Versatility of Silsesquioxane-Based Materials for Antimicrobial Coatings

Bogdana Simionescu [1], Cristian Ursu [2], Corneliu Cotofana [2], Andreea Chibac [2] and Mihaela Olaru [2,*]

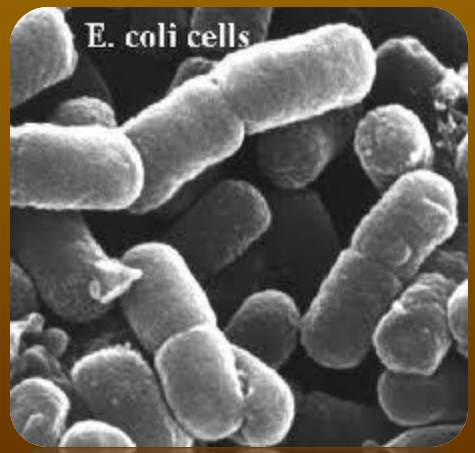
[1] "Costin D. Nenitescu" Centre of Organic Chemistry, Bucuresti, Romania
[2] "Petru Poni" Institute of Macromolecular Chemistry, Iasi, Romania

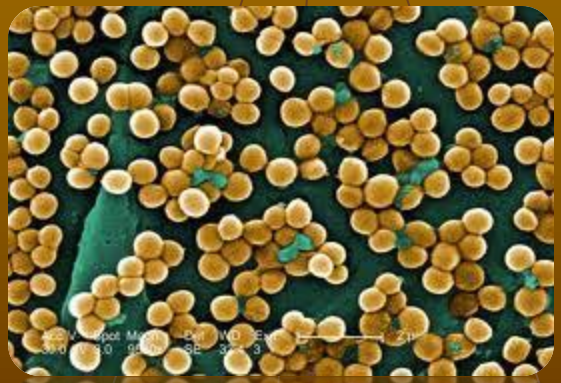
1st International Electronic Conference on Materials
Functional Materials and Interfaces for Biomedical Applications

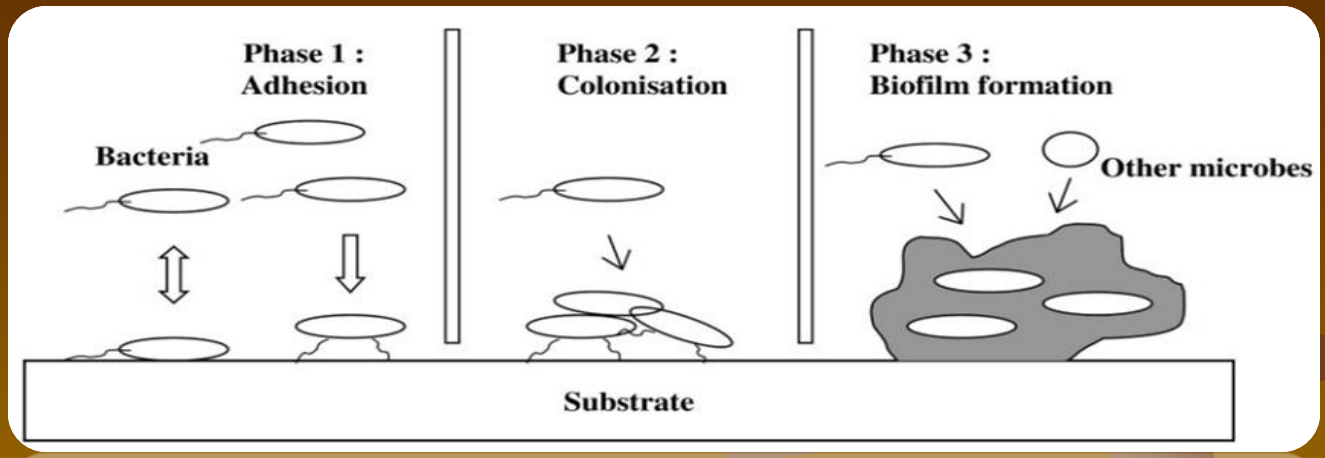
26 may – 10 june 2014

The world of microorganisms

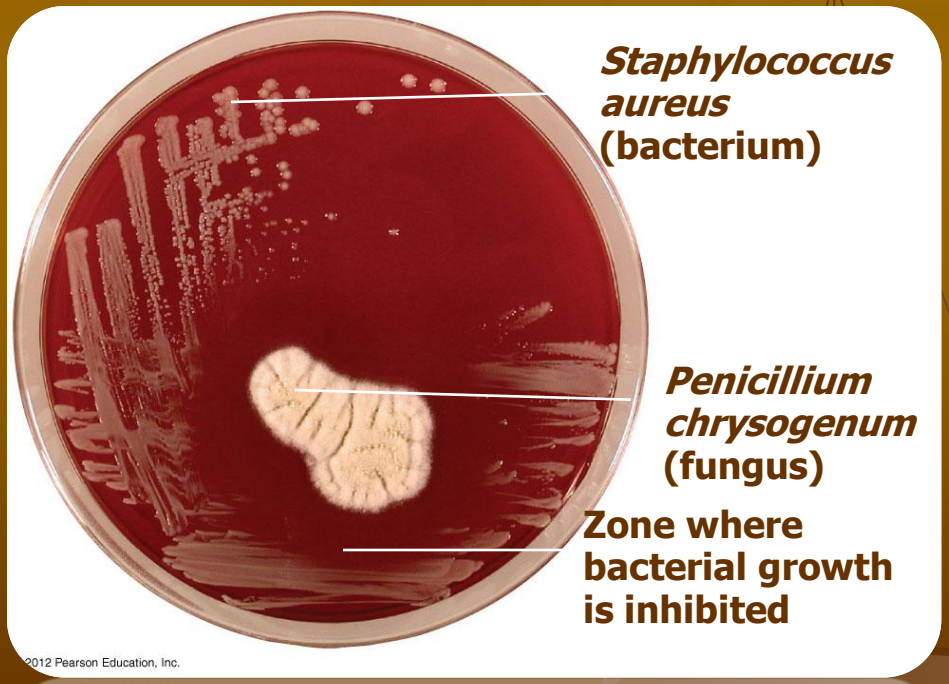
- microorganisms - bacteria, viruses, fungi, archaea, protozoa, and algae with characteristic cellular composition, morphology, mean of locomotion, and reproduction
- beneficial in producing oxygen, decomposing organic material, providing nutrients for plants, and maintaining human health
- some of them can be pathogenic and cause diseases in plants and humans
- control of the contact with pathogenic organisms is an effective way to prevent being infected with diseases

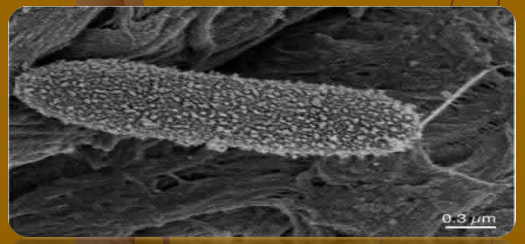






Schematic representation of biofilm formation





Antimicrobial coating – alternative way to control infections

Prevention from the source

- bacteria can be killed before contact with human body
- can be used for different applications
- especially important for MedTech applications - surfaces of medical devices, implants, drug delivery devices a.s.o.
- equally important for electrical devices and especially portable electrical devices, cell phone, notebook computer

