MICRO - AND NANOAPPLICATIONS OF POLYMERS AND POLYMER-BASED HYBRID MATERIALS

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FOREWORD

The *Symposium on micro/nano-interactions and systems based on natural or synthetic polymers (MNS)*, organized at *Petru Poni Institute of Macromolecular Chemistry* in the frame of Iasi Academic Days, has become a traditional scientific event since 2003. Six editions of the meeting were held until now and this autumn the seventh Edition will run at the end of September, as usually. The symposium started under the auspices of CENOBITE network, the first one intended as a research center for nanobiotechnologies, and was continued with partial financing of two other networks also focused on bio/nano topics, namely NANOMATFAB and RO-NANOMED, all of them in the frame of MATNANTECH National Research Program. In 2006 and 2007 the symposium was also sponsored from the European project FP6-2004-ACC-SSA-2 – Romanian Action for Integrating, Networking and Strengthening the ERA (RAINS).

Nanoscience is a recent scientific area which concerns itself with the study of materials that have very, very small dimensions – from hundreds to tens of nanometers in size. Nanotechnology is a field of applied science focused on the design, synthesis, characterization and application of materials and devices on the nanoscale. Nanoengineering is the practice of engineering on the nanoscale. Nanobiotechnology (or bionanotechnology, or biomolecular nanotechnology) is a new wing in nanoscience and nanotechnology, developed last years at the crossroad of biology, biotechnology, medicine and nanoscience. Polymers are a frequent partner in the nanoworld. We could define a polymer nanoscience, dedicated to theoretical and fundamental aspects, and the polymer nanotechnology, which deals with nanomaterials and nano-objects based on polymers. There is a huge amount and a great variety of research and results in this field. A tentative of clustering the nano-objects could be done as follows, according to the number of nanodimensions: nano 3D objects, such as nanoparticles, nanospheres, nanocapsules, dendrimers; nano 2D objects, such as biopolymers, nanofibres, nanowires; and nano 1D objects, such as very thin films, multilayers, etc.

This volume gathers a selection of the papers presented during the first and second edition of MNS; of course, the contributions were up-dated and completed with new information. The main feature of these papers is they focus on the use of polymers or related materials for nano/bioapplications. After starting with two contributions of general interest, the selected papers are balanced between nanomaterials or nanocomposites and nanobjects of the class 3D – nanoparticles, nanocapsules, 2D – natural polymers, or 1D – thin layers fabricated from various

polymers by different methods. The synthesis and characterization of various polymers are presented, as well as the properties of related materials or objects and the application in advanced fields such as electronics, non-linear optics, nanobiotechnologies and many others.

The volume is addressed to those working in the nano-topic, from academic or industrial media. The students and PhD students could be also interested to gain some approach on this fascinating area.

We are thankful to the co-ordinator of *Micro and Nanoengineering* Series, acad. Dan Dascalu, for accepting the publication of this volume. The support of the Romanian Academy is gratefully acknowledged. Last but not least, we wish to express our gratitude to all the colleagues who accepted to contribute to this volume.

The Editors,
February 2008

Ethical Issues in Research

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1. ETHICAL SCIENTIFIC RESEARCH: HISTORY

Driven by advances in biotechnology and biomedicine, the role of ethics has evolved with each Framework Programme of the European Community. Questions by the European Parliament on a small pilot programme on the human genome (predictive medicine) at the start of the 2nd Framework Programme (1987-91) resulted in a first *ad hoc* ethics committee (ELSA) aimed to consider the Ethical Legal and Social Aspects of research. The role of ethics was taken further in the 3rd Framework Programme by provisions for specific research on medical ethics and studies to assess the impacts of biotechnology. The 4th Framework Programme started bioethical research in the Life Sciences and ethical review of proposals raising sensitive issues such as the use of embryonic or foetal tissue and the use of animals. The 5th Framework Programme extended the scope of ethical review to all other programmes, in particular to the *INCO programme* and to the *Competitive and sustainable growth* (GROWTH). Finally, a new unit dealing with *Ethics in Science and Research* was established and located in the directorate dealing with *Science and Society*. The EC published in December 2001 the Action Plan on Science and Society including six actions on ethics. Regarding the EU's Seventh Framework Programme for Research, participants in FP7 projects must conform of course to current legislation and regulations in the countries where the research will be carried out. They must seek the approval of the relevant ethics committees prior to the start of the research activities, if ethical issues are involved, and respect *international conventions and declarations*. European Parliament and Council Decision 1982/2006/EC of 18 December 2006 concerning the 7th FP stipulated that all research activities carried out under the Seventh Framework Programme shall be carried out in compliance with fundamental ethical principles. There are several fields excluded from FP7 for ethical reasons: research activity aiming at human cloning for reproductive purposes; research activity intended to modify the genetic

heritage of human beings which could make such changes heritable; research activities intended to create human embryos solely for the purpose of research or for the purpose of stem cell procurement, including by means of somatic cell nuclear transfer.

The **European Group on Ethics** is an independent, pluralist and multidisciplinary body, which advises the European Commission on ethical aspects of science and new technologies. It has helped guide the Community policies on culturally sensitive ethical questions in science. The members of the Group are experts drawn from fields such as biology and genetics, medicine, informatics, law, philosophy or theology. The Group of Advisers on the Ethical Implications of Biotechnology (GAEIB, 1991–1997) has provided opinions on subjects such as human tissue banking, human embryo research, gene therapy, personal health data in the information society, doping in sport and human stem cell research. At a specific request of the President of the Commission, Romano Prodi, the Group also wrote the Report on the Charter of Fundamental Rights related to technological innovation [http://ec.europa.eu/research/science-society/action-plan/10_action-plan].

The main activities of the D.G. Research in promoting responsible research in Europe comprise:

– pursuing the part of the Science and Society Action Plan dealing with the ethical dimension in science and the new technologies (the Action Plan was adopted by the European Commission in December 2001);

– applying the ethical rules for the Research Framework Programmes;

– performing an ethical assessment of research projects funded by the European Commission;

– supporting, through the European Union's 6^{th} and 7^{th} Framework Programme for Research, research on ethical and social issues raised by developments in science and technology;

– making known International Rules and Conventions related to ethics.

As for the framework that defines ethics in scientific research, it is worth noting that the Commission considers sensitive ethical issues to be those which involve human beings, for example, in clinical trials, which use human tissues, in particular embryonic and foetal tissue, which use animals, in particular, genetically modified animals and non-human primates. Other important ethical issues concern data production. Actions to raise awareness of good scientific practices, including the ethical dimension, research integrity and the key elements of European legislation, conventions and codes of conduct should be encouraged.

The **European Legislation on Ethics** includes:

- Charter of Fundamental Rights of the European Union
- Directives of the European Union
- Ethical rules of the Sixth Framework Programme
- Conventions and Protocols of the Council of Europe
- European Group on Ethics in science and new technologies
- Opinions of the European Group on Ethics relevant to research activities

• Resolution of the European Parliament on Human Cloning
• European Science Foundation: policy briefings
• European Commission Staff Working Paper - Report on human embryonic stem cell research
• Procedural modalities for research activities involving banked or isolated human embryonic stem cells in culture to be funded under Council Decision 2002/834/EC
• EU strategy on sustainable development.

Several international organisations (governmental and non-governmental such as - Council of Europe, European Science Foundation, UNESCO, WHO, World Medical Association, FAO and others) are actively promoting ethics in science and research. International conventions concerning ethical research comprehend:

• Universal declarations within the United Nations
• World Medical Association - Declaration of Helsinki
• The Nuremberg Code
• Ethical considerations in HIV preventive vaccine research
• Codes of conduct.

In the European Union's Framework Programmes for Research there are ethical review panels which are composed of independent experts of different disciplines such as law, sociology, psychology, philosophy and ethics, medicine, molecular biology and veterinary science. They have a parity of scientific and non scientific members, and also a gender and geographical balance. Civil society representatives may be invited, for example as representatives of patients' organisations or animal welfare organisations. These independent experts are bound to the European Commission requirements concerning conflict of interest and confidentiality. The European Commission takes into account the results of the scientific evaluation and the ethical review when deciding on the proposals to be funded. Projects which are contrary to fundamental ethical principles are excluded from the selection procedure [Eurobarometer: Europeans, science and technology, December 2001].

2. RESPONSIBILITY OF SCIENTISTS

The idea of whether scientists are responsible or not for the potentially negative consequences of their discoveries was tested with two formulations. The first, very general attributes a share of responsibility to them “as members of society”. The second formulation involves scientists more directly since it presupposes their responsibility for the “misuse of their discoveries by others”. Another question evokes the potential threat from the connection between science and power. A fourth way of viewing the responsibility of scientists is, on the contrary, to disavow it by subscribing to the idea that a scientific discovery is neither a good or bad thing in itself and that what matters is the use made of it. The question of whether or not scientists should be allowed to conduct experiments on animals is another ethical problem. The degree of control of the freedom of

scientists with regard to ethical rules was measured on the basis of two questions, the first implying a powerful notion of constraint, while the second confines itself to a type of control of the scientists. The results of the inquiry focusing on these issues are presented in the table below
[http://ec.europa.eu/research/press/2001/pr0612en-report.pdf, p. 36].

	Inclined to agree	Inclined not to agree	Don't know
As members of society, scientists share in the responsibility of any use - whether good or bad - of their discoveries	69.1	18.4	12.5
Scientists are responsible for the misuse of their discoveries by others	42.8	42.3	14.8
Scientists' knowledge gives them a power which makes them dangerous	63.2	24.8	12
A discovery in itself is neither good nor bad, what is important is the use which is made of it	84.4	8.1	7.5
Scientists should be allowed to carry out experiments on animals such as dogs and monkeys if that can help solve human health problems	45.4	41.3	13.3
The authorities ought to formally oblige scientists to observe ethical rules	80.3	8.3	11.3
Scientists ought to be free to pursue their research as they wish so long as they observe ethical rules	73.5	14.7	11.8

3. OPTIMISM REGARDING SCIENCE

A series of questions were formulated on the general theme of the promises of science and technology. These questions are listed in the table below together with the percentages of replies indicating confidence in scientific and technical development [http://ec.europa.eu/ research/press/2001/pr0612en-report.pdf, p. 29].

	Inclined to agree	Inclined not to agree	Don't know
Scientific and technological progress will help to cure diseases such as Aids, cancer, etc.	80.5	9.1	10.4
Thanks to science and technology, there will be greater opportunities for future generations	72.4	13.6	14.1
Science and technology make our lives healthier, easier and more comfortable	70.7	19.9	9.4
The application of science and new technologies will make work more interesting	62.4	19.7	17.9
Science and technology cannot really play a role in improving the environment	28.0	58.8	13.2
The benefits of science are greater than the harmful effects it could have	50.4	24.2	25.4

New inventions will always be found to neutralise the harmful consequences of scientific and technological development	48.7	27.9	23.4
Science and technology will help to eradicate poverty and famine in the world	30.4	52.0	17.6
All things considered, computers and automation in factories will create more jobs than they eliminate	28.1	54.1	17.8
Thanks to scientific and technological progress, the earth's natural resources will be inexhaustible	21.4	61.3	17.2
Science and technology can solve all problems	16.5	72.8	10.7

4. ETHICAL ISSUES CONCERNING THE NANOTECHNOLOGIES

In 2004 the Royal Society and Royal Academy of Engineering published the report *Nanosciences and nanotechnologies: opportunities and uncertainties* (RS &RAEng 2004). By commissioning this report, the UK Government was recognised internationally as having taken the lead in establishing the framework necessary to realise the great potential of nanotechnologies in a responsible manner. The remit of the study was to:

- define what is meant by nanoscience and nanotechnologies;
- summarise the current state of scientific knowledge about nanotechnologies;
- identify the specific applications of the new technologies, in particular where nanotechnologies are already in use;
- carry out a forward look to see how the technologies might be used in future, where possible estimating the likely time scales in which the most far-reaching applications of the technologies might become reality;
- identify what health and safety, environmental, ethical and societal implications or uncertainties may arise from the use of the technologies, both current and future and identify areas where additional regulation needs to be considered.

The report concluded that nanotechnologies could have a wide range of beneficial applications, and many of these applications pose no new health or safety risks. However, it expressed concerns over the potential health, safety and environmental hazards posed by free, manufactured nanoparticles and nanotubes. Free nanoparticles and nanotubes often have very different physical and chemical properties to the same chemical in larger size and these new properties are being exploited in a range of applications, for example in medicine and cosmetics. These new properties also mean that their toxicology cannot be inferred from that of the same chemical in larger form. The toxicology of nanoparticles is likely to be different because of two size dependant factors: the larger surface area of small particles compared with larger particles, given equal mass, and the probable ability of nanoparticles to penetrate cells more easily and in a different manner than larger ones. Evidence from studies of exposure to other small particles and fibers, including air pollution, mineral dusts and pharmaceuticals also suggest that some

manufactured nanoparticles and nanotubes are likely to be more toxic per unit mass than larger particles of the same chemical [RS policy document 35/06].

In a paper concerned with the health and environmental impact of nanotechnology and the toxicological assessment of manufactured nanoparticles, a number of critical risk assessment issues regarding manufactured nanoparticles have been identified, such as: the exposure assessment of manufactured nanoparticles; the toxicology of manufactured nanoparticles; the ability to extrapolate manufactured nanoparticle toxicity using existing particle and toxicological databases; the environmental and biological fate, the transport, persistence, and the transformation of manufactured nanoparticles; and the recyclability and overall sustainability of manufactured nanomaterials [Toxicological Sciences **77,** 3–5 (2004)].

Potential health hazards of nanotechnology – a couple of questions

- How are nanoparticles absorbed into the body through the skin, lungs, eyes, ears, and alimentary canal?
- Once in the body, can nanoparticles evade natural defenses of humans and other animals?
- What is the likelihood of immune system recognition of nanomaterials?
- What are the sizes, aspect ratios, and surface activity determinants of nanoparticle impacts on living organisms (research must be conducted for specific nanoparticles)?
- What are potential exposure routes of nanomaterials both airborne and waterborne?
- Are the current toxicity tests used for chemicals appropriate and/or useful for nanomaterials?

Potential environmental pollution of nanotechnology – another couple of questions

- How biodegradable are nanotube-based structures?
- Could nanoparticles enter the food chain by getting into bacteria and protozoa and accumulating there?
- How will nanomaterials enter the environment and will they change when moving from one medium (e.g., air) to another (e.g., water)?
- How can we identify and dispose of nanomaterial litter?
- How might nanoparticles get into plants and other organisms?

[Source: American Council for United Nations University, The Millenium project "2005 State of the Future"].

Such type of questions and the concern to find valuable answers are the subject of different projects and programs launched by European and American governmental or academic entities. They represent a major challenge, as well as the scientific ones.

