor porous organization of the material.

Although it is possible to use the mesoporous silica in basic catalysis, most of the applications found in literature involve acidic catalysis,[11,123] which is carried out by incorporation of moderate of strong acidic sites in the silica framework.

The mesoporous catalysts have been used in many reactions such as conversion of phenol, generation of *p*-cymene and alcohol dehydration.[123,131,136] In the last decade an important application corresponds to the use of mesoporous silica as catalytic support[137–139] or template for the synthesis of carbon nanotubes.[140–143] In the former case, the mesoporous silica ensures an adequate dispersion of catalytic metal owing to its high surface area, generating metallic clusters of small size, which produce carbon nanotubes with smaller diameter, homogenous distribution and good structural regularity. In the case of mesoporous silica as template, the pores act as a mold for the carbon nanotubes, which are purified by acidic treatment in order to eliminate the mold.

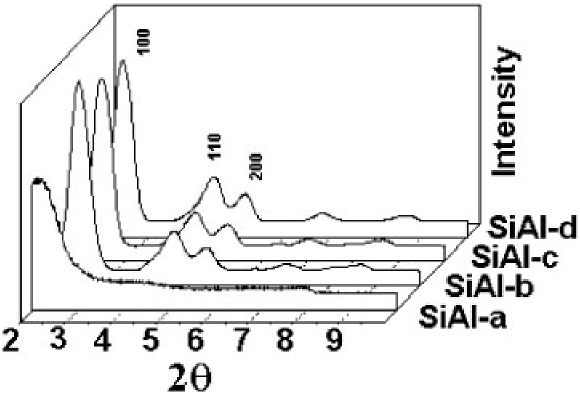


Figure 5.
XRD patterns for the samples with different Si/Al molar ratio: a = 10, b = 41, c = 70, d = 112.[132]

Polymer Reinforcement

The use of fibers and fillers to improve mechanical, thermophysical and electrical properties of polymer-based materials (PBMs) constitutes a rapidly growing field. Among others silica or titanium oxides, zeolites and carbon nanotubes are used.[144–147] The improvement of the PBMs properties depends on the type of interaction between both phases: as the interaction is high better properties are obtained. It has been also shown that the mechanical performance of reinforced PBMs increases proportional to the surface area of the silica.[148,149]

Recently, the use of silicas as fillers is growing[150] since better tribological, chemical[151] and thermomechanical properties can be achieved in comparison to carbon black, because the silanol groups on their surface make them easily modifiable with different functional groups.[152] The precipitated silicas are widespreadly used as fillers for many industrial applications, but their surface area is lower than 200 m^2/g.

Mesoporous silicas offer a new alternative in this field due to the fact that they present higher surface area and organized mesoporosity which are able to trap polymer chains. Consequently, higher interaction polymer/silica can be obtained. Mark et al.[153] reported the preparation of poly(ethylene oxide)/MCM-41 mesoporous silica composites and they found that after pressing the physical blend at 100 °C the polymer melting transition was vanished. That effect was more clearly seen for polymers with low molecular weight.

Composites of Styrene Butadiene Rubber (SBR)/mesoporous silica MCM-41 prepared by physical blending showed higher polymer/filler interaction than the same polymer reinforced with precipitated silica VN3. The interaction polymer/filler was measured by NMR and determination of bounded rubber.[154] Differential scanning calorimetry (DSC) experiments also showed that the crystallization of a small crystalline fraction of butadiene was suppressed when the mesoporous silica was the filler.[155]

These composites also presented a better thermomechanical behavior as determined by dynamical mechanical analysis. The composite reinforced with mesoporous silica presents a higher elastic modulus at every evaluated temperature indicating a higher polymer chains stiffness due to the stronger interaction mesoporous silica/SBR.[155,156]

The use of MSU-X mesoporous silica as filler for SBR decreases the vulcanization time. It seems that they have a catalytic effect since the activation energy for the crosslinking reaction, measured by DSC, is lower when the filler is mesoporous silica than for precipitated silica VN3.[156]

Recently, composites prepared by in situ polymerization of monomers and filler is a growing field in composites research since a better dispersion of the filler can be achieved, especially when a mesoporous silica is the filler: the monomers can easily penetrate the silica pores and therefore the polymer chains grow inside.[157] Wang et. al.[158] polymerized polymethyl methacrylate, polystyrene and polybutyl acrylate inside the pores of MCM-41 mesoporous silica and that composite was used as filler for polypropylene. An increasing in the tensile properties was observed. The composite filler presented higher dispersion in the polymeric matrix. He et. al.[159] reported the reinforcement of polystyrene and polyvinylacetate with mesoporous silica MCM-48 containing different intrapore polymer. These composites presented higher toughness when the intrapore polymer was flexible.