Antimicrobial surface coatings must exhibit

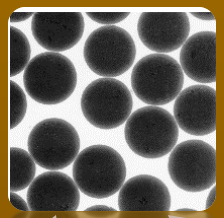
- effective control of bacteria, molds and fungi
- selective activity towards undesirable microorganisms
- absence of toxic effects for both the manufacturer and the consumer
- durability of antimicrobial activity on treated surfaces
- compatibility with other finishing agents
- easy application, compatibility with common thin film processing

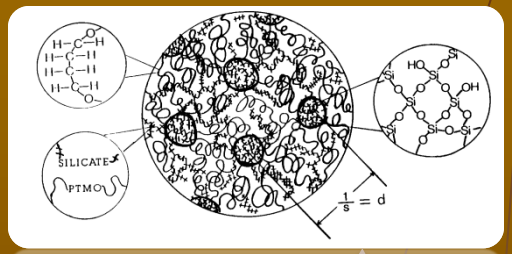
Hybrid nanocomposites with silsesquioxane units

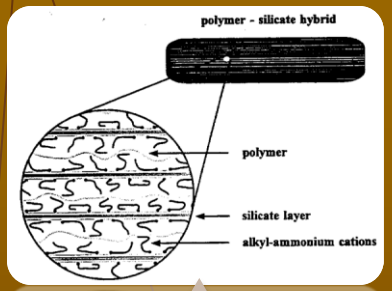
- The term “nanotechnology” is used to describe materials, devices, or structures with feature sizes less than 100 nm
- For composite materials, properties can deviate from simple rules of mixing when phase domains are less than 1 micron

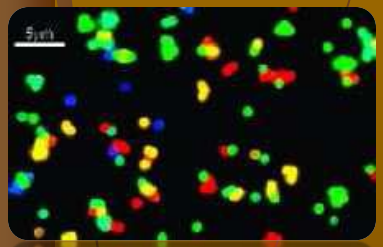
The evolution of nanocomposites

$SiCl_4$
$+ H_2O$









1900 — 1950-1960 — 1970 — 1980 — 1990 — 2000

1900: Silane, Hydrolysis, Carbon black

1950-1960: Stöber process, Fumed silica, Precipitated oxides

1970: Sol-Gel processing, Fullerenes

1980: Highly ordered Nanocomposites, Nanoparticles

1990: Quantum dots, Nanowires, Nanotubes

POSS polyhedral oligomeric silsesquioxanes

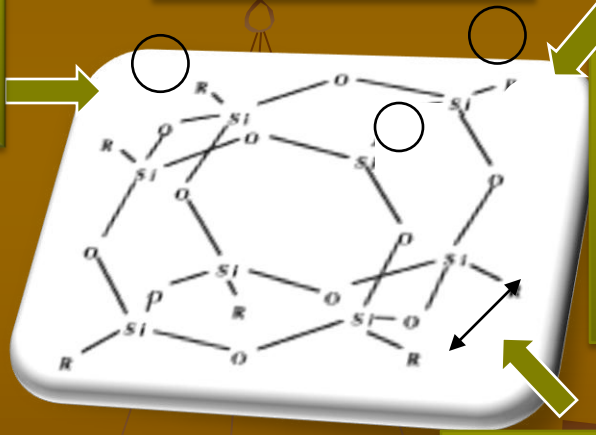
- Improved mechanical (Young' modulus) at low loading
- Increase viscoelastic properties
- Low dielectric properties
- Crystallinity
- Increase of the thermal properties
- Flame retardancy

$R = H, OSi(CH_3)_2H$

Eight corn substituted cage

Function, epoxy, alcohol, C=C

Nonreactive organic (R) groups for solubilization and compatibilization

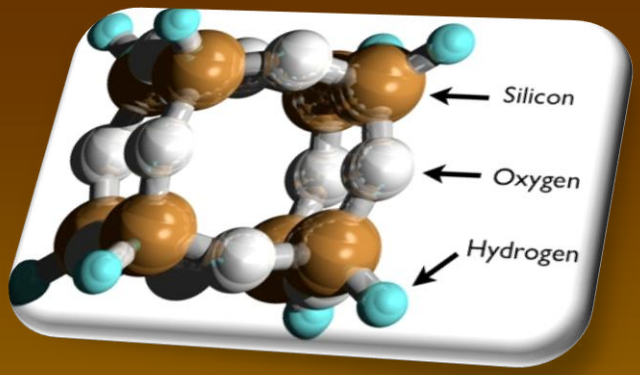


May possess one or more reactive groups suitable for further chemical reactions, (co-) polymerization or grafting

Nanoscopic in size with an Si-Si distance of 0.5 nm and a R-R distance of 1.5 nm

Thermally and chemically robust hybrid (organic-inorganic) framework (stable bond)

- Functions: chemical modification or grafting of existing polymers (modulation of the number of grafted chains)
- Polymerizable group (copolymerization with other monomers *via* ATRP, coordination polymerization, ring opening...)

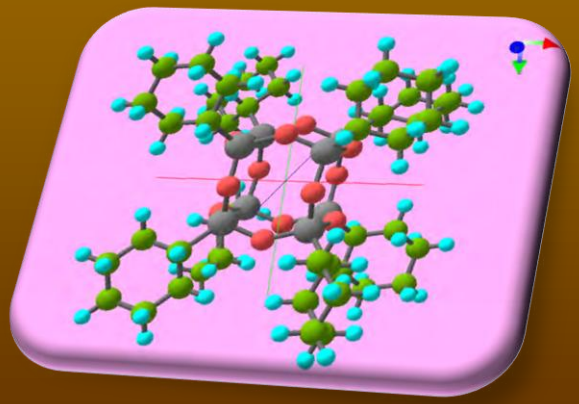


Schematic of a polyhedral oligomeric silsesquioxane (POSS) cage

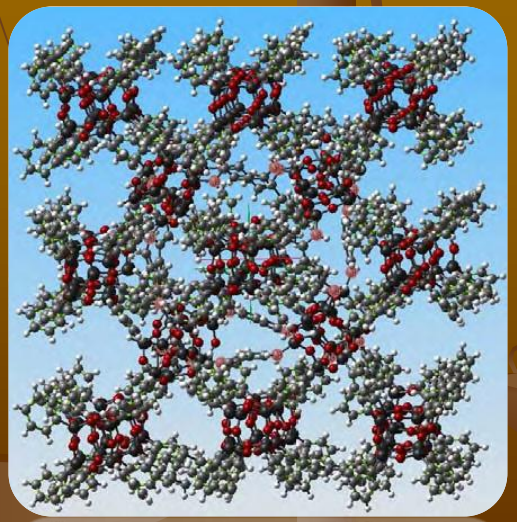
Commercially POSS applications - additive for heat and abrasion resistant paints, space resistant resins, precursors to ceramic matrices, dental composites, a.s.o.