Polymers and Nanoworld

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MOTTO: Big things are happening in the science of the very small
*[*** UCLA Medicine, 24(1), 14 (2004)]*

1. INTRODUCTION

Already in 1959 prof. Richard P. Feynman (Nobel Prize Winner, 1969), in his lecture given at Caltech, Pasadena was making a brilliant and prophetic forecast on the fulgurant exponential development of the nanoworld. He said that in the future it will be possible to print the whole 24 volumes of the *Encyclopedia Britannica* in the head of a stick pin [1].

After this early futuristic vision, during almost 50 years, the interest for ultra small objects, devices, structures, or mechanisms was in a steady growing process by an interdisciplinary research effort of mathematicians, physicists, chemists (specialized on ceramics, metallurgy or polymers), microbiologists, biologists, with the help of engineering or computer sciences. Simultaneously with a huge research effort supported by the governments or the private sectors, especially in USA, Japan, Western Europe, China, and even in other countries, the attention paid by national and international scientific community in this domain could also be observed.

Now the nanoworld develops the following main directions:

a) *Nanoscience*, which is oriented to fundamental research, focused on the accumulation of basic knowledge on the synthesis and diversified instrumental characterization of nanoentities and nanostructures. The comportment of such nanoscale systems leads to fundamental advances in this domain and in our

[†] Deceased in July 23, 2010
[††] Deceased in April 17, 2009

understanding of biological, environmental and planetary systems. Nanoscience is concerned with phenomena and manipulation of materials at the nanolevel, in essence an extension of existing sciences into the nanoscale. Nanoscience is the world of atoms, molecules, *macromolecules*, *quantum dots*, and supramolecular assemblies, and is dominated by surface effects such as *Van der Waals force* attraction, *hydrogen bonding*, electronic charge, *ionic bonding*, *covalent bonding*, *hydrophobicity*, *hydrophilicity*, and *quantum mechanical tunneling*, to the virtual exclusion of *macro-scale* effects such as *turbulence* and *inertia*. Nanoscience offers the most exciting opportunities for innovation in nanotechnology [2].

b) *Nanotechnology*, which focused its goals on applying the results of nanosciences which could lead to well-defined nanoobjects with the aim to find new practical applications. Nanotechnology encompasses both the study and the engineering of structures with at least one dimension between one and one/several hundred nanometers. Specialists in this field are working with the tiniest possible components and mechanisms [3].

c) *Nanoengineering* is the practice of *engineering* on the *nanoscale*. It derives its name, like other "nano" domains, from the *nanometer*, a unit of measurement equalling one billionth of a *meter*. Some typical techniques of the nanoengineering are *Photolithography*, *Electron Beam Lithography*, *Scanning Probe Lithographies* (*Scanning Tunneling Microscopy*), *Self-assembly*, for example the creation of custom proteins from DNA sequences or strands. Nanoengineering is closely related to *nanotechnology*. In fact, the nanoscientists, the nanotechnologists and the nanoengineers work in close collaboration, in a multidisciplinary research effort to expand the performance of nanostructures and nanoobjects and to find appropriate methods to fabricate them by innovative ways. However, very important challenges remain in the fundamental understanding of systems on this scale before the entire potential of nanotechnology can be realized.

d) *Nanobiotechnology* (bionanotechnology, biomolecular nanotechnology) is a new wing in nanoscience and nanotechnology [4], developed in the last years at the crossroads of biology, biotechnology, medicine and nanoscience. It is based on the principles and chemical pathways of living organisms, ranging from genetic-engineered microbes to custom-made organic molecules. It encompasses the study, creation, and illumination of the connections between structural *molecular biology* and *molecular nanotechnology*, since the development of nano-machinery might be guided by studying the structure and function of the natural nano-machines found in living cells. Bionanotechnology seeks to modify and find technological uses of natural nano-components like the nano-motors of *ATP synthase* (*enzyme* that can synthesize *adenosine triphosphate*) and things like using the scaffold of the *enzyme* complex of *cellulosomes* for adding new enzymes to make "nanosomes". This new domain has encouraged the possibility to valorise the structures and processes of biomolecules or novel functional materials, biosensors, nanobioelectronic devices, polymer nanocontainers, nanoparticle molecular labels and medical applications.

In connection to the above definitions, the nanomaterials are defined. *Nanomaterials* are materials possessing grain sizes of the order of nanometers[*]. They manifest extremely fascinating and useful properties, which can be exploited for a variety of structural and non-structural applications. More exactly, nanomaterials are characterized as structured components with at least one dimension less than 100 nm. Materials that have one dimension in the nanoscale (and are extended in other two dimensions) are nanolayers (mono or multilayers), such as thin films, coatings or surfaces. Materials that are nanoscaled in two dimensions (and extended in one dimension) are nanowires, nanotubes, nanofibers or biopolymers. Materials with three nano dimensions are nanoparticles obtained by a variety of methods from inorganic or organic substrates. In this category are also included quantum dots, nanocrystals, fullerenes or dendrimers. Materials with three nanodimensions are used as components in nanocomposites, magnetic materials, lubricants, sensors, catalysts, etc. [5].

It is worthwhile enumerating a few of coordination bodies, institutes or centres involved in research activities in nanoscience, nanotechnology or nanobiotechnology: Center for Nanotechnology and Biomaterials, University of Queensland, Australia; Nantional Institute of Nanotechnology, University of Alberta, Edmonton, Canada; Research Institute of Nanomaterials, Nanjing University of Aeronautics and Astronautics, P.R. China; Department of Physics and Nanotechnology, Aalborgy University, Denmark; Science et Inginérie Supramoléculaire (ISIS), Université Strasbourg, France; Institut Charles Sadron, Strasbourg, France; Max Planck Institute of Colloids and Interfaces, Potsdam, Germany; Fraunhofer Institute Golm, Germany; Interdisciplinary Research Institute for Nanotechnology and Nanoscience, Tel Aviv University, Israel; National Nanotechnology Laboratory, University of Lecce, Italy; Nanotechnology Research Institute AIST Tsukuba, Japan; Nanotechnology Centre, Institute of Physics London, UK; The National Nanotechnology Initiative (NNI), a Federal R&D Program Established to Coordinate the USA Multiagency Efforts in Nanoscience, Engineering and Technology, Washington DC, USA; Nanoscience and Technology Institute (NSTI), Cambridge Ma, USA, etc.

According to the growing interest for nano domains, more and more periodicals dedicate a part of their contents to the papers concerning nano topics, and several new ones were issued. We note here some titles of the most prestigious publishing houses:

- American Chemical Society: *Biomacromolecules, Chemistry of Materials, Journal of American Chemical Society, Langmuir, Macromolecules, Nanoletters*;
- American Scientific Publishers: *Journal of Nanoscience and Nanotechnology*;

[*] All materials are composed of grains, which in turn comprise many atoms. These grains are usually invisible to the naked eye, depending on their size. Conventional materials have grains varying in size anywhere from hundreds of microns (μm) to millimeters (mm). A nanomaterial has grains of the order of 1-100 nm. The average size of an atom is of the order of 1 to 2 angstroms (Å) in radius. 1 nanometer comprises 10Å, and hence in one nm, there may be 3-5 atoms, depending on the atomic radii.

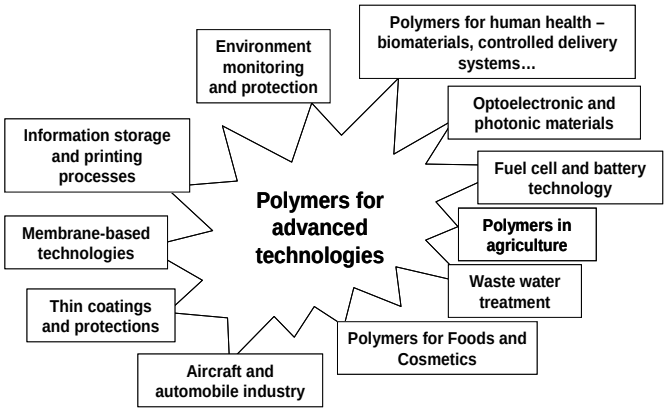
- Elsevier: *European Polymer Journal* (with a recent section dedicated to *Macromolecular Nanotechnology*), *Thin Solid Films*;
- Springer Verlag: *Colloid and Polymer Science, Colloids and Surfaces: A - Physicochemical and Engineering Aspects; B - Biointerfaces, Current Opinions in Colloid & Interface Science, Journal of Nanoparticle Research, Microfluidics and Nanofluidics*;
- Kluwer: *Biomedical Microdevices (Biomems and Medical Nanotechnology)*;
- Wiley VCH Weinheim: *Advanced Materials, Advanced Functional Materials, Angewandte Chemie International Edition; Small – Nano – Micro*;
- Taylor&Francis, UK: *Journal of Microencapsulation* (Microcapsules, liposomes, nanoparticles, microcells, microspheres);
- Other: *Nanotechnology* (Institute of Physics UK), *Nature – Materials* (The Nature Publishing Group, UK).

In Romania the publication of *Micro and Nanotechnologies Bulletin,* starting from 2000, was a proof of the interest for the nano topic.

2. NANOSCIENCE AND NANOTECHNOLOGY IN THE POLYMER FIELD

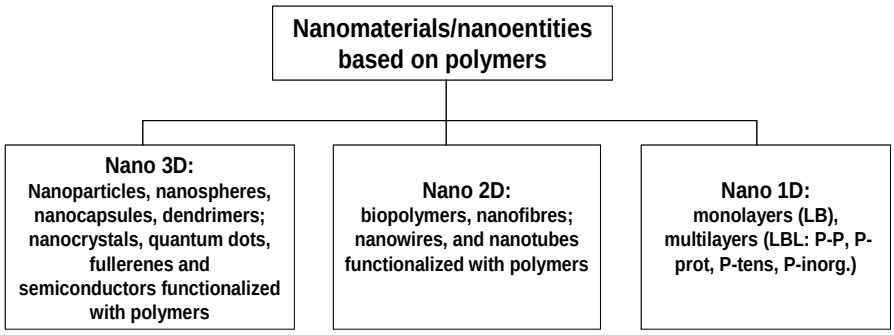
The widespread use of polymer materials requires detailed knowledge of the relationships between behavior and function on one hand and the molecular structure, dynamics and organisation of the macromolecules on the other hand. Miniaturisation of devices, the development of nanocomposites and combinatorial materials science also provide currently new challenges for polymer synthesis and characterisation [http://www.mpip-mainz.mpg.de/documents/bmbf/bmbf.html].

The current uses of polymers consist mainly in: plastics, elastomers, natural, artificial and synthetic fibres/yarns, coatings, paintings and foams, sealants or gaskets, functional polymers (reactive polymers, linear or cross-linked polyelectrolytes, additives for paper, textiles or leather industry), thermal or electric insulators. Besides these traditional fields, new advanced applications of polymers are developing, as presented in Scheme 1.



Scheme 1. Advanced applications of polymers.

Polymers are a frequent partner in the nanoworld. We could define a polymer nanoscience, dedicated to theoretical and fundamental aspects, and the polymer nanotechnology, which deals with nanomaterials and nanoobjects based on polymers. There is a huge amount and a great variety of research and results in this field. A tentative of clustering could be done based on the classification according to the number of nanodimensions, as presented in Scheme 2. In this scheme LB means Langmuir-Blodgett films, LbL means Layer-by-Layer deposition technique, while P, Prot, Tens and Inorg mean polymer, protein, tenside and inorganic partner, respectively.



Scheme 2. The most frequent nanomaterials or nanoentities based on polymers.

3. POLYMERIC NANOPARTICLES

Nanoparticles are defined as having the diameter under 100 nm. They can be obtained from metals, ceramics, glasses, oxides, semiconductors, or polymers. There are several approaches concerning the synthesis of polymeric nanoparticles, namely:

- Synthesis by polymerization processes or by interfacial polycondensation. Emulsion techniques in water (for hydrophobic monomers) or in organic solvents (for hydrophilic monomers) are used. To reach the nano dimensions emulsion polymerization is performed using a sonicator or a rotor-stator-type mechanical homogenizer. The sonicator breaks up the emulsion into submicron monomer entities of a water insoluble monomer with a soluble component to retard the monomer diffusion from the submicron monomer entities, while the homogenizer generates the submicron entities by forcing the emulsion through small openings in the stator [6, 7]. The polymerization can be performed by the classical radical method or by modern techniques such as ATRP, RAFT or ROMP processes.

- Nanodispersion of bulk natural or synthetic polymers, oligosaccharides or hemicelluloses generated by using sonication, mechanical homogenization, spray drying, phase separation, simple or complex coacervation, nebulization followed by final crosslinking of entities which contain functional groups. Figure 1 presents an example of set-up for the preparation of nanoparticles from cationic and anionic polymers [8].

- Diversification of polymeric nanoparticles is also achievable by the chemical transformation or grafting with monomers of already obtained particulates. Any kind of polymeric or inorganic nanoparticulates (metal oxides, metals, semiconductors, nanocrystals, nanowires) could be coated with various polymers especially with polyelectrolytes by LbL technique or even with small molecules [6].

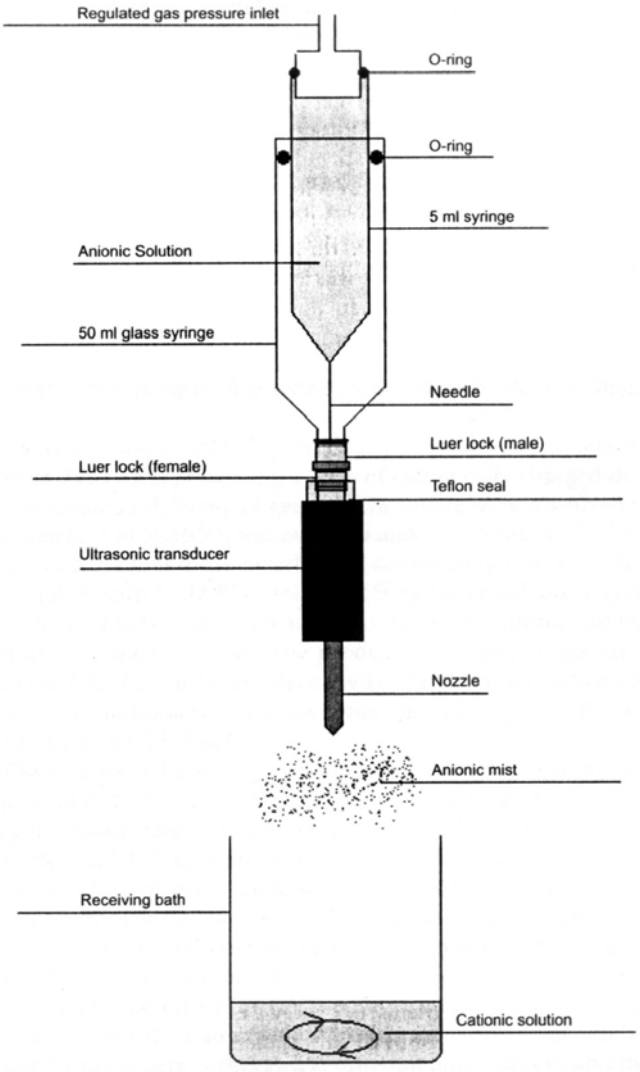


Fig. 1. Diagram of a batch set-up for preparation of nanoparticles. The cationic bath solution is initially purely cationic, however, when the production begins by introducing an atomized anionic polymer solution it will be in part converted into the final product, a suspension containing nanoparticles. The mist was captured from a 3-inch distance (cf. [8]).