Recently, we reported the synthesis of a polymethylacrylate/MCM-48 mesoporous silica nanohybrid structure.[160] Methylacrylate monomer was bulk polymerized in the presence of methyl functionalized mesoporous silica MCM-48. TGA analyses showed two different degradation temperatures for the composites. We assign the higher weight-loss at the lowest temperature to the polymer matrix and the second one at the highest temperature to the polymer occluded inside the silica pores. The best thermomechanical properties were obtained with 5 wt% of MCM-48 mesoporous silica. With this composition the silica was better dispersed and as a consequence a higher polymer amount was trapped inside its pores. Figure 6 shows the relative improvement of mechanical properties for these composites.

Porous Silica as Hard Template

Porous carbon materials with different pore sizes and structures have been synthesized during the last ten years using microporous, mesoporous and hierarchically porous material as hard templates.[161] Ryoo et al[162] were the first to report the preparation of an ordered mesoporous carbon denoted as CMK-1 by using an MCM-48 silica as template and infiltration of sucrose inside the mesoporous silica sample. After that, the nanocasting pathway using nanostructured porous silica such as MCM-48, SBA-15, MSU-X and Mesostructured Cellular Foam (MCF) as templates and different sources of carbon has allowed to obtain mesoporous carbons with new compositions, several controllable pore structures, uniform pore sizes and high pore size and volumes, opening the road to highly porous solids with interesting application perspectives.[163–165]

In general, the synthetic procedure for obtaining carbon replicas involves infiltration of the template pores with an appropriate carbon precursor, its carbonization, and subsequent template removal by HF or NaOH leaching.[163,166] The template needs to exhibit three-dimensional pore structure in order to be suitable for the ordered mesoporous carbon synthesis, otherwise disordered microporous carbon is formed.[166] In order to reduce the cost of the preparation of mesoporous carbon, the mesoporous silica has been synthesized by low cost templating agent and sodium silicate.[167,168] The infiltration of mesoporous silica can be carried out by liquid impregnation or chemical vapor deposition,[169] using different carbon sources sucrose, furfuryl alcohol, propylene, pitches, acrylonitrile, organic resins.[170,171]

The ordered mesoporous carbons are interesting materials either for the characterization of the original silica[172,173] or for specific applications such as adsorption of molecules, manufacturing of electrochemical double-layer capacitors and chroma-

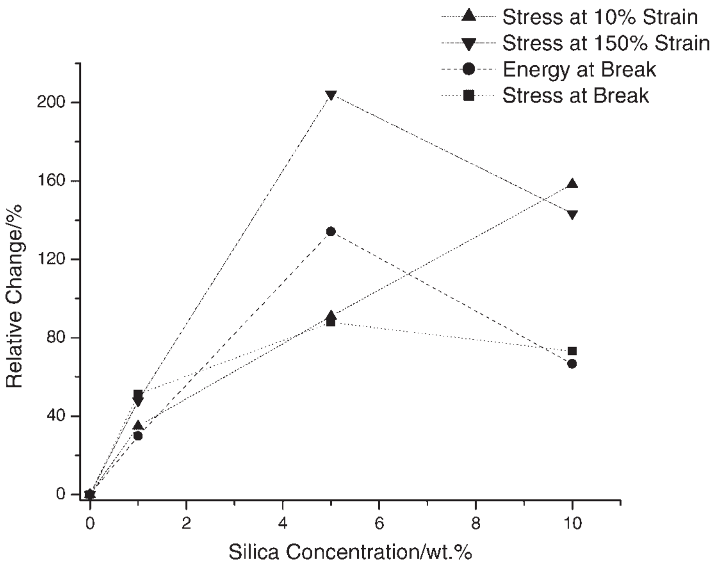


Figure 6.

Relative change in the mechanical properties for the composites prepared by in situ polymerization of methyl acrylate with mesoporous silica MCM-48.[160]

tography.[174] If they are going to use as stationary phase the morphology must be controlled. In this sense some authors have shown that is possible to preserve the morphology of the particles.[153,175] We reported the control of particle morphology and hydrophobic characteristics of mesoporous carbons, obtained as replicas of a SBA16-type mesoporous silica by liquid impregnation of sucrose and their application in RP-HPLC.[176] Also the porous characteristics are important for technical applications. The modulation of these have been achieved by selecting the mesoporous silica template,[172,177] the source of carbon[171] or varying the sucrose to silica weight ratio.[178]

In summary, the mesoporous materials present surface areas and pore diameters higher than 600 m^2/g and 2 nm respectively. Due to those properties they are prominent materials for being applied in different fields that our research group has explored, such as catalyst, enzymes immobilization, chromatography columns development, polymers reinforcement and synthesis of new materials by using templates.

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