Silsesquioxane properties

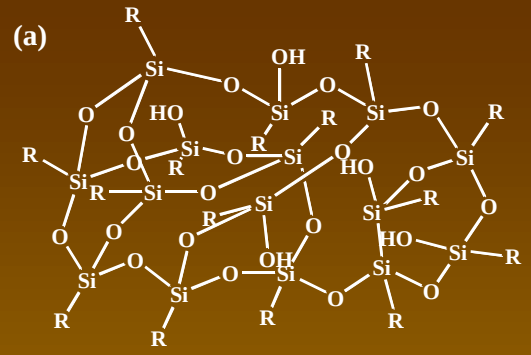
- **Particule size = 1,5 nm**
- **M_w = 900 – 1.770 g/mol**
- **Appearance: T8 high func. (white powder), T8 low func. (viscous liquid)**

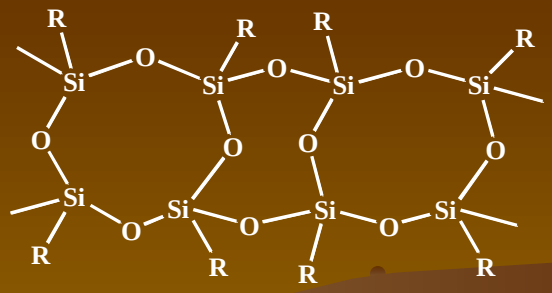


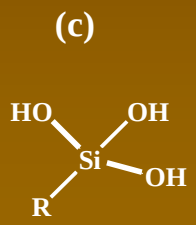
Silsesquioxane Nanocube



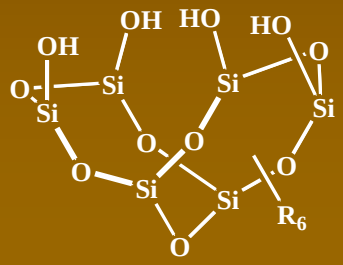
Perfect nano building blocks



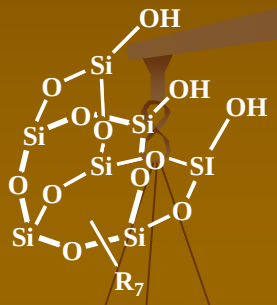




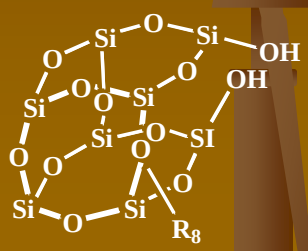
Silanetriol



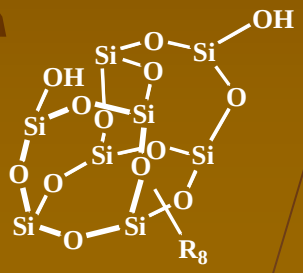
$T_6(OH)_4$



$T_7(OH)_3$

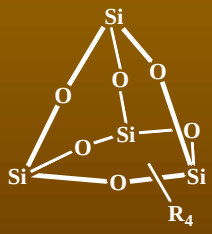


T_8(*endo*-OH)$_2$

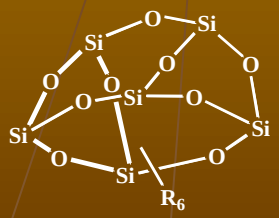


T_8(*exo*-OH)$_2$

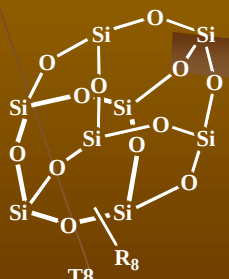
Different architectural structures of incompletely condensed silesquixanes: (a) random, (b) ladder and (c) partial-caged