Tables 1 and 2 present some data on the fabrication of nanoparticles from natural or synthetic polymers.

Table 1. Standardized methods (concentrations are given in g/100 mL [8]

System 1		System 2	
Anion (core)	Cation (shell)	Anion (core)	Cation (shell)
0.1 TPP	0.05 chitosan	0.05 alginic acid	0.05 spermine
0.1 κ-carageenan	0.1 $CaCl_2$	0.05 CS	0.15 mL 50% PMCG
0.4 ovalbumin	1.0 Pluronic	0.5 ovalbumin	0.05 $CaCl_2$
			1.0 Pluronic
100 mL water	100 mL water	100 mL water	100 mL water

Table 2. Other examples based on polymers [8]. PMGC and F68 signify poly (methylene-co-guanidine) hydrochloride and Pluronic, respectively

Core	Corona (shell)
alginic acid, gellan	PMCG, $CaCl_2$, F68
alginic acid, DNA	PMCG, $CaCl_2$, F68
alginic acid, chitosan	PMCG, spermine, $CaCl_2$, F68
alginic acid, chitosan, ovalbumin	spermine, $CaCl_2$, F68
alginic acid, chitosan	PMCG, $CaCl_2$, F68
accacia gum, alginic acid, ovalbumin	bovine serum albumin, $CaCl_2$
kapa-carrageenan, ovalbumin	chitosan, F68
chitosan, poly(vinyl alcohol), $CaCl_2$…	heparin, F68

The nanoparticles and their functionalised counterparts are used for numerous advanced applications: drug targeting by embolization, photodynamic therapy, gene transfer, light-emitting diodes, photovoltaic cells and other photonic devices, catalysts, chemical and biological sensors, decontaminants or sensors in biological or chemical terrorism, etc.

Dendrimers are a category of 3-D nanoobjects which are worth a brief presentation. They are highly branched cascade molecules that spread from a central core through a step-wise repetitive reaction sequence. The most known scientists who have developed dendrimers are D. Tomalia, G. Newkome, F. Woegtle or J. Fréchet. The design of such molecules consists of three topologically different regions: a small initiator core of low density, an interior with multiple branching units (the density increases with the increasing separation from the core), and a rather densely packet shell. An example is the preparation of the fifth-generation polypropyleneimine dendrimer synthesized by E. W. Meijer.

This multiple-step synthesis was diversified: graphite like dendrimers, light-harvesting dendrimers, dendrimers with cross-linked surfaces or self-destructing dendrimers. Researchers have used the hollow cavities within the branching structures to entrape metal nanoparticles, drugs or imaging agents. One of the most recent dendrimers, based on poly(lysine) with 32 naphtalenedisulfonic moieties attached *via* amide linkages to the molecule surface, was used as microbiocide gel against HIV-infections. The fast development of dendrimers is demonstrated by the about 1000 papers published in 2004 [9].

Fullerenes are another category of unusual 3-D nanobjects. The discovery of fullerene C[60] in 1985 by H. W. Kroto, R.F. Curl jr. and R. E. Smalley was one of the major scientific events of the 20th century. This achievement was rewarded with the Nobel Prize (1996). This molecule is formed by 60 atoms of carbon connected together as hexagons and pentagons in a symmetrical and aesthetic spherical structure with a diameter of 1nm. The main characteristics of this wonderful molecule are superconductivity, reversible redox behavior, polymerization ability, NLO, magnetic and catalytic properties. Other important characteristics are multifaced chemical reactivity and capacity to trap atomic guests in their hollow interior [15]. A recent review [16] deals with progress in studies of polymeric covalent and noncovalent modifications of fullerenes (mainly C_{60}) and their applications. By using functional polymers to react with fullerenes, or synthesizing polymers in the presence of fullerenes, various kinds of polymeric fullerenes can be prepared: side-chain polymers, main-chain polymers, dendritic fullerenes, star-shaped polymers, fullerene end-capped polymers, etc. Furthermore, by controlling the functional groups in polymer chains and reaction conditions, many well-defined fullerene polymers have been prepared.

4. POLYMERIC NANOWIRES

Nanowires could play a crucial role as interconnects and active components in nanoscale devices. A striking aspect of nanowires relates to assembly atoms in the unique nanostructure in a controlled fashion. These entities were fabricated using nanolithography, such as electron-beam, focused-ion writing, or X-Ray lithography. For these products a large palette of materials including semiconductors were used. Chemical methods were also used, including solution and vapor based methods as well as solvothermal or hydrothermal methods. For all these methods generally inorganic materials, metals or oxides were used. Concomitantly some polymers were used as starting materials; for instance, nanowires were obtained from poly(3-hexyl-tiophene), poly(aniline), poly(pyrrole), or poly(4-ethylenedioxythiophene). These nanowires can be used as transistors for signal amplification, biosensors including addressable conducting polymers, or electrojonctions. Nanowire structures were elaborated from end-capped poly(tiophenes) as well as from their diblock and triblock copolymers, with very high electrical conductivity. Other nanowires were obtained by introducing Au, Ag, Pt and Ge in polypeptide nanotubes and used as chemical and biological detectors, photonic switches, solar cells, etc. [12].

5. POLYMERIC NANOMULTILAYERS

The first attempt to obtain a film by alternative adsorption was achieved by R. Iler in 1965 using as partners colloidal particles and proteins. The true impulse in this field was made in the early 90s by G. Decher in his seminal patents and

papers, in which the layer-by-layer technique, using anionic and cationic polyelectrolytes, is claimed [13]. The main techniques to fabricate nanomultilayers can be grouped as follows:

- alternate dipping (immersion) in aqueous solutions of cationic and anionic polyelectrolytes with intermediate rinsing and final drying;
- alternate deposition of cationic and anionic polyelectrolytes on adequate surfaces by spraying with intermediate rinsing and final drying;
- deposition of alternating layers of cationic and anionic polyelectrolytes by spin coating devices.

The dipping techniques can be performed with mechanical or programmable automatic commercial or man-made devices. The supports used for deposition can be lamella of glass, quartz, platinum, silver, gold, polystyrene. Preliminary operations are necessary for removing the impurities and/or generate active centers such as the treatment with chemicals (Pyranha mixture) or the irradiation in cold plasma.

Figure 2 shows the scheme of operations in the so-called Layer-by-Layer Deposition (LbL) technique [13].

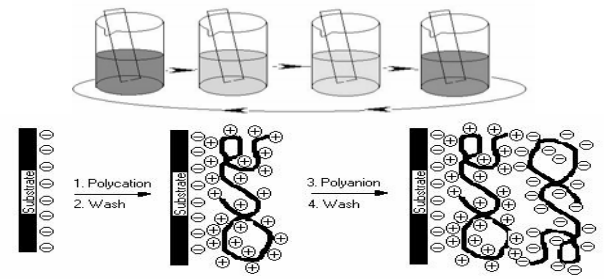


Fig. 2. Layer-by-Layer deposition (cf. [13]).

The partners used in the construction of multilayers can be [13]:

- polymers: linear, branched, star-shaped copolymers, dendrimers;
- colloids: polymeric, metallic, oxidic;
- biomacromolecules: proteins, polynucleotides, bioaggregates;
- small molecules: drugs, surfactants (neutral or ionic), dyes, fullerenes, aminoacids, etc.

Several post-preparations, treatments, such as annealing, patterning, indentations, lithography were elaborated. The advantages of LbL technique are: deposition on surface of almost any kind and any shape of supports, broad processing window, multiple control parameters (concentration, adsorption time, ionic strength, solvent composition, temperature, etc.).

The advent of nanoscience and nanotechnology has determined significant progress in medicine, especially in drug delivery systems. The synthesis of functionalized polymeric nanoparticles, nanospheres, nanocapsules or nanomultilayered films is of interest for controlled release, active and passive site-specific

targeting of drugs or for nonviral carriers for gene transfection. Other nanoproducts used in medicine are: nanobiosensors, nanodevices for diagnostic (lab-on-a-chip), nanoporous polymeric gels for DNA separations, nanoliposomes, nanomicelles, nanovesicles, nanoclusters. The implant coatings obtained from polyelectrolytes (LbL technique) with antimicrobial properties, the nanocontainers for therapy, the quantum-dots for biological labeling are also hot subjects in nanobiotechnology and nanomedicine [14].

Besides the methods previously discussed there are several advanced techniques used in nanotechnology and nanofabrication: laser ablation technique, soft ablation technique, electro-spinning for nanofibers extrusion, nanowire electro-spinning, deep pen nanolithography (DPN), electro-chemical deep pen nanolithography, electrostatic deep pen nanolithography, photo lithography, nanoimprint lithography, size reduction lithography, nano-extrusion mold, nano-contact printing, microcontact printing, scanning probe contact printing, controlled polarity induced self-assembly (CPISA), directed evaporation induced self-assembly (DEISA), evaporation induced self-assembly (EISA), template assisted self-assembly (TASA), computer simulation and modeling of nanodevices, nanoparticles and nanostructures [10].

6. ORGANIC - INORGANIC HYBRID MATERIALS

These materials have been well-known for a long time in the paints and more recently in the plastics industries in which inorganic pigments and fillers are used. In the plastics industry the fillers are used in different types of admixtures. By reducing the filler dimension polymer composites and then polymer nanocomposites were elaborated. The recent explosive development of new types of hybrid materials was possible with the contribution of different domains of chemistry, including intercalation chemistry and the rise of soft inorganic chemistry processes. More recently the interest is shifted from structural hybrid materials in which the mechanical properties are important, to the functional hybrid materials having chemical, electrochemical and biochemical activity or magnetic, electronic, optical or other physical properties as well as a combination of them.

The design and synthesis of functional hybrids are made by [15, 16]:

- the conventional sol-gel method using organo-functional or bridged alkoxides;
- the self-assembling procedures by the organization or texturation of growing inorganic and hybrid networks templated by organic structure directing agents;
- the assembling of well-defined nanobuilding blocks (NBB) by using perfectly calibrated preformed objects which maintain their integrity in the final material;
- the combination of self-assembly and NBB routes;
- integrative synthesis using the new recently developed micro-molding techniques.

7. INSTRUMENTAL METHODS FOR CHARACTERIZATION OF NANOOBJECTS, NANOASSEMBLIES AND NANOSTRUCTURES

Microscopy: optical microscopy, confocal optical microscopy, near-field scanning optical microscopy (NFSOM), confocal fluorescence microscopy (CFM), transmission electron microscopy (TEM), scaning electron microscopy (SEM), field emission scanning electron microscopy, atomic force microscopy (AFM), scanning tunneling microscopy*, scanning probe microscopy (SPM), Brewster angle microscopy, coherent anti-stokes Raman scattering microscopy, confocal spectral laser scanning microscopy, lateral force scanning probe microscopy (LFM), scanning electron chemical microscopy (SECM), environmental scanning electron microscopy (ESEM).

Spectroscopy: UV-spectrophotometry, infra-red spectroscopy, infra-red reflection spectroscopy, ATR-FTIR spectroscopy, confocal Raman spectroscopy, surface enhanced resonance Raman spectroscopy (SERRS), matrix-assisted laser desorbtion-ionization time-of-flight mass spectrometry (MALDI-TOF-MS), surface assisted laser-adsorbtion ionization laser spectrometry, time-of-flight secondary ion mass spectrometry (TOF-SIMS), static secondary ion mass spectrometry (SSIMS), plasmon resonance spectroscopy (PRS), Auger electron spectroscopy.

X-Ray based methods: X-Ray diffraction (XRD), extended X-Ray absorbtion fine structure (EXAFS), X-Ray photoelectron spectroscopy (XPS), X-Ray absorbtion near edge spectroscopy (XANES)

***Methods based on Nuclear Magnetic Resonance (NMR)*:** NMR spectrometry for ^{13}C or for solid phase, NMR imaging (NMRI), magic angle spinning NMR (MASS-NMR).

***Other methods of particle and surface characterization*:** single particle light scattering (SPLS), ultracentrifugation, zeta potential electrophoresis, capillary electrophoresis, ellipsometry, quartz crystal microbalance.

8. FINAL OBSERVATIONS

This survey of polymers in the nanoworld allows some remarks on the present state and trends in the coming years. A constant increase of the contribution of natural or synthetic polymers to the realization of nanoentities, nanostructures or nanodevices could be observed. A similar trend can be observed in the functionalization with polymers of other nanomaterials based on carbon or inorganic compounds. These two tendencies have as a main result the diversification of nanoproducts and their successful application in nanotechnology

* The inventors E. Ruska, G. Binning and H. Rohrer were awarded the Nobel Prize in 1986.

or bionanotechnology/medicine. The first commercial nanoproducts were issued or are in an advanced state of implementation, especially in the fabrication of polymeric nanocomposites or elaboration of new tools for diagnostic using nanocrystals or quantum dots functionalized with polymers. Nanowires and their counterparts functionalized with polymers have determined a major impulse for their use in sensors, light emitting diodes and other nanophotonic devices.

An important trend in introducing advanced instrumentation and methodology to analyse the polymeric nanoobjects and devices is noticeable. The progress in nanotechnology ensures an important improvement of the arsenal of means to improve the health of humans and animals by fighting diseases, creating new drug delivery systems, new biomaterials for the construction of implants or artificial organs and as scaffolds in tissue engineering.

A major preoccupation was aroused for the investigation of toxic effects of all type of nanomaterials, especially the evaluation of their citotoxicity. It was also aroused the necessity to evaluate the benefits and threats of nanoentities and nanostructures on the environment. The growing importance of the development of an adequate educational infrastructure for the instruction of new-comers in nanoscience, nanotechnology, nanobiotechnology or nanofabrication was recognized.

A stringent necessity is to fulfil unitary and correct terminology or nomenclature in nanoscience and nanotechnology and consequently to elaborate a nano dictionary. Recently ASTM in USA, British Standard Institution (BSI) in UK, IUPAC and IUPAP organization have started a program with this objective.

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Oxide and Hybrid Nanocomposites Obtained by Sol-Gel Method

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Abstract. The world-wide goal of all solution sol-gel work has been, from the moment of its discovery, the obtaining of *ultrahomogeneity,* while, since the early 1980s, the newest goal in this area has been the re-direction of the process to the preparation of *nanocomposites* that exhibit *ultraheterogeneity* or *nanoheterogeneity.* In the present contribution, a discussion of the possibilities offered by the sol-gel method to obtain oxide and hybrid inorganic-organic nanocompozite materials is presented.