T4



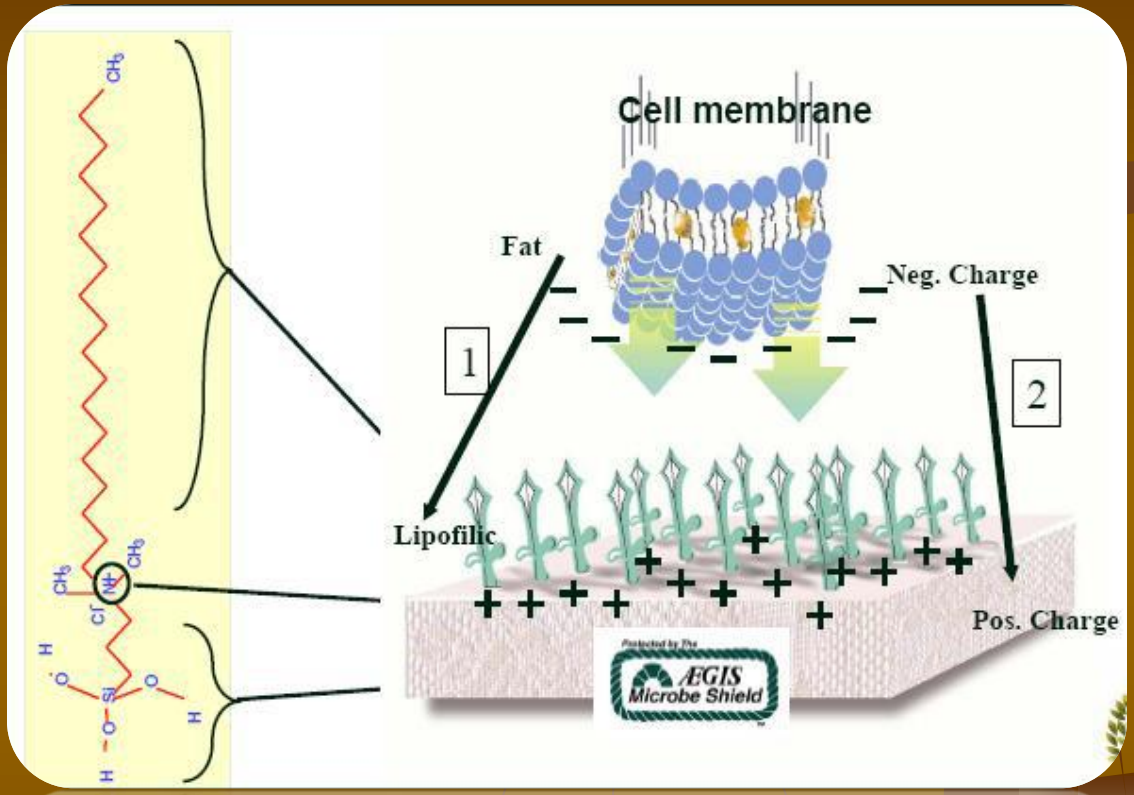
T6



T8

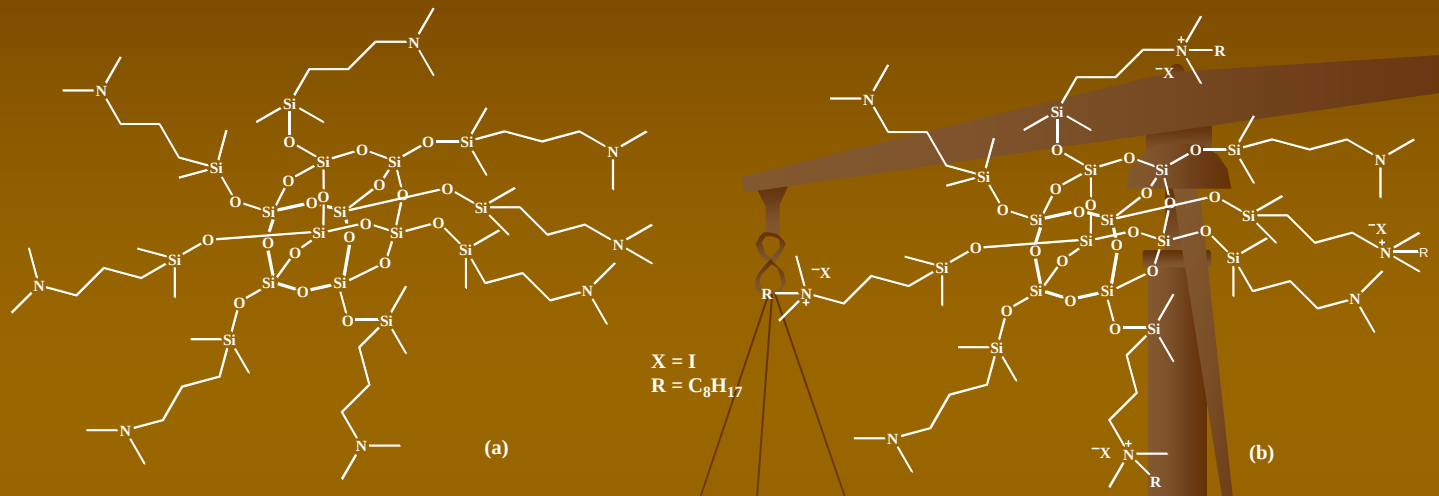
Schematic representation of cage-like silsesquioxanes (T_4, T_6 and T_8 structures)

Antimicrobial coating with quaternary ammonium salts



(i) quaternary ammonium groups polymers adsorption on bacterial cell surface and (ii) diffusion through cell wall, (iii) adsorption onto cytoplasmic membrane, (iv) disruption of cytoplasmic membrane and (v) leakage of cytoplasmic membrane constituents, and finally (vi) cell death

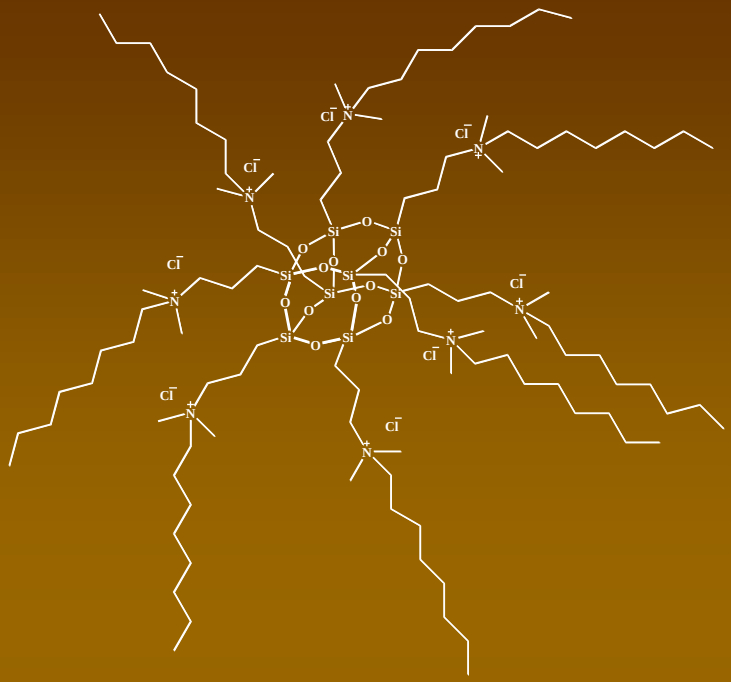
Polymers containing quaternary ammonium groups (QAs)
- advantages over other biocides – an effective action on a wide pH range, low vapor pressure, low human toxicity, as well as lack of unpleasant odors



Schematic representation of (a) dimethylamino-functionalized POSS; (b) Q-POSS idealized structure

- synthesis of a dimethylamino-functionalized POSS quaternized (40 % quaternized degree) with 1-iodo-octane
- good antimicrobial activity toward both gram-negative (*Escherichia coli*) and gram-positive (*Staphylococcus aureus*) bacteria, activity depending on alkyl chain length and charge density

Majumdar, P.; Lee, E.; Gubbins, N.; Stafslien, S.J.; Daniels, J.; Thorson, C.J.; Chisholm, B.J. Synthesis and antimicrobial activity of quaternary ammonium-functionalized POSS compounds, *Polymer Preprints* 2008, *49(1),* 883



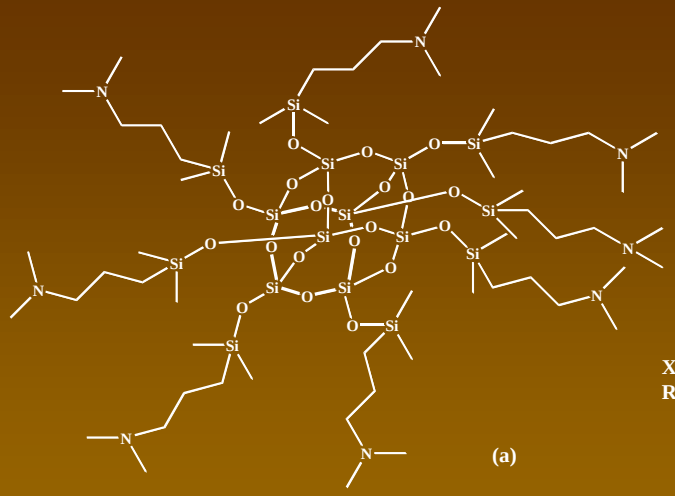
Schematic representation of a polysilsesquioxane containing secondary n-amylammonium salt

- bacteriocidal activity of several oligo- and polysilsesquioxanes with ammonium salts of variable quaternization degrees (octa(3-chloropropylsilsesquioxane) and poly(3-chloropropylsilsesquioxane)

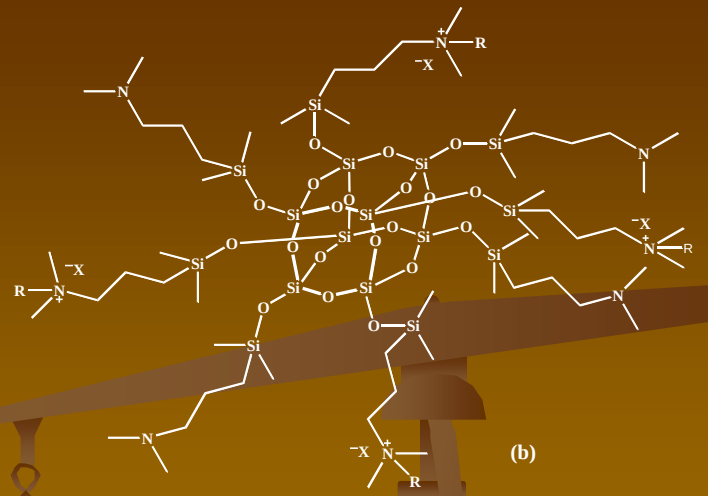
- the best antimicrobial activity, i.e., grow inhibiting of *Enterococcus hirae* , *Staphylococcus aureus* and *Escherichia coli* - attained for the compounds characterized by a 50 % conversion degree

- the oligomers almost fully substituted with the ionic QAs units proved to be very active against gram-positive bacteria only in suspension, manifesting a lower activity in solution

Chojnowski, J.; Fortuniak, W.; Rosciszewski, P.; Werel, W.; Lukasiak, J.; Kamysz, W.; Halasa, R. Polysilsesquioxanes and oligosilsesquioxanes substituted by alkylammonium salts as antibacterial biocides. *J. Inorg. Organomet. Polymer Mater.* **2006**, *16*, 219-230.



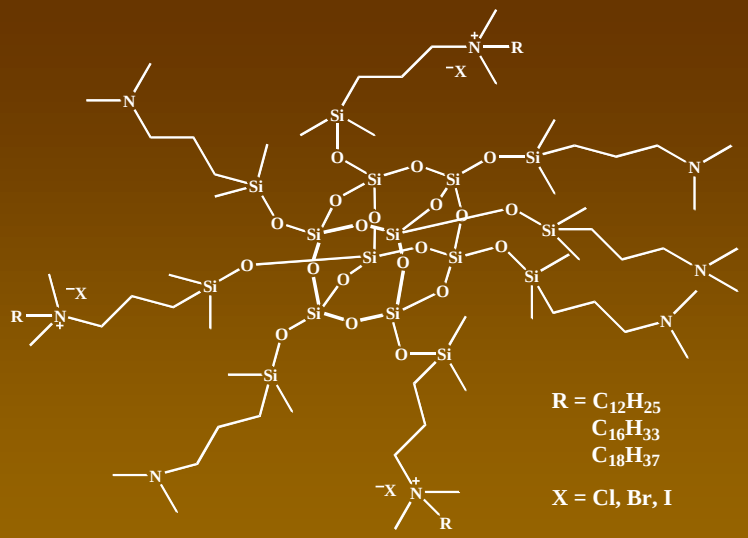
X = I
R = C_8H_{17}



Schematic representation of (a) dimethylamino-functionalized POSS; (b) Q-POSS idealized structure

- hydrosilylation of an octasilane POSS with allyldimethylamine - functionalized POSS containing eight tertiary amino groups
- Q-POSS compounds with different lengths and extent of quaternization - incorporated in two different moisture-curable polysiloxane coatings
- Q-POSS-based coatings possessing the lowest quaternization extent (~ 40 mol %) - the best antimicrobial activity
- presence of Q-POSS at coating's surface (nanoscale surface roughness) in the coatings of low quaternization

Majumdar, P.; Lee, E.; Gubbins, N.; Stafslien, S.J.; Daniels, J.; Thorson, C.J.; Chisholm, B.J. Synthesis and antimicrobial activity of quaternary ammonium-functionalized POSS (Q-POSS) and polysiloxane coatings containing Q-POSS. *Polymer* 2009, ***50***, 1124–1133



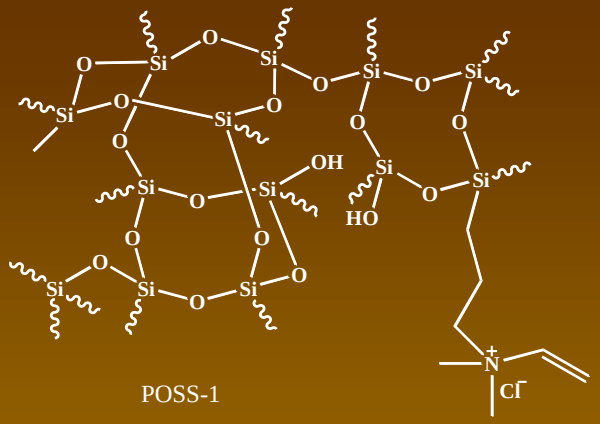
Schematic representation of octasilane Q-POSS compounds

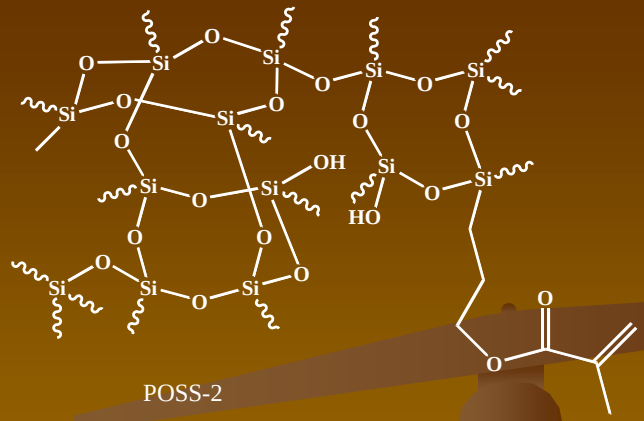
- quaternization of several octasilane Q-POSS compounds with different alkyl chain lengths (from $-C_{12}H_{25}$ to $-C_{18}H_{37}$), functionalized with QAs units through various counter ions, i.e., chlorine, iodine, bromine

- both alkyl chain length and counter ion were found to affect Q-POSS antimicrobial properties, the highest antimicrobial efficiency against *Escherichia coli* and *Staphylococcus aureus* being proved by Q-POSS with C_{12} alkyl chain length and chlorine counter ion

- Q-POSSs incorporated into a moisture-curable polysiloxane coating - all coatings were more efficient against *Staphylococcus aureus,* followed by *Candida albicans fungus* and *Escherichia coli*

Majumdar, P.; He, J.; Lee, E.; Kallam, A.; Gubbins, N.; Stafslien, S.J.; Daniels, J.; Chisholm, B.J. Antimicrobial activity of polysiloxane coatings containing quaternary ammonium-functionalized polyhedral oligomeric silsesquioxane. *J. Coat. Technol. Res.* **2010**, *7(4)*, 455–467