1. GENERAL CONSIDERATIONS ON THE SOL-GEL METHOD

It is well known that, among the non-conventional wet chemical processes of obtaining oxide materials, the sol-gel method is the one used and studied mostly. The sol-gel process represents the formation of an inorganic polymeric network by reactions in the solution at low temperatures and the conversion of the inorganic amorphous polymers into glasses at temperatures far lower than the melting temperature of the corresponding oxides or in crystalline materials at temperatures much lower than the usually needed temperatures [1].

The most common reagents in the sol-gel process are the alkoxides that could be normal or organically substituted. Their general formulas are the following: $M(OR)_n$, or R_x-$M(OR)_{n-x}$, respectively. Together with alkoxides other precursors could be used in the sol-gel reactions, especially when poly-component materials are intended to be obtained: inorganic salts (chlorides, nitrates, etc.) or organic salts (acetates, acetylacetonates, etc.).

The reactions that take place during the transformation of an alkoxide into a solid material are the following:

$$Si(OR)_4 + H_2O \rightleftharpoons HO\text{-}Si(OR)_3 + ROH \quad (1)$$

$$HO\text{-}Si(OR)_3 + H_2O \rightleftharpoons (HO)_2Si(OR)_2 + ROH$$

$$(HO)_3SiOR + H_2O \rightleftharpoons Si(OH)_4 + ROH \quad (2)$$

$$\equiv Si\text{-}OR + HO\text{-}Si\equiv \rightleftharpoons \equiv Si\text{-}O\text{-}Si\equiv + ROH \quad (3)$$

$$\equiv Si\text{-}OH + HO\text{-}Si\equiv \rightleftharpoons \equiv Si\text{-}O\text{-}Si\equiv + H_2O \quad (4)$$

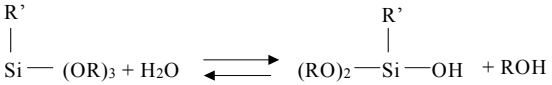
They are reactions of hydrolysis (reactions 1–2) and polycondensation (reactions 3–4) that take place simultaneously leading to the formation of a geleous hydroxide.

$$Si(OR)_4 + 4H_2O \rightleftharpoons Si(OH)_4 + 4ROH \quad (5)$$

The transformation of the geleous hydroxide into a glass or crystallized material by thermal treatment takes place with water evolution and densification of the material:

$$Si(OH)_4 \rightleftharpoons SiO_2 + 2H_2O \quad (6)$$

In the case of an organically substituted alkoxide the sol-gel reactions are the following:



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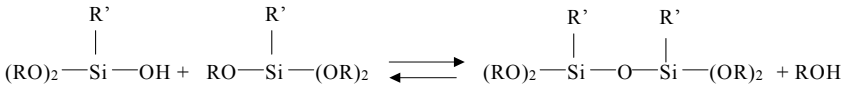

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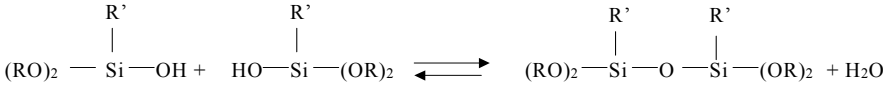


(9)

In this case the Si-C bond is not broken during the hydrolysis-polycondensation reaction leading to the obtaining of an inorganic-organic hybrid material that contains permanently bonded organic radicals on the inorganic -Si-O-Si- network.

Some advantages of the sol-gel method were summarized by Mackenzie already in 1982 [2], and these are:

- better homogeneity – from raw material;
- lower temperature of preparation;
- better purity – from raw materials;
  - save energy;
  - minimize evaporation losses;

  - minimize air pollution;
  - avoid reaction with container, and so ensure purity;
  - by-pass phase separation;
  - by-pass crystallization;
- new non-crystalline solids outside the range of normal glass formation;
- new crystalline phases from new non-crystalline solids;
- better glass products determined by special properties of gel;
- special products such as films.

More recently, the possibility offered by the sol-gel method of obtaining hybrid and nanocomposite materials has enlarged the number of its advantages. The most promising advantage of the sol-gel method is the fact that it offers the possibility to prepare solids with pre-determined structure by varying the experimental conditions.

Generally, solutions containing a large amount of water and/or catalyzed by ammonia lead to non-linear or network colloidal polymers in hydrolysis-polycondensation process that could be converted to bulk gels or powders [3]. Solutions with small water content, when catalyzed by HCl, lead to linear polymers. Fiber could be easily drawn from such solution immediately before gelation or films could be deposited. So, materials of different shapes such as films, fibers, powders, bulk, could be obtained.

When substituted alkoxides are used in the sol-gel reaction and inorganic-organic hybrid materials are obtained, the inorganic-organic hybrid materials can offer multifunctionality and allow properties tailoring from subnanometer (atomic) to submilimeter (mesoscopic) length scales, depending on the type of the alkoxide's substituents. The organic groups can modify the inorganic backbone by reducing the connectivity of the gel network allowing thick film deposition and lowering the processing temperature. These films could play a significant role in the field of micro- and nano-photonic devices (waveguides, emitting devices, quantum dot devices, photonic band gaps and holographic materials).

Some disadvantages of the sol-gel method are the following: [2]

- high cost of raw materials
- large shrinkage during processing
- residual fine pores
- residual hydroxyl
- residual carbon
- health hazard of organic solution
- long processing time

Among these disadvantages, the presence of large shrinkage, residual fine pores, residual hydroxyls and residual carbon is directly connected to the properties of the resulted material.

The world-wide goal of all solution sol-gel work has been, from the moment of its discovery, the obtaining of *ultrahomogeneity*, while, since the early 1980s, the newest goal in this area has been the re-direction of the process, to the preparation of *nanocomposites* that exhibit *ultraheterogeneity* or *nanoheterogeneity.*

Roy, Komarneni *et al* [4-8] first coined the term "nanocomposites" during the period 1982-1983. Di- and multi-phasic nanoheterogeneous sol-gel materials were prepared and documented in 1984.

2. GENERAL CONSIDERATION ON THE NANOCOMPOSITES

"*Nanocomposites*" refers to composites of more than one Gibbsian solid phase where at least one dimension is in the nanometer range and typically all solid phases are in the 1–20 nm range. The solid phases can be amorphous, semi-crystalline or crystalline or a combination thereof, inorganic or organic, or both, and essentially of any composition.

Nanocomposites should be clearly differentiated from *nanocrystalline* and *nanophase* materials, which refer to single phases in the nanometer range. Generally, nanocomposites can be classified as other composites based on connectivity [8]. Komarneni used another classification based especially on their temperature of formation [9]. Five major groups of nanocomposites were identified:

- *sol-gel nanocomposites*, which are composites made at low temperatures (< 100°C)
- *intercalation-type nanocomposites*, which can be prepared at low temperatures (< 200°C) and lead to useful materials upon heating to modest temperatures (< 500°C)
- *entrapment-type nanocomposites*, which can be prepared from three-dimensionally linked network structures such as zeolites that can also be synthesised at low temperatures (< 250°C)
- *electroceramic nanocomposites*, which can be prepared by mixing nanophases of ferroelectric, dielectric, superconducting and ferroic materials in a polymer matrix at low temperatures (< 200°C)
- *structural ceramic nanocomposites*, which are prepared by traditional ceramic processing at very high temperatures (1000–1800°C).

One may notice that the sol-gel nanocomposites are obtained at the lowest temperatures allowing the embedment of the organic components into an inorganic matrix.

Sol-gel nanocomposites are further subdivided into six categories:

(a) *compositionally different sol-gel nanocomposites*, such as Al_2O_3–SiO_2, SiO_2–MgO, Al_2O_3–TiO_2, etc.

(b) *structurally different sol-gel nanocomposites*, such as Al_2O_3 gel +α-Al_2O_3 seed, TiO_2 film on a TiO_2 single-crystal substrate, etc.

(c) *both compositionally and structurally different sol-gel nanocomposites,* these are a combination of the above two types, such as ZrO_2–SiO_2, ThO_2–SiO_2, Al_2O_3–MgO.

(d) *nanocomposites of gels with precipitated phases,* obtained by soaking the gel in metal salt solution and subsequent precipitation of the metal with selected anions (e.g. photochromic glasses and catalytic materials)

(e) *nanocomposites of xerogels with metal phases,* xerogels of Al_2O_3, SiO_2 and ZrO_2 have been prepared as matrices with Cu, Pt and Ni (5–50 nm) as the dispersed metal phases

(f) *nanocomposites of inorganic gels and organic molecules (dyes),* the organic species including polymers during gelation or the organic molecules can be introduced into the sol-gel matrices.

Komarneni's classification criteria are of practical interest and have been adopted especially for the classification of the sol-gel nanocomposites [9, 10].

It is worth mentioning that the nanocomposites from class (f) lead to inorganic-organic hybrid materials. As Avnir *et al* [11] assume, the possibility of obtaining hybrid materials by the sol-gel method could be limited only by the imagination. So the class (f) of composite materials could be redefined as: *inorganic-organic hybrid nanocomposites* that include:

(f1) *nanocomposites of inorganic gels and organic molecules (dyes)*

(f2) *nanocomposites of hybrid gels and organic molecules*

(f3) *nanocomposites of hybrid gels and inorganic molecules.*

3. OXIDE NANOCOMPOSITES CONTAINING FE_XO_Y

According to the classification presented above, sol-gel nanocomposites containing Fe_xO_y belong to the *both compositionally and structurally different sol-gel nanocomposites*.

Sol-gel oxide materials prepared in the Fe_2O_3–SiO_2 system may display specific magnetical, electrical, as well as catalytic properties both in bulk and in film forms. Using different methods, iron oxide nanoparticles in glass [12], polymers [13], LB films [14], zeolites, clays [15] and mesoporous silicate [16] were prepared. The first study on the Fe_2O_3–SiO_2 amorphous magnetic composites systems was made by Yoshida *et al* [17] already in 1981.

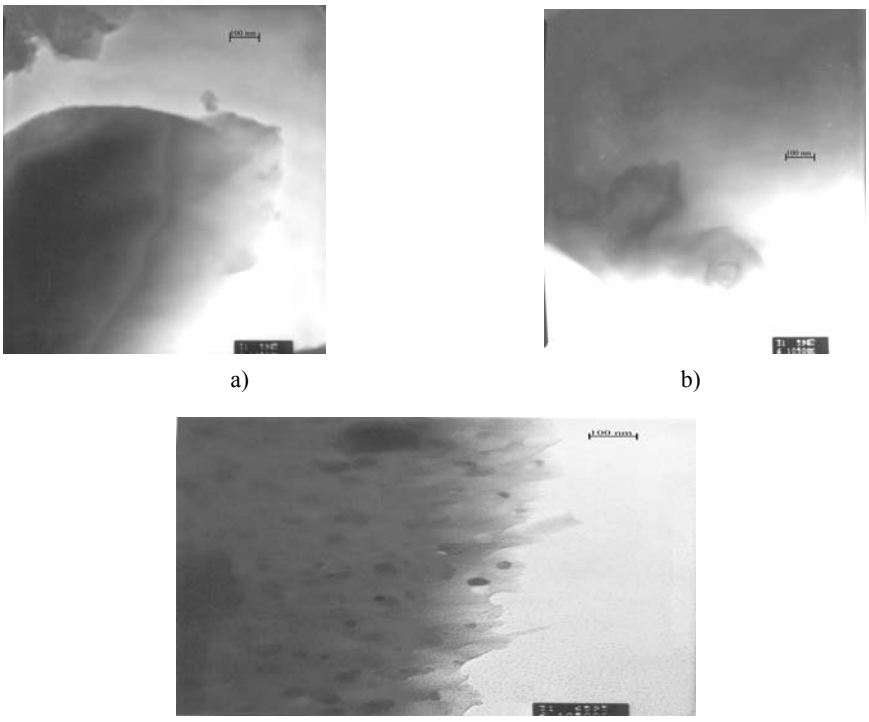
A very interesting study on Fe_2O_3-SiO_2 system was made by Lopez *et al* [18, 19]. In this case, some systems which contained iron between 0.1–15% wt were studied. One of these studies inquired the thermal stability of nanocomposites [18], and the other examined the structural evolution with temperature of this kind of nanocomposites [19].

In our studies the influence of the inorganic or hybrid matrix on the nanophase formation as well as the influence of Fe^{3+} sources were studied [20–27]. As SiO_2 precursors substituted and non-substituted silicon alkoxides were used, mainly tetraethoxysilane, $Si(OC_2H_5)_4$ (TEOS), methyl triethoxy silane, CH_3–$Si(OC_2H_5)_3$ (MTEOS) and colloidal silica Ludox 30. As Fe_xO_y precursors, salts and oxides were used such as: $Fe(SO_4).7H_2O$, $Fe(NO_3)_3.9H_2O$ and Fe_3O_4 The compositions of the studied systems were 97% SiO_2 – 3% Fe_xO_y and 90% SiO_2 – 10% Fe_xO_y.

The TEM micrographs of the nanocomposites obtained in different silica matrices but containing the same iron content and the same iron source are presented in Figures 1 and 2.

Significant differences could be observed between the two samples. When TEOS was used as precursor, homogenous gels were obtained in which the iron was bonded in -O-Si-O-Fe-O-Si-O- chains. The iron oxide nanoparticles occurred only after thermal treatment at 1000ºC (Figure 1c) when the mentioned chains were broken and α-Fe_2O_3 crystallized with particle dimensions in the 9-19 nm range.

In the case of the samples obtained with MTEOS, the formation of iron oxide nanoclusters could already be observed in the initial gel (Figure 2a). These clusters appear because the matrix obtained using a substituted alkoxide has a hydrophobic character, determined by the presence of the alkyl substitutent. It could be supposed that in such cases not all iron ions are connected in -O-Si-O- Fe-O-Si-O- bonds.