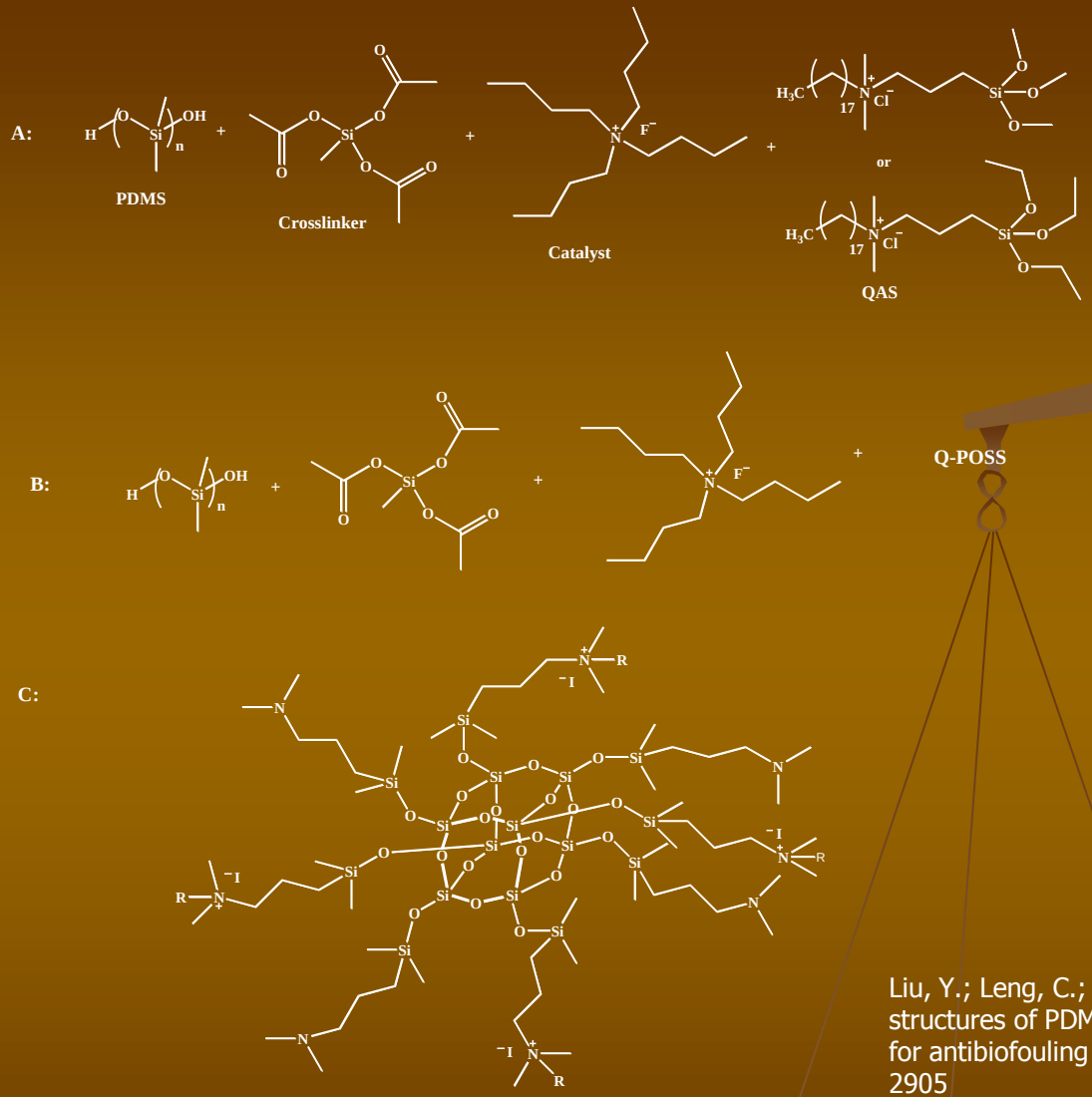




Presumed structure of silsesquioxane-based hybrid nanocomposites (POSS-1, POSS-2)

- the first report on the use of hierarchical assemblies with silsesquioxane and quaternary ammonium units intended for antimicrobial monumental stone coating
- hierarchical structures comprising nanofibrillar micelles confined within semi-cylindrical shells - ascribed to the presence of multiple intermolecular ionic interactions, intermolecular Van der Waals forces and hydrophobic interactions acting among the constituent molecules
- both silsesquioxane-based polymer blend coatings were more effective against *Staphylococcus aureus,* followed by *Candida albicans fungus,* while no action was registered against *Escherichia coli*

Simionescu, B.; Bordianu, I.-E.; Aflori, M.; Doroftei, F.; Mares, M.; Patras, X.; Nicolescu, A.; Olaru, M. Hierarchically structured polymer blends based on silsesquioxane hybrid nanocomposites with quaternary ammonium units for antimicrobial coatings. *Materials Chem. Phys.* **2012**, *134*, 190–199

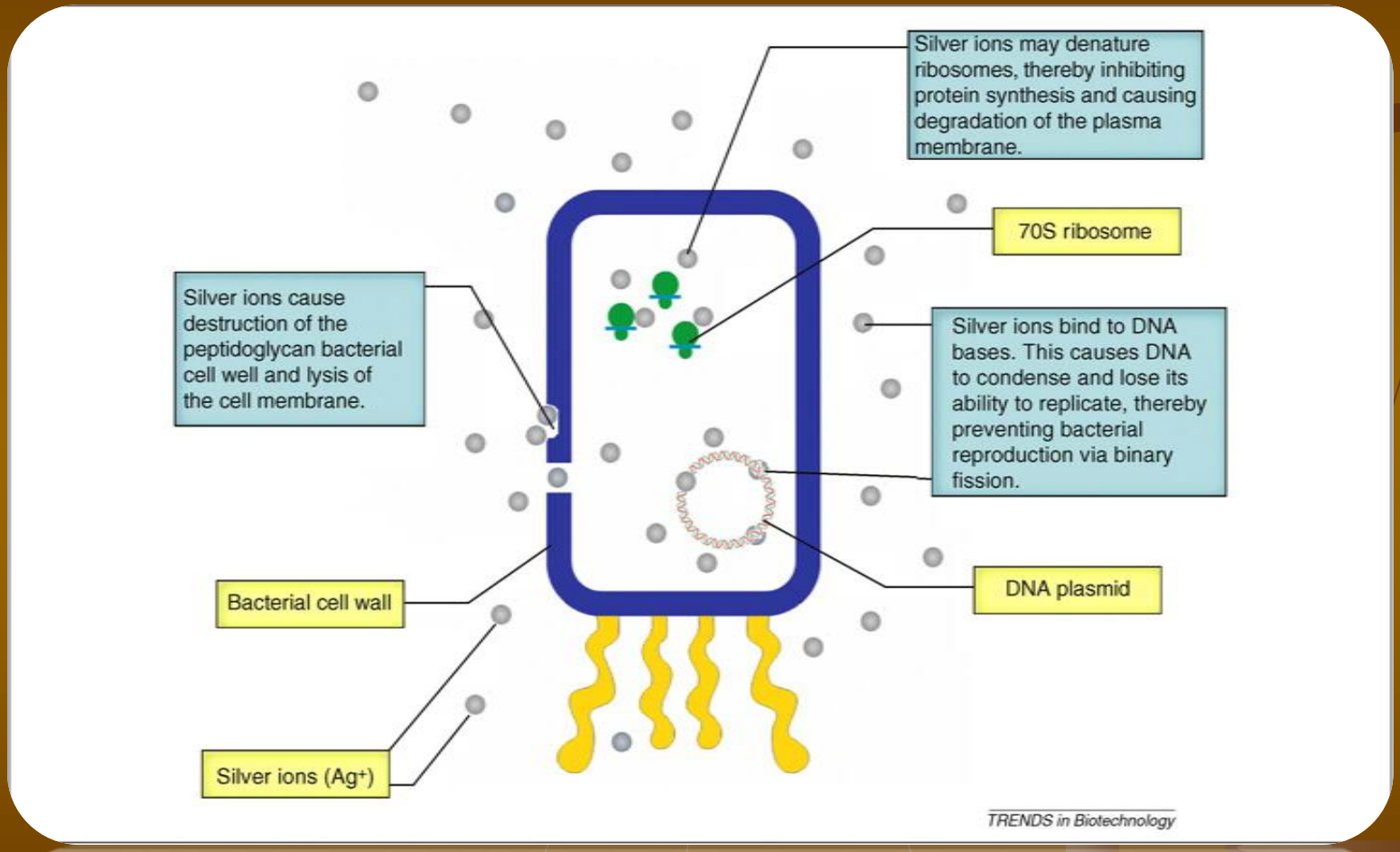


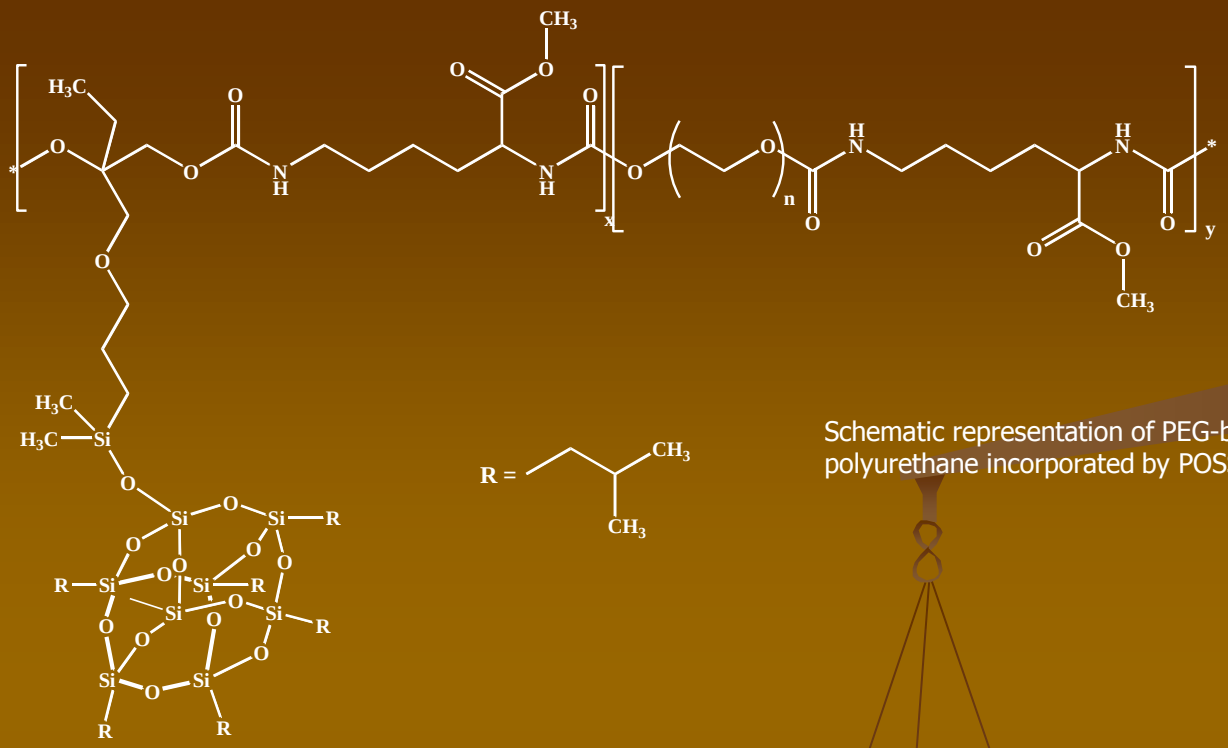
- PDMS coatings containing QAS or Q-POSS
- relationships between interfacial surface structures and their antifouling properties
- lower extent of Q-POSS quaternization and use of ethoxy functional QAs groups facilitated the extension of the alkyl chains away from the nitrogen atoms, thus favouring the neutralization of marine microorganisms upon contact

Liu, Y.; Leng, C.; Chisholm, B.; Stafslien, S.; Majumdar, P.; Chen, Z. Surface structures of PDMS incorporated with quaternary ammonium salts designed for antibiofouling and fouling release applications. *Langmuir* **2013**, *29*, 2897–2905

Chemical structures of the QAS-incorporated PDMS systems: (A) QAS-tethered system. (B) Q-POSS-incorporated PDMS system. (C) Q-POSS structure