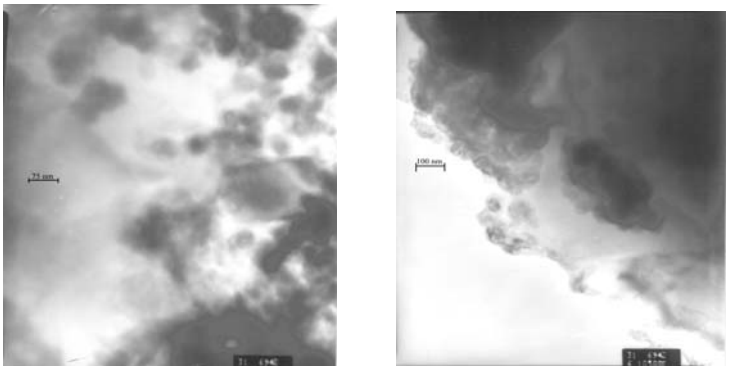
a) b)

c)

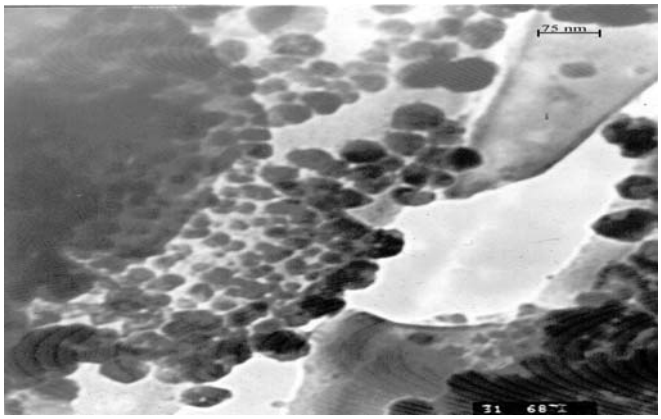
Fig. 1. TEM micrographs of the nanocomposites in the Fe_2O_3-SiO_2 system started from TEOS at: a – 200ºC; b – 550ºC; c – 1000ºC.

The iron ions, which were not involved in polymer chains, were isolated in the hydrophilic part of matrix and created iron oxide nanoclusters on the surface. In the micrographs presented in Figure 2a, besides the iron nanoclusters, a dark field is observed which can be assigned to the amorphous part of the sample. In the case of sample treated at 550ºC (Figure 2b) the same behavior was observed. In the case

of the sample treated at 1000ºC (Figure 2c), the nanocrystallization of Fe_2O_3 nanoclusters could be observed. The dimension of the particles in the Fe_2O_3–SiO_2 system obtained with MTEOS did not significantly increase for the sample thermally treated at 1000ºC as compared to the sample annealed at 200ºC. Their size is larger in the latter case, ranging between 22–51 nm.



a) b)



c)

Fig. 2. TEM micrographs of the nanocomposites in the Fe_2O_3-SiO_2 system started with MTEOS at: a – 200ºC; b – 550ºC; c – 1000ºC.

The nanocomposites obtained in inorganic matrix starting with TEOS were experimented for adsorption process of the As ions from solutions. The results are presented in Table 1, comparatively with the results obtained using a commercial resin. One may observe that the samples thermally treated at 200°C, at pH ~ 2.6, present promising results for As separation from aqueous solutions. The advantage of the embedment into a sol-gel matrix consists in a much higher thermal stability, as compared to the commercial resin.

Table 1. Comparison between the adsorption capacity of arsenium on the commercial resin and nanocomposite material thermally treated at different temperatures

pH	Adsorption capacity of the resin mg As/gFe	Temperature (°C)	pH	Adsorption capacity of the nanocomposite mg As/gFe
0.83	284.00	70	1.96	293.94
1.26	444.84		2.85	289.61
1.51	467.75		3.14	280.73
2.10	419.24	200	1.83	271.85
2.60	365.34		2.79	303.32
3.22	323.04		3.01	252.70
3.88	269.56	500	1.90	166.79
4.39	248.26		2.99	184.65
6.25	222.57		3.32	152.70
6.80	244.95	1000	1.94	50.470
6.95	180.14		3.82	35.050

4. INORGANIC - ORGANIC HYBRID NANOCOMPOSITES

According to the Komarneni's definition, the studied hybrid materials belong to the *nanocomposites of inorganic gels and organic molecules.* As SiO_2 precursors, tetraethoxysilane, $Si(OC_2H_5)_4$ (TEOS), a non-substituted silicon alkoxide as well as sodium silicate were used. As secondary phases the following were used: bromcrezol purple (PBC) and enzymes (glucose oxidase, protease).

SiO_2 – PBC nanocomposites [28]

A large variety of organic dyes can be incorporated in the sol-gel glasses in order to obtain transducer layers for chemo-optical sensors or biosensors. In our case, porous layers doped with photochromic substances were used as transducing layers for chemo-optical sensors.

The diagram of the chemo-optical sensor for ammonia, based on the hybrid sensitive layer obtained by embedding bromcresol purple into a silica gel matrix, is illustrated in Figure 3. The input waveguide is split in two arms. One arm is coupled to the reference photodiode and the other one is coupled to the measuring photodiode. The sol-gel layer, doped with bromcresol purple, is deposited on this arm. The bromcresol purple changes its optical properties (absorption) function on NH_3 concentration. The absorption maximum is shifted from the range 427–431nm to the range 588–590 nm and the absorption increases when ammonia concentration increases. The sol-gel layer acts as cladding for the waveguide. As its optical properties change, the waveguide propagation constant also changes. This system can be used to measure ammonia concentration in the range 50–1000 ppm.

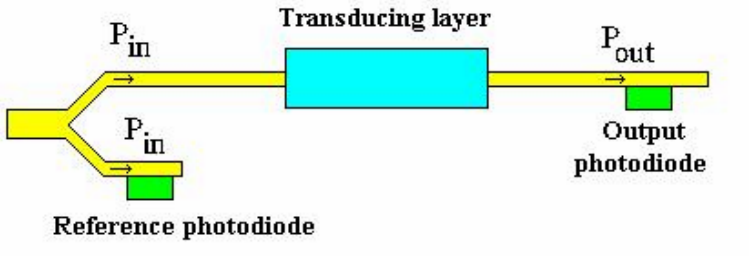


Fig. 3. The diagram of the chemo-optical sensor for ammonia.

In Figure 4 the curves absorbance – wavelength are presented for different ammonia concentrations. The curve 1 was recorded in the conditions of the exposure of PBC containing the sol-gel SiO_2 films in atmosphere of saturated ammonia vapors and curves 2 and 3 after one and two hours of exposure, respectively. The curves after 1 and 2 hours of exposure were identical and were considered as representing the absorbency at zero concentration. From the presented curves one may conclude:

- the SiO_2 sol-gel film containing PBC absorbed the radiation at λ = 400-700 nm;
- the maximum absorbance in the conditions of exposure at saturated vapors is realized at the wavelengths of 580 nm.

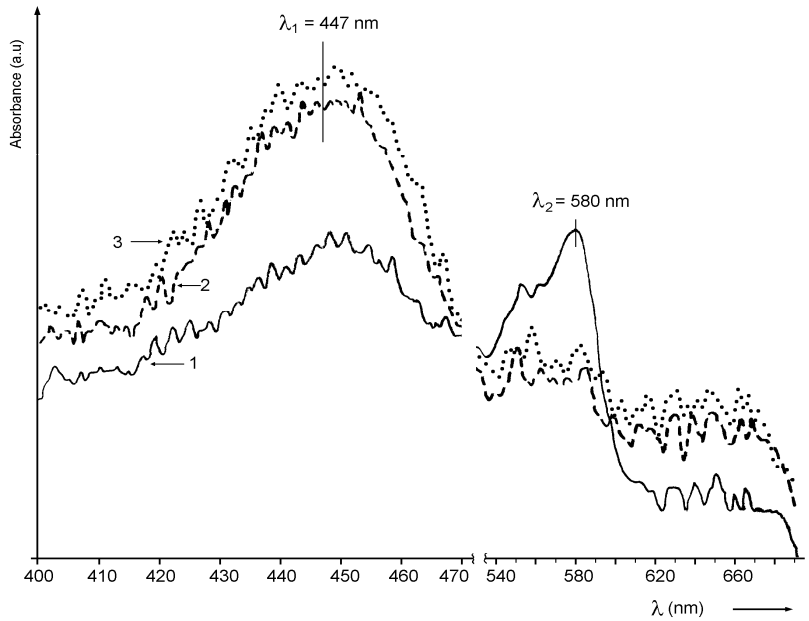
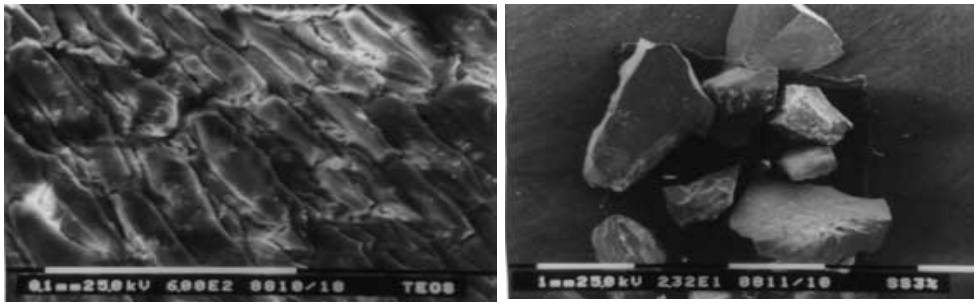


Fig. 4. Adsorption spectra of the PBC - doped SiO_2 chemo-optic sensor in saturated gaseous ammonia: __initial ammonia vapor atmosphere; after 1 hour exposure; --- after two hours exposure.

SiO_2 Nanocomposites – enzyme for analytical devices

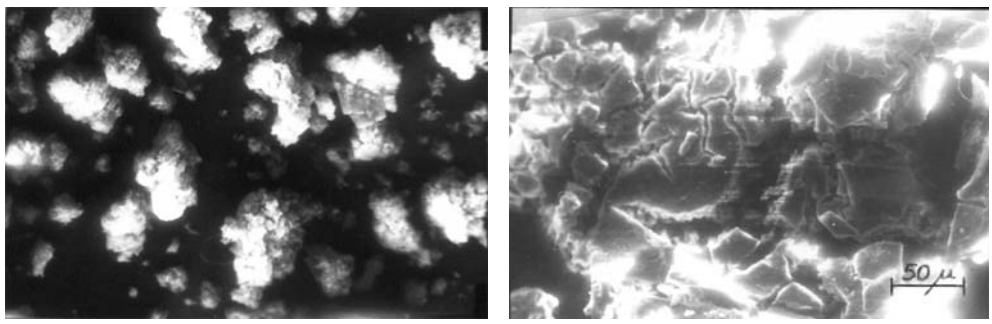
The glucose oxidase (GOD) represents one of the most studied enzymes. Whatever the interest domain is (the biomedical one or the food industry), there is a problem which remains unsettled so far, respectively its stability, the most important factor from the point of view of the utilization. Although now it is widely recognized that the immobilization procedures improve the stability of the enzymes [31–35], there are a lot of parameters to study in order to obtain some satisfactory results [11, 32, 35]. The advantage of the sol-gel method in the case of enzyme immobilization consists in the fact that a one-step procedure could be established in which both enzyme and chromogen could be embedded in the silica-based matrix [36-38]. The benefit of the method consists in the enhancement of the homogeneity and dispersion of enzyme and chromogene phase in the whole matrix.

The SEM studies presented in Figures 5 and 6 illustrate very clearly the major difference between the morphology of SiO_2 gels derived from TEOS and the sodium silicate solution, respectively, both in the absence and in the presence of glucose oxidase.



a) b)

Fig. 5. SEM micrographs of the silica gels issued from TEOS (a) and sodium silicate (b).



a) b)

Fig. 6. SEM micrographs of the silica gels issued from TEOS (a) and sodium silicate (b) in the presence of glucose oxidase.

In Figure 7 the influence of GOD concentration on the activity and stability of the two types of biomaterials is presented, while in Figure 8 the influence of chromogen concentration (chosen to be p-hydroxybenzensulphonate and 4-aminoantipyrine) in the domain of 20–60 mg per sample on the activity and stability of immobilized GOD is shown. Some differences between samples with SiO_2 matrix obtained starting from TEOS or starting from sodium silicate solution were evidenced.

Both enzymatic activity and time-stability of the doped materials are better for the samples obtained using sodium silicate comparatively with the samples obtained from TEOS, being well known [34] that the conventional sol-gel procedures generally use large quantities of alcohol as a solvent that can be harmful for the proteins, leading to their denaturation.

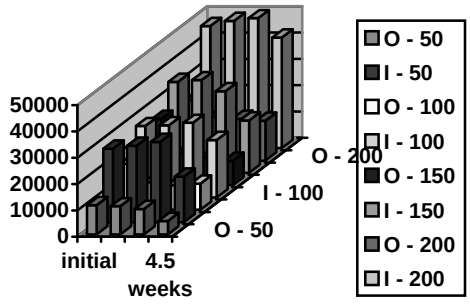


Fig. 7. The influence of GOD concentration on the activity and stability of the two types of nanocompozite (I – issued from sodium silicate; O – issued from TEOS).

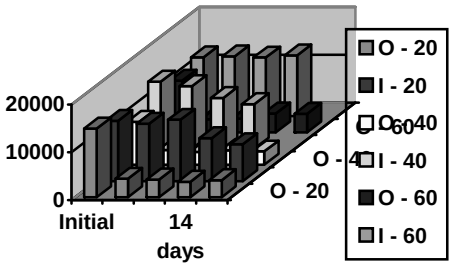


Fig. 8. The influence of chromogen concentration on the activity and stability of immobilized GOD.

5. CONCLUSION

Some general considerations on the sol-gel process and the possibilities offered to prepare different types of nanocomposites were discussed. Some recent results in the field of different nanocomposites compositionally and structurally, as well as in the field of inorganic-organic nanocomposites were also presented.

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Poly[(N-Acylimino)Ethylene] Derivatives for Nanostructured Materials

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Abstract. Poly[(N-acylimino)ethylene] derivatives represent appropriate intermediates or components of micro- and nanostructured materials, due to their well-controlled design and high versatility, responding to the requirements of the present technical development. Our contribution is dealing with the synthesis of several water-soluble poly[(N-acylimino)ethylene] macromonomers and their application in the preparation of polymeric micro- and nanoparticles with narrow size distribution or as intermediates in the synthesis of copolymers, hydro/amphigels and interpenetrating polymer networks as complex, multi-functional polymer materials.

1. INTRODUCTION

Nanostructures and nanotechnologies represent a new approach to materials science and engineering, as well as in the design of new devices and processes. The integration of nanotechnologies and new materials for improved security and quality of life implies as a specific target to direct them to the service of health. In this context, the implementation of technological developments – and in particular of smart and hybrid materials – represents a real potential for the improvement of sensors, actuators and devices, leading to a greater security, safety and welfare of people and environment. Thus, the design and synthesis of new (tailor-made) materials, especially directed to specific tasks, as a tool in the preparation of controlled (ordered) nanostructured and responsive surfaces, with specific (multi)functionalities are of great interest.

Branched polyethylenimine and 2-oxazoline polymers have histories of more than seventy or thirty years, respectively, as reported in some recent reviews [1–3].

Poly[(N-acylimino)ethylene]s (PROZO), mainly, are known as materials with large applicability in both technical and biomedical domains (dispersants, nonionic surfactants, compatibilizers, biocatalysts, sorbents etc.). Due to the specific properties (precise control of polymer synthesis by living cationic polymerization of 2-substituted-2-oxazolines, biocompatibility or low toxicity, facile modification to polyethylenimine - polymer with chelating properties, able to immobilize biocompounds) PROZO derivatives may intermediate the preparation of multi-functional polymeric materials with controlled structure and functionality. As an example, the synthesis of functional, even multisensitive PROZO hydrogel systems able to respond to stimuli such as heat, light and redox conditions, has been claimed [4, 5]. PROZO – silica hybrid material, realized by the sol-gel method, was used to prepare (by pyrolysis) porous silica with 800 m^2/g surface area and controlled average radius of the micropores (r =18 Å, 0.5cm^3/g pore volume [6]). Supramolecular assemblies like stable Langmuir monolayers have been also obtained by the use of 2-substituted-2-oxazoline monomers with appropriate bearing groups or of amphiphilic polymers with a PMOZO hydrophilic chain [7, 8].

The high versatility of cyclic imino ethers, able to perform a large range of ring opening reactions (double isomerization polymerization, no-catalyst alternating copolymerization *via* a zwitterion intermediate, ring-opening addition reactions) [1–3], and the specific features of the living polymerization systems allowed the formation of various polymeric architectures with a defined structure – starting from macromonomers and telechelics to block and graft copolymers, networks, dendrimers, star polymers and hyperbranched polymers. The present paper is dealing with the synthesis of several water-soluble poly[(N-acylimino)ethylene] macromonomers [9, 10] and their application in the preparation of polymer micro- and nanoparticles with narrow size distribution or as intermediates in the synthesis of copolymers, hydro/amphigels and interpenetrating polymer networks as complex, multi-functional polymer materials.

2. MACROMER SYNTHESIS

Taking into account the living character of the cationic polymerization of 2-substituted-2-oxazolines, precisely controlled macromonomers were synthesized by quenching the oxazolinium species in 2-methyl-2-oxazoline (MOZO) polymerization with cinnamic acid [9] or by end-capping of the living PROZO (R: methyl – PMOZO, ethyl – PEOZO) growing chains with maleic acid [10]. Poly(4-vinylpyridine-co-divinylbenzene) beads of Φ = 0.4 mm were used as a macromolecular proton scavenger [11]. The synthesis approach was proved to be not only convenient but also efficient, giving rise to a quantitative functionalization and high yields (greater than 85 %). Depending on coupling reaction conditions, *i. e.* by varying the functionality of the initiating system and the ratio of the nucleophile to oxazolinium ends, mono-, bi- or multi-functional macromonomers with the formula presented below were obtained.

C_6H_5-CH_2-$(ROZO)_n$-O-CO-CH=CH-C_6H_5
Cin_n

C_6H_5-CH=CH-CO-O-$(ROZO)_{n/2}$-CH_2-CH=CH-CH_2-$(N$-CH_2-$CH_2)_{n/2}$-O-CO-CH=CH-C_6H_5
$BCin_n$

C_6H_5-CH_2-$(ROZO)_n$-O-CO-CH=CH-COOH
MA_n

C_6H_5-CH_2-$(ROZO)_{n/2}$-O-CO-CH=CH-CO-O-$(ROZO)_{n/2}$-CH_2-C_6H_5
BMA_n

[-CO-CH=CH-CO-O-$(ROZO)_{n/2}$-CH_2-CH=CH-CH_2-$(ROZO)_{n/2}$-O-]
PEN_n

3. MICRO- AND NANOPARTICLES

Polymer micro- and nanoparticles have utility in a variety of applications, *i. e.* in environmental management, technical areas or biomedical related domains [12]. Chemical or physical methods may be used to achieve their preparation. Among them, the heterogeneous copolymerization of a main monomer with a water-soluble functional comonomer or macromonomer is one of the most suitable approaches for the synthesis of functional latexes [12, 13] due to the possibilities offered to control particle size and size distribution, as well as their surface functionality. The addition of water-soluble PROZO macromonomers (PEOZO or PMOZO macromonomers with styryl or butadiene end group, amphiphilic block type PROZO macromers with styryl or vinyl ester polymerizable group) [1–3] in the recipe of dispersion or soapless emulsion copolymerization with styrene, methyl methacrylate or vinyl acetate resulted in the preparation of polymeric microspheres with narrow size distribution or even monodisperse particles [1–3]. The before mentioned PMOZO macromonomers were tested as stabilizers in the dispersion copolymerization with styrene and as comonomers in the soapless emulsion copolymerization with this monomer. In all cases, an improved stability, narrower particle size distribution and lower particle size were reached as compared to those obtained in their absence. Typical micrographs are shown in Figure 1. A thoroughly, comparative study evidenced that the characteristics of the colloidal system and of the prepared microparticles are strongly dependent on the macromonomer structure, its average molecular weight and its concentration in the system. Thus, by varying the synthesis parameters and the recipe formulation, a wide range of polymer particles, with diameters in the micrometer range, with the surface enriched with hydrophylic, biocompatible PMOZO chains may be prepared. Some of the most important results of the experiments are included in Table 1 [10, 14, 15]. The influence factors involved are specified. As can be seen, the best results were achieved by the use of monofunctional macromonomers, *i. e.* of Cin_n type in dispersion copolymerization [9, 14] and of MA_n type in soapless emulsion copolymerization [15], respectively. By comparison with the polymerization systems using PMOZO macroazoinitiators [16, 17] a higher solid

content (up to 15 wt % against to 4.5 wt %) and higher yields (more than 85% as compared to maximum 60 wt %) may be reached. In soapless emulsion recipes the concentration of the PMOZO macromer may be varied in a large range, in accordance with the required surface functionality, while in dispersion polymerization and for the use of PMOZO macroazoinitiators an optimum value – corresponding to a maximum solid yield and to the narrowest particle size distribution – is recommended.

Table 1. Factors of influence in heterogeneous polymerization. Comparative data

Polymerization system	Factors of influence	Effect on Dn	Effect on PI	Results
Dispersion polymerization	macromer structure			Stabilization efficiency Cin~BCin>MA>BMA>>PEN
	macromer concentration ↑	↓	↓	
	macromer dimension ↑	↓	↓	
	medium polarity ↑	↓	min	Dn: 500-1000 nm Dn = 462 nm, PI =1.02,
	initiation mode			
	initiator concentration ↑	↑	↑	
	monomer nature			
Soapless emulsion polymerization	macromer structure			Stabilization efficiency MA>BCin~Cin>BMA>>PEN
	macromer concentration ↑	↓	↓	Dn =100-400nm
	macromer dimension ↑	↓	↓	Dn =120, PI = 1.002, 10 wt% MA_{40} relative to monomers
Microemulsion polymerization	macromer presence	↓	↓	Dn : 12-50nm Dn = 40nm, PI =1.1, SDS/monomer = 0.08 wt/wt Cin_{25}/SDS =2:1 wt/wt 0.002g SDS/ml - w

Dn =ΣNi Di/ΣNi; Dw=$\Sigma NiDi^4/\Sigma NiDi^3$; PI =Dw/Dn; SDS – sodium dodecyl sulphate

Such functional, monodisperse microparticles, able to self-assemble in nanostructures, may be used to create nanoscopically patterned thin films, with application in novel *bottom up* lithography techniques.

The synthesized monofunctional PMOZO macromonomers were also tested (to our knowledge, for the first time) as cosurfactants in the microemulsion polymerization systems, using sodium dodecyl sulphate as the main surfactant and methyl methacrylate (MMA) and butyl methacrylate (BMA) as comonomers [18]. The introduction of the PMOZO derivative allowed the diminishing of the amount of the main surfactant required and a lowering of the nanoparticle diameters. An improvement of surface functionality and film forming ability due to the presence of the hydrophilic, biocompatible PMOZO chains may be also considered.

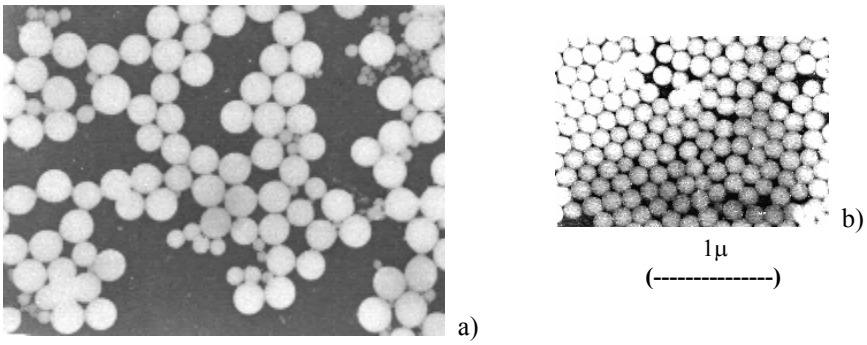


Fig. 1. Typical micrographs of the soapless emulsion polymerization systems of styrene: a) without macromer; b) with 10 wt% macromer MA_{40} relative to monomer.
Polymerization conditions: 5% St, $K_2S_2O_8$ – 2% relative to monomers, 75°C, Ar, 6h

4. COPOLYMERS, GELS, INTERPENETRATING POLYMER NETWORKS

The great interest in new materials focuses on smart polymers, defined as materials able to respond to external stimuli, leading to systems exhibiting temperature- or chemical- sensing properties. Most of the temperature sensitive polymer materials, proved to be useful tools in biological applications (enzyme immobilization, thermal affinity separation, controlled drug release, immunodiagnostics, gene therapy etc.) have been produced as homopolymers or copolymers of N-isopropylacrylamide. Poly(N-isopropylacrylamide) (PNIPAM) presents a temperature-dependent solubility in water, exhibiting a lower critical solution temperature (LCST) of ~ 32°C [19]. Above LCST, the hydrated polymer collapses to a globular state forming micelles. This behavior enables it to act as drug or therapeutic protein carriers. Several advantages may be taken into account. No exogenous molecules need to be added to a pharmaceutical dosage form, the phase separation being driven only by a temperature change. The bioactive compound may be conjugated without crosslinking agents; hence the probability of altering protein structure is reduced. In such a polymer–bioactive compound conjugate the polymer is expected to control the protein delivery kinetics and the exposure of the therapeutic component to the biological tissue. The LCST value and the response rate to external temperature of PNIPAM based materials can be effectively controlled by incorporating charged units, hydrophobic or hydrophylic moieties [20, 21].

In this context, we have studied the synthesis and the behavior of poly(N-isopropylacrylamide)/poly[(N-acetylimino)ethylene] thermosensitive block and graft copolymers in aqueous solution. The synthesis was performed by radical polymerization of NIPAM in water or ethanol, *via* PMOZO macroazoinitiators (MI) [22] (block copolymers), or monofunctional macromers of MA_n or Cin_n type (graft copolymers) (Table 2) [23].

Table 2. Copolymerization data

Sample Code	NIPAM (wt %)	PMOZO derivative Type	PMOZO derivative Conc. (wt %)	Solvent	Temperature (^oC)	Reaction duration (h)	Yield (%)
C_1	31	MI	8	ethanol	25	4	< 10
C_2	31	MI	8	water	25	6	80
C_3	31	Cin_{28}	8	ethanol	70	16	80
C_4	25	Cin_{28}	12.5	ethanol	70	16	85
C_5	25	MA_{22}	12.5	ethanol	70	16	90

Thermosensivity of the copolymers was investigated by means of the turbidimetric technique. All resulted polymer materials possess a cloud point situated in the therapeutic domain. As shown in Figures 2 and 3, copolymer behavior is dependent on composition and on PMOZO sequence length. The increase of the PMOZO content has as effect the increase of the transition temperature, the hydrophylic residues allowing the chains to remain in solution up to higher temperature. For a similar copolymer composition the increase of the PMOZO graft length shifts the LCST to higher values. This behavior was attributed to an increased steric hindrance lowering the response rate, the modification of chain conformation becoming more difficult. Thus, biocompatible thermo-sensitive materials with prerequisite properties can be prepared by the control of the synthesis conditions. The facile modification of PMOZO to polyethylenimine may increase the polymer functionality.

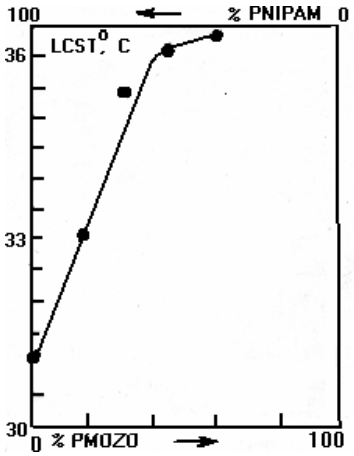


Fig. 2. LCST dependence on PMOZO content in PNIPAM/PMOZO graft copolymers.

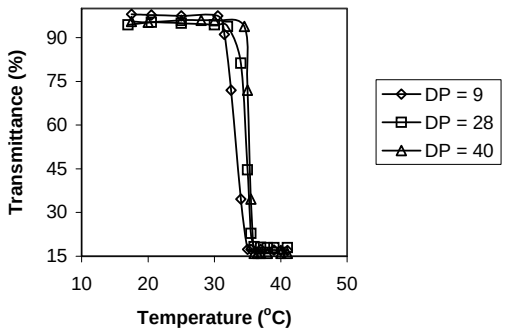


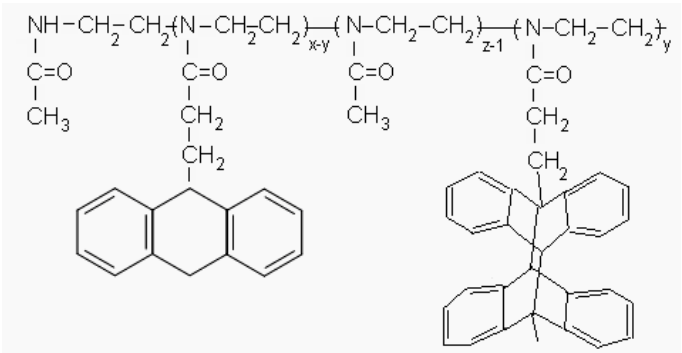
Fig. 3. Temperature dependence of the optical transmittance of the aqueous solutions (1 wt %) of the graft copolymers obtained *via* macromers of MA_n type with a different dimension for the PMOZO sequence. Content of NIPAM structural units: 73-75 wt %.

The inclusion of a multifunctional macromer of PEN type in the copolymerization system together with appropriate methacrylic monomers resulted in hydro-or amphigels.

Hydrogels are three-dimensional hydrophilic polymer networks capable of imbibing a large amount of water or biological fluids, yet insoluble in water, but swellable when immersed.