Antimicrobial coatings with silver

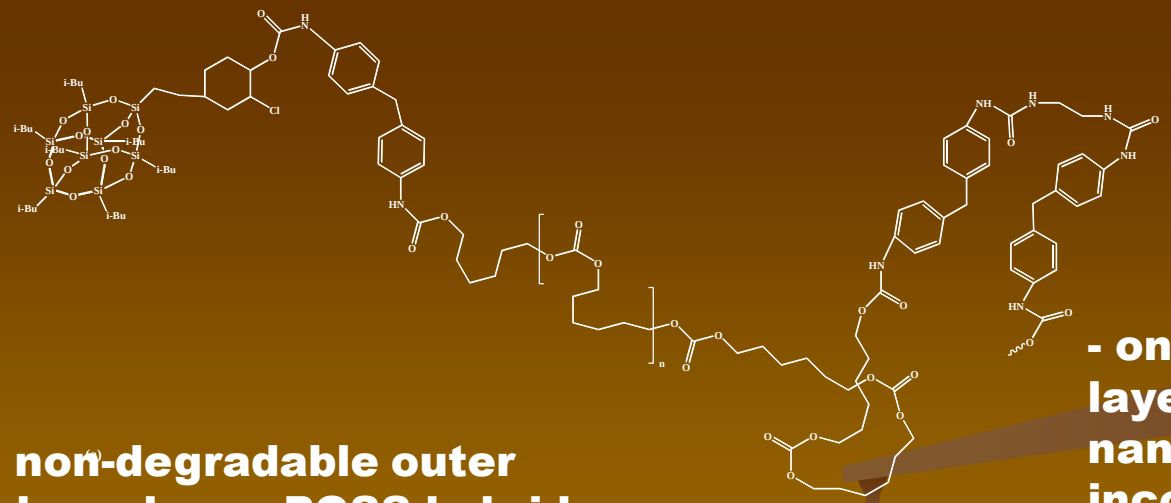




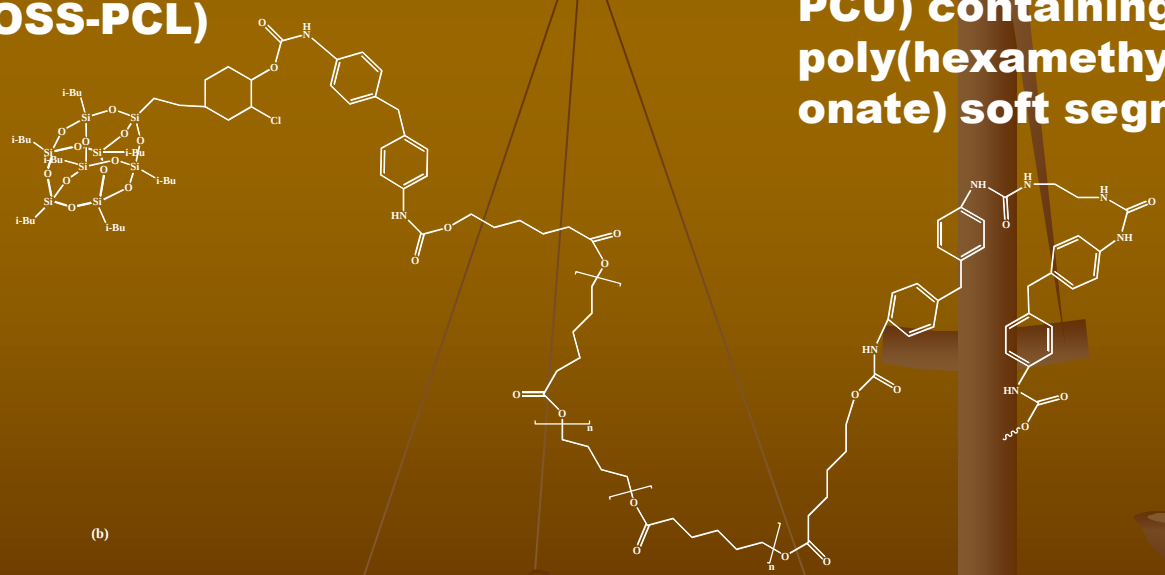
Schematic representation of PEG-based multiple-block thermoplastic polyurethane incorporated by POSS macromer

- nanofibrous webs based on silver-containing thermoplastic hydrogels were obtained starting from multiblock poly(ethylene gylcol) – POSS polyurethanes
- lack of swelling - wound dressing applications
- nanofibrous webs - able to suppress the formation of *Escherichia coli* biofilm for a 14 days extended period

Wu, J.; Hou, S.; Ren, D.; Mather, P.T. Antimicrobial properties of nanostructured hydrogel webs containing silver, *Biomacromolecules* **2009**, *10*, 2686–2693



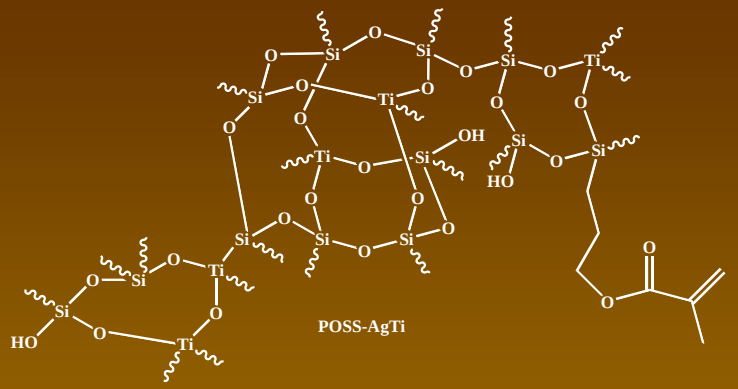
- one non-degradable outer layer based on a POSS hybrid nanocomposite incorporated inside a poly(caprolactone-urea)urethane (POSS-PCL) compound

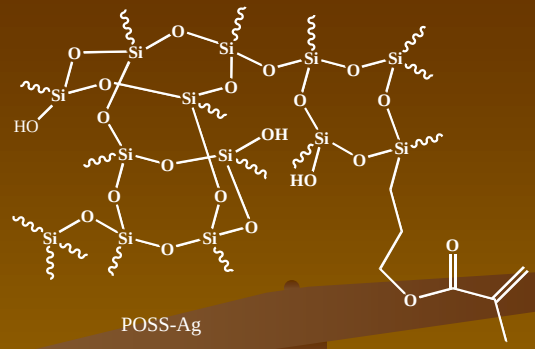


- one inner biodegradable layer – POSS hybrid nanocomposite incorporated inside a poly(caprolactone-urea)urethane (POSS-PCU) containing a poly(hexamethylenecarbonate) soft segment

Schematic representation of (a) non-biodegradable POSS-PCU; (b) biodegradable POSS-PCL

Chawla, R.; Tan, A.; Ahmed, M.; Crowley, C.; Moiemen, N.S.; Cui, Z.; Butler, P.E.; Seifalian, A.M. A polyhedral oligomeric silsesquioxane- based bilayered dermal scaffold seeded with adipose tissue-derived stem cells: in vitro assessment of biomechanical properties. *J. Surg. Res.* **2014**, *188(2),* 361–372





Presumed structure of silsesquioxane-based hybrid nanocomposites (POSS-Ag, POSS-AgTi)

- a first study on the use of silver nanoparticles in antibacterial coatings for monumental stones
- new types of silsesquioxane-based hybrid nanocomposites with methacrylate units, containing either only silver nanoparticles (POSS-Ag) or a combination of titania and silver nanoparticles (POSS-AgTi)
- self-assembling structures (semi-cylindrical shells) with homogeneous distribution of metalic nanoparticles
- both synthesized compounds showed high antibacterial/antifungal efficiency against *Escherichia coli* and *Candida albicans fungus,* better results being obtained in POSS-AgTi case

Aflori, M.; Simionescu, B.; Bordianu, I.-E.; Sacarescu, L.; Varganici, C.-D.; Doroftei, F.; Nicolescu, A.; Olaru, M. Silsesquioxane-based hybrid nanocomposites with methacrylate unitscontaining titania and/or silver nanoparticles as antibacterial/antifungal coatings for monumental stones, *Mat. Sci. Eng. B* **2013**, *178*, 1339–1346

Conclusions

- two main strategies to design silsesquioxane-based antimicrobial materials active against a wide-range of microorganisms, i.e., incorporation of quaternary ammonium units and incorporation of metals
- recent research has been focused on POSS structures with quaternary ammonium units, although such type of systems are not always the best solutions to assure an efficient antimicrobial coating against a wide-range of microorganisms
- since POSS materials are resistant to degradation, biocompatible, safe, compliant, anti-thrombogenic, and allow neo-endothelialization, it is expected that new lines of research will be developed in the field of antimicrobial coatings
- reduction of cytotoxicity while maintaining or even enhancing the antimicrobial activity will stand among the efforts to be made in the future