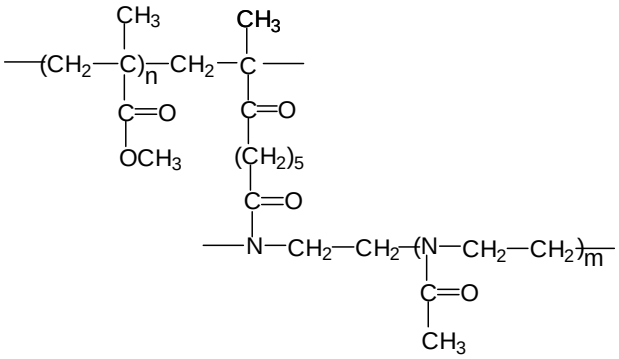
The numerous applications of the hydrogels, particularly in medical and pharmaceutical fields (microbiological culture media, drug delivery systems, components of biomedical devices, *i. e.* as hemodialysis membranes) emerged in an increased interest for the synthesis and characterization of such a material – if possible with controlled physico-chemical properties. Poly[(N-acylimino)ethylene]s, as components of gels, offer the possibility of tuning properties depending on the substituent of the N-acyl group that can induce hydrophilicity or hydrophobicity of the resulted material. Different crosslinking approaches were applied. Usually, gelation was achieved by (1) PROZO modification (*i.e.* by partial hydrolysis) followed by a crosslinking reaction of the functional prepolymers with polyfunctional compounds [1–3], (2) random copolymerization of 2-substituted-2-oxazolines with bisoxazoline monomers, or (3) specific reactions of functionalized PMOZO (*i.e.* photodimerization of the photosensitive pendant groups or coordination of the metal ions to reactive inserted groups [4]). Recently, Rueda and coworkers [24, 25] reported the synthesis of new hydrogels by the copolymerization of PMOZO bis(macromonomers) with N-vinylpyrrolidone or by the initiation of the copolymerization of the MOZO and bisoxazoline with a "macroinitiator" consisting in a random copolymer of chloromethylstyrene with styrene or methyl methacrylate.

Considering the literature data, PMOZO hydrogels were prepared by the UV irradiation of presynthesised or *in situ* formed random copolymers of 2-methyl-2-oxazoline and 2-(9-anthrylethyl)-2-oxazoline (AEOZO) [26], the crosslinking being the result of a photodimerization process of the anthryl substituent groups [27] (1).



(1)

Amphigels with structure (2) (δ = 10.61 – 11.47 $(cal/cm^3)^{1/2}$), characterized by a relatively high equilibrium swelling degree, both in water (~ 80%) and in organic solvents (acetone ~ 370 %, ethanol ~ 420 %) were prepared by photocopolymerization of a bifunctional monomer, 2-(5-methacryloyl-penthyl)-1,3-oxazoline [28] with MMA followed by a subsequent copolymerization with MOZO [29].



(2)

However, the mentioned synthetic routes gave materials with a random structure and composition, a better design of this materials being required in order to obtain a controlled response. Taking advantage of the living nature of the cationic isomerization polymerization of MOZO, one can control the dimension of the PMOZO sequences inserted between the polymerizable groups along the chain of the multifunctional macromers of PEN type. Their use in the copolymerization with methacrylic monomers (HEMA, MMA) allows the preparation of hydro- or amphigels with a well-defined structure at a sub-micron level, as shown in Figure 4. The dark areas are attributed to the PMOZO microdomains which selectively absorb OsO_4.

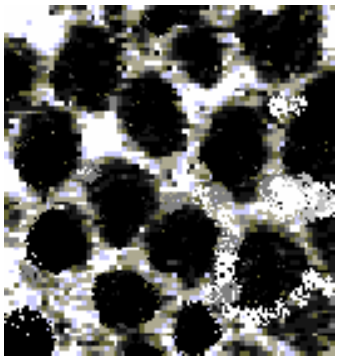


Fig. 4. Typical morphology of PMOZO/PHEMA gels. PHEMA / (PHEMA+PMOZO) = 0.6

The properties of the synthesized gels (*i.e.* flexibility, swelling behaviour) depend on the composition and on the dimension of the PMOZO inserted

sequences which are modeling the shape and area of the separated microphases and the crosslinking density (Figure 5 and Tables 3, 4). Thus, materials with prerequisite properties may be obtained by an appropriate selection of the comonomers and of the synthesis conditions.

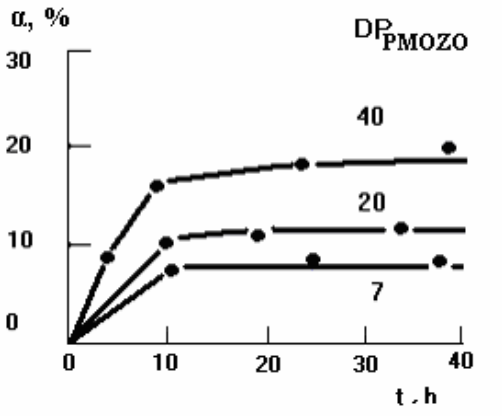


Fig. 5. Variation of the equilibrium swelling degree in water for the PMOZO/PMMA gels with the length of the inserted PMOZO sequences. (PMOZO content ~ 15 wt %)

As expected, the swelling degree in water or methanol is increasing for higher polymerization degrees of the PMOZO (DP_{PMOZO}) inserted sequences (lower crosslinking density).

Table 3. Dependence of the gel properties on the composition for PHEMA/PMOZO copolymers (DP_{PMOZO} = 25)

PHEMA PHEMA+PMOZO in copolymer	0.75	0.65	0.60	0.20
T_g (ºC)	110	105.5	93	110
α_e (%)[a]	100	85	70	350

[a] - equilibrium swelling degree in water: $\alpha_e = (Ws-Wd)/Wd \cdot 100$

The variation of the swelling degree with copolymer composition is also influenced by the comonomer nature. Thus, the water uptake in PHEMA/PMOZO hydrogels reached maximum values for the highest content in one or another of the two comonomers, while the lowest value was obtained for a near equimolar composition, when a minimum value of the pores of the networks is realised. As shown in Table 3, except for the sample with the largest amount of PMOZO, the DSC plots present only one T_g, slightly increased with respect to PHEMA content. The forced compatibilization is the result of the dense packing of the network and is facilitated by the presence of hydroxyl groups in the methacrylic moieties.

By contrast, when MMA was employed as a comonomer (Table 4), the swelling degree of the resulted amphigels in methanol monotonously increases with the content of PMOZO in the copolymer due to the selective alcohol absorption of the later. However, as observed from Table 4, which summarizes the swelling behavior data, the hydrogel prepared by PMOZO macromer homopolymerization retains a lower amount of alcohol as compared to the copolymer with about 80 % PMOZO. This can be explained by a higher crosslinking density and a dense packing of the neighboring PMOZO chains in the resulted hydrogel.

Table 4. Swelling behavior of the PMOZO/PMMA amphigels as a function of composition

PMMA / PMMA+PMOZO	0	0.20	0.35	0.50	0.65	0.80	0.86
α_e in methanol (%)	140	260	130	120	100	55	30

The amphigels based on PMOZO are known as appropriate materials for membranes with high selectivity. On the other hand, taking into account the facile modification of the two sequences by hydrolysis, which yields the formation of different new, reactive and pH sensible groups able to immobilize biocompounds (–NH– and –COOH), one can easily imagine the application of such materials with tailored architecture in the controlled, selective release/capture of substances (*e.g.* for environmental reasons, or drug delivery) as a response to external stimuli (*e.g.* pH).

The goal of the present investigation was to develop, based on the synthesized gels, thermoplastic and biocompatible materials, and possessing good physico-mechanical properties. With this aim, polysiloxane or polyurethane [30] were added to the mentioned PMOZO/PMMA gels (brittle materials), in order to form (semi)interpenetrating polymer network (SIN, IPN) structures with an improved morphology and thermoplastic processability. An IPN is an intimate combination of two polymers, both in a network form, one of which is synthesized and/or crosslinked in the presence of the other [31]. The forced compatibilization of both polymers induces a better mechanical behavior and an increased functionality of the resulted complex material. The most popular and well studied IPN and SIN system is cross-polyurethane-inter-cross-poly(methyl methacrylate) (PU-PMMA) [32]. As far as we know, there is only one earlier report focusing on the synthesis of such materials having as one of the components polyethylenimine derivatives. It deals with the preparation of a simultaneous semi-interpenetrating polymer network of crosslinked PMMA and poly(2-benzyl-2-oxazoline) [33] by a solvent-free reaction process. Note that poly[(N-propionylimino)ethylene] and poly[(N-

acetylimino)ethylene] are immiscible with PMMA in their blends, but the amphipathic graft or block copolymers of these poly[(N-acylimino)ethylene]s may act as compatibilizers with most commodity polymers [3].

A mixture of PMOZO/PMMA gel (12.5 wt% PMOZO, DP_{PMOZO} = 20), polysiloxane (polysiloxane: PMOZO/PMMA gel gravimetric ratio = 70:30) and crosslinking catalyst (tin octanoate) in chloroform was cured at 60ºC. The crosslinked cast film is soft and transparent, permeable to oxygen, with a swelling degree of 6 % in water and of 56 % in ethanol. The maintenance of the transparency in the interpenetrated polymer network was explained by the forced compatibilization of the two materials (a single glass transition, *i. e.* $T_g = -82.5$ ºC), as well as by the TEM analysis (Figure 6), in accordance with a mutually relative uniform distribution of the implied polymeric materials at a submicronic level. The polysiloxane sequences are partially crystallised, a melting peak being observable in the registered DSC plot at −47.5 ºC. Further optimized materials could be envisaged for optical lenses.

A semi-interpenetrated network was also prepared by a sequential interpenetrating method involving the radical copolymerization of the PROZO multifunctional macromer with MMA (initiator – AIBN, 50ºC, 24h) in the presence of polyesterurethane (PU) or poly(ester-siloxane)urethane (PUS), followed by a curing at 70ºC, for 24h, and at 120ºC for 4h, in vacuum, in order to achieve network stability.

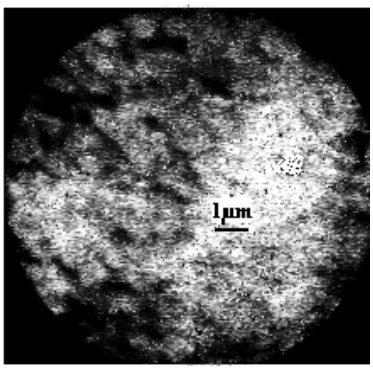


Fig. 6. TEM micrograph of the PSiO:PMMA/PMOZO interpenetrating polymer network.

A PEOZO macromer of unsaturated polyesther structure was selected considering the advantages offered by the lower T_g comparative to PMOZO and the specific thermosensitive properties [3] (it possesses a cloud point at about 36ºC), complementary to its biocompatibility. The interpenetration of the elastomer chains with the PEOZO/PMMA network yielded an increased flexibility, as seen in Figure 7.

Considering their properties, such materials may be used for the preparation of surgical dressing.

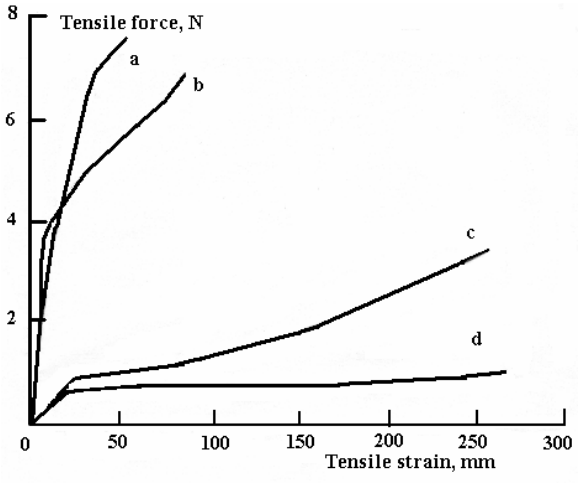


Fig. 7. Stress *vs* strain diagrams for:
a – PU
b – PUS
c – PUS : PEOZO/PMMA (80:20)
d – PU : PEOZO/PMMA (80:20)

To conclude, it is obvious from this short presentation that poly[(N-acylimino)ethylene] derivatives, due to their well-controlled design and high versatility, represent appropriate intermediates/components of micro- and nanostructured materials, responding to the requirements of the present technical development.

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Degradation Phenomena in Polymers Used for Microtechnologies

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Abstract. The study of degradation phenomena in polymers becomes one of the key issues in microtechnologies. In this contribution, the main degradation / failure mechanisms were identified, together with the methods to diminish these phenomena. A central role is played by the access to modern techniques for failure analysis, allowing the accurate identification of the involved phenomena. An important idea emerged from the paper: a closer co-operation between researchers in polymers and those in microtechnologies is needed.

Introduction

Any product made by human activity and intended to be used for a specific purpose succeeds in fulfilling its function only for limited time duration, because the entropic tendency (degradation, ageing, death) is not only an inexorable law for a living creature, but also a reality of the technical systems. Even the Egyptian pyramids, a symbol of the time resistance for a human artefact, built 5000 years ago, were significantly degraded during ages. Confronted with this situation, man tries to restore the monuments (and books also), intending to re-create the original pattern. Hence, these are repairable products (or renewable ones).

The electronic objects used daily by each of us (computers, refrigerators etc.) may be also repaired, by replacing one or more failed components. But these components are, generally, unrepairable products, this being especially true for electronic components. We must say that the components are the „atoms" of the technical systems, the „bricks" used to build these systems. In this case, the degradation and failure must be prevented by specific methods of designing and manufacturing.

As a general idea, man always tried to fight against the degradation of the products. This fight was called „reliability concern" only after World War II, when

this approach arised. In this work, we will try to discuss the degradation phenomena arising in some unrepairable products, such as those manufactured by microtechnologies and using polymers as building material. But first, in order to define the terms, the basic elements will be presented.

The Microtechnologies are defined as technologies allowing obtaining structures, subsystems and technical systems with the functional dimension of the order of micrometer (e.g. microsystems). Besides precision engineering, manufacturing and putting together very small elements, the microtechnologies grown from microelectronics ensure the simultaneous manufacturing of many components (subsystems, microsystems, etc.) in the same manufacturing process, and without requiring a subsequent assembling.

We must specify that *the microsystem* is a technical system obtained by microtechnologies and able to perform multiple functions. There are biomimetic microsystems (built on principles imitating the basic principles of the living matter) and intelligent microsystems (fulfilling various functions, such as: sensing, processing and/or actuating, and combining two or more operating modes: electrical, mechanical, optical, chemical, biological, magnetical, etc., integrated in a single structure or a hybrid one).

The microtechnologies arising from microelectronics, the manufacturing technology is fundamentally the same, but with more and more important specific features, as the microtechnologies are developing. Initially, the basic material was silicon, but now a large range of materials are used.

The polymers were intensely used in microelectronics (and in microtechnologies), especially as photoresists (in lithography) and encapsulating material. But now, new applications are appearing. The first chapter of this work is dedicated to these applications, the main degradation phenomena being indicated in each case. Then, in the second chapter, after a short description of the basic elements in reliability, a reliabilistic approach to the degradation phenomena in polymers used in microtechnologies will be made. Eventually, the last chapter is dedicated to those situations when polymer degradation is beneficial, being used as a functioning principle for some devices.

1. THE USE OF POLYMERS IN MICROTECHNOLOGIES – DEGRADATION PHENOMENA

1.1. Plastic Encapsulation

In the last years, plastic (polymer) encapsulation has become the main choice for the products obtained by microtechnologies. The reason is the significant improvement of the quality of plastic cases, which are sometimes better than metal and ceramic ones. A milestone of this trend is the so-called “Acquisition Reform”, launched in June 1994 by the US Army: the acceptance of plastic

encapsulated devices as fulfilling military requirements. Furthermore, the idea of military components was rejected, because the commercial ones seemed to be good enough to be used in military equipments. This does not mean that polymer used in plastic encapsulated devices will last forever. Degradation phenomena are still identified and some examples are presented in the following.

Oxidative degradation The oxygen degrades the polymers by diminishing the molecular weight, by reacting with the free radicals of the polymers forming peroxy and hydro peroxides free radicals [1], producing chain scission. The properties of the polymers are drastically modified. Even a reduction of the molecular weight with 5-10% may produce failure. As a means of prevention, it is recommended to avoid the contact with oxygen and the use of an antioxidant. But processing the polymers used for encapsulation may involve the high temperature needed for reducing melt viscosity. The presence of oxygen, in small amounts, can produce the degradation of the polymer, even if an antioxidant is used. The solution is to optimize the processes, but in order to do this reliable methods of analysis are needed, allowing to verify rapidly the various solutions. To identify the oxidative degradation, differential calorimetry, infrared spectroscopy and measurement of the changes in molecular weight are used. These methods allow identifying any oxidative degradation.

Breaking at the combined action of stress and environment (*Environmental Stress Cracking* - ESC) is one of the main causes of failure for components encapsulated by plastic injection. ESC is an accelerated fracture of the polymeric material caused by the combined action of the mechanical stress to the case and the environment. This phenomenon was identified from the beginning of polymer use for encapsulating electronic components and could not be entirely stopped, although remarkable steps were made in this direction. In order to control the susceptibility of a plastic material for ESC [2], one must verify: chemical exposure, mechanical stress, working temperatures, humidity, and exposure to ultraviolet radiations. In this respect, NPL Materials Centre (UK) produced a programme called CAMPUS (Computer Aided Material Pre-selection by Uniform Standards), allowing to choose the appropriate polymer type for the required application.

1.2. Sensors with Polymers

This is a very important field for using polymers in microtechnologies. The polymer can be the dielectric of a capacitor, or their conductive properties may be exploited.

Polymer as a dielectric The humidity and temperature sensors are realized as capacitors, the polymer being the dielectric. In this field, some improved devices have been developed lately, with better time stability of the performances. As an example, the Swiss company Sensirion AG [3] produced a new generation of temperature and humidity sensors, fully integrated, digital and calibrated, by using the micromachining CMOS technology. The new product, SHT11, is a multisensor

one-chip-module, for temperature and relative humidity, with a calibrated digital output, easy to integrate in a system. The polymer used as a dielectric may adsorb and release the water, proportionally with the relative humidity, modifying the capacitor capacity. The temperature and humidity sensor are a single device, so the calculation of the dew point is more accurate. The degradation phenomenon for this type of sensor is *the ageing of the polymer layer*, producing important variations in sensor sensitivity. The process becomes critical because the dimensions of the sensing elements are relatively high: 10-20 mm^2. But there is design methods able to minimize the failure risk emerged from polymer ageing.

The conductive polymers are newcomers, but they already have many applications in microtechnologies [4]. A polymer becomes conductive by injecting mobile charge carriers in polymeric chains. This may be done by the reaction with an oxidant (used to remove the electrons from the polymer) or with a reductant (injecting electrons in the polymer), in an analogous way as n and p doping in semiconductors. For this discovery, three scientists working in USA (Alan J. Heeger, Alan G. MacDiarmid and Hideki Shirakawa) received the 2000 Nobel Prize for Chemistry. There are basically two main methods to synthesize conductive polymers: *electropolymerization* (used especially to obtain polymer films: the electrodes are inserted into a solvent solution containing the monomer and the dopant electrolyte; when biased, a polymer film grows on the working electrode, usually on a platinum one), and *chemical reaction* (the monomers react with an oxidant in excess, dissolved in a solvent; the polymerization occurs spontaneously, the method being used especially for obtaining volume polymers), respectively.

The most important applications of conductive sensors in microtechnologies are in biological and chemical sensors, using conductive polymers as sensitive material. The advantages on conventional materials used for this purpose are important:

- the great variety of polymers,
- the electrochemical preparation allows mass production and sensor miniaturizing,
- the biomaterials (enzymes, etc.) can be easily incorporated in polymers,
- the oxidation state of the polymer can be easily changed after deposition, hence one may build the sensitive characteristics of the film.

Due to these advantages, the conductive polymers are used in various types of sensors: pH mode (pH variation), conductometric modes (conductivity variation), amperometric mode (current variation), potentiometric mode (variation of the open circuit potential), etc. As an example, the gas sensors working in a conductometric mode use the conductivity (or resistivity) time variation when the polymer is surrounded by gas molecules. Some examples of polymers used for gas sensors are polypyrrole and polyaniline.

The degradation phenomenon that occurs to conductive polymers is *the modifying of the electrical resistance* when the polymer is exposed to air for a

longer time period, because the oxygen produces a time increase of the resistance. So far, the optimization of the manufacturing process about this degradation mechanism has been unsatisfactory.

1.3. Polymer Micromachining

This is a very new direction in the field, used e.g. for biochip manufacturing [5]. The Swedish company Amic AB reports in 2002 the draw up of micromachining technology for polymers in order to achieve a CD microlab. The basic idea is to manufacture polymer microchips, achieved by replicating from polymer a master obtained on silicon. The microlab contains capillars, reaction chambers, mixers, filters and optical elements. The dimension of these microfluidical structures ranges from 10 μm to some mm (lateral dimensions) and from 5 μm to a hundred of μm (layer depth). All these are first achieved on silicon, the polymer replica being obtained as CDs. The advantages are obvious: the multiplying in polymer is much cheaper and less complicated than mass production on silicon of these microlabs. The CD microlabs do not require tubes, because the microfluids are conducted through the centrifugal action, by CD spinning. The micro-optical elements are integrated on the rear of the CD: the optical surface collects the luminescence from CD reaction chambers. Hence, one may avoid using external collector lens and the micro-optical elements are integrated on a chip.

The company MIC (Denmark) [6] developed, in the frame of the programme μTAS, researches on polymer micromachining. Thereafter, in November 2001, a "spin-off" called POEM (*Centre for Polymer Based Microsystems Dedicated to Chemical and Biochemical Analyses*) appeared, focusing on manufacturing of integrated chemiluminescence sensors and miniaturized electrochemical sensors, and also on fundamental researches on polymer micromachining. POEM developed collaboration relations with European companies interested in methods for micromachining micro- and nanostructures on various polymers.

Obviously, polymer micromachining is a field with a bright future. Some advantages are listed bellow:

- the mass production is cheaper than for silicon devices, allowing to manufacture single use devices (*e.g.* for blood analysis);
- many polymers are transparent for visible light, being appropriate for systems based on optical detection;
- the polymers can be made resistant to most chemicals used for microsystem manufacturing.

2. A RELIABILISTIC APPROACH TO POLYMER DEGRADATION

2.1. Basic Reliability

The investigation into the reliability of a product may be compared with the effort of a private investigator to search out the cause of a crime: the same

requirements to know the history of the studied subject, the same precaution should be taken not to disturbe the details before investigation (in this case: to eliminate any processing on the failed product between the failure moment and the start of the investigation), the same need for more and more sofisticated analysis methods in order to establish the real causes of the event. In principle, the differences are in the element called premeditation. The huge majority of the product failure arises from design & manufacturing deficiencies, unwanted by the manufacturer. Sometimes, he knows the causes, but for financial reasons (or because he has underestimated their nocivity) he is unable (or does not want) to suppress them.

But first, before being able to analyze the failure of the components used in electronic equipments, one must perform laboratory testing of these components, in order to study the reliability of the bench of devices, the so-called reliability analysis of the manufacturing of products. Only after this information is obtained, failed devices of the same type may be analyzed *post festum* and the failure causes can be identified.

Hence, the reliability analysis is the necessary step for each product. This must cover the following steps:

- samples withdrawn from the bench of devices undergo reliability tests simulating real functioning
- failed products are carefully analyzed by physical and chemical methods
- degradation and failure mechanisms are identified (including the root causes)
- modelling of the reliability is performed, allowing to predict the future behavior of the studied device
- corrective actions are established (if necessary)
- a system of accelerated tests is built in order to shorten the time for establishing the reliability level.

As one can notice, identifying the degradation and failure mechanisms is the key element of the reliability analysis.

2.2. Why do Products Fail?

The failure is fostered by internal causes (referring to the design & manufacturing and use) and by external ones (referring to the exploitation environment). The internal causes can be split into three categories, from the point of view of the source of degradation / failure:

- improper design
- improper manufacturing
- improper use.

Hence, the designer, the manufacturer and the user are involved. The most direct way to reduce the failures is to disseminate the newest knowledge in the field (typical failure mechanisms and recommended cures) to all these, in order to be aware of the possible improper actions. Then, the “customer voice” must become an important element at the design phase, in order to design a reliable product. This

will allow developing a preventive strategy about failures, typical for concurrent engineering.

The main external causes for polymer failure are [7]:

- heat (distribution and duration during processing)
- oxidation
- temperature – humidity combination
- mechanical strain
- energy absorption and dissipation capability
- electrical properties
- irradiation
- environmental stress (the marine environment is particularly hostile).

2.3. Failure Criteria

For any product, the catalogue sheet defines the so-called failure criteria: the limit values for the main parameters of the product. Beyond these limits, the product is adjudged as failed. Certainly, these failure criteria depend on the application of the product: the function to be fulfilled and the functioning environment.

Today, the failure criteria are more and more restrictive, due to the new applications where improved characteristics are required. The recent progresses in polymer manufacturing are easy to detect, but the mentioned increase in the severity of the failure criteria did not allow noticing a similar increase in the reliability level. Hence, the reliability concerns are still a key issue for the products of microtechnologies.

The medical industry is a good example of a field with restrictive failure criteria. Special care is needed, because any failure of a device may have unpredictable effects on patient's health. So, the manufacturing process is strictly monitored, with many visual inspections, intended to detect any detail able to be detrimental for the product quality. Even products with minor defects are rejected, which normally could not disturb the functioning, but products with the best quality must be delivered. As an example, the so-called "cosmetic" defects (referring to the surface aspect) lead to product rejection, if intended for medical purposes. The "cosmetic" defects are produced by contamination from external sources, and establishing efficient corrective actions starts from identifying the cause of these defects.

2.4. Defect Characterization Techniques

The understanding of degradation / failure mechanisms is needed in order to be able to make long-term predictions on the reliability of components and systems. The range of usable techniques is very large. But the use of visual inspection as the primary technique for identifying failure mechanisms must not be neglected, only for the sake of using sophisticated methods. Often, this is the only required technique [8], allowing to identify rapidly the causes of the failure. Hence, it is

necessary to establish a procedure for failure analysis, having the visual inspection as the first step, and with a well justified appeal to sophisticated techniques.

In the world, there are many specialized labs on techniques for ageing expertise for polymers. An example is the company MATCO Associates Inc., Pittsburgh, USA (details are given at *http://matcoinc.com*). But a more revealing example is given by Sandia National Laboratories (USA), ready to do the following:

- analyse the properties of ageing polymers and identify the most significant characteristics of degradation monitoring;
- design experimental devices needed for monitoring polymer ageing;
- analyse property changes in order to determine the physical and chemical mechanisms involved in degradation;
- design and lead experiments on accelerated ageing in various environments (thermal, high energy radiations, ultraviolet radiation, humidity, mechanical stress, electrical stress) and process the obtained results, developing prediction models for polymer life.

To fulfil these objectives, Sandia National Laboratories use up-to-date facilities, allowing (among others):

- to age polymer samples for a long time period, in various environments;
- to use standard techniques for polymer analysis;
- to measure the necessary parameters for modelling/understanding degradation effects;
- to analyse oxidative degradation mechanisms, by using spectroscopic techniques;
- to increase the polymer resistance to degradation by plasma treatments;
- to model the electric field distributions and electrically induced stress in dielectric;
- to develop chemical sensors specialized in degradation monitoring;
- to perform analyses of gaseous atmosphere, in order to monitor the degradation of products stored in closed jar;
- to determine the composition profile and density in polymer films, with a resolution of nanometers.

As a conclusion, one may say that a reliabilistic approach to the polymer degradation starts from developing the capacity to perform reliability analyses (tests, failure analyses, modelling, etc.) and pursues with effectively performing such reliability analyses. Only by this way real solutions to diminish degradation phenomena that occur in polymers used in microtechnologies may be found.

2.5. Degradation / Failure Mechanisms

In a polymer exposed to various stress types (heat, light, air, water, radiation, mechanical strain) chemical reactions produce the change of chemical composition and molecular weight, inducing modifications of physical and optical properties of the polymer. In practice, any change of the polymer properties is called degradation.

As a rule, these degradations are detrimental for the device in which the polymer is used. But there are also some situations (see chapter 3) when the degradation is beneficial for device functioning.

Polymer degradation may be the result of the action of an aggressive environment or an external agent, unforeseeable by the device designer [9]. The main failure mechanisms of polymers are: thermo-oxidation, photo-oxidation, degradation due to ionizing radiation, chemical attack, environmental stress cracking, electrochemical degradation, biodegradation.

One may notice that the oxidation is the most encountered degradation mechanism in polymers. It is important to note that if the oxidation is started (by thermal or photo effects), a chain reaction is produced, accelerating the degradation. The solution to stop the oxidation degradation is to use stabilizers able to stop the oxidation cycle.

As we said before, one of the causes of oxidation initiation is exposure to sunlight or to some radiation types. As an example, ultraviolet radiation may affect the life of the polymers, by breaking their chemical bounds. This process, called photodegradation, determines eventually breaking, colour changing and loss of physical properties. To be noted that, in principle, polymers do not absorb violet radiation. But traces of other compounds in polymer (degradation products, catalyst residuum, etc.) may absorb the ultraviolet radiation. For sunlight, the photo degradation is accomplished by thermodegradation.

The failure may originate also from the contamination with inclusions (non-polymeric materials). These inclusions may act as stress concentrators and may cause premature mechanical failure, far below the mechanical stress limit considered for the design.

Another class of failure originates in external sources: an unusual distribution of the additives and modifiers in polymer. These additives are intended to protect the polymer against oxidative degradation, so that an unusual distribution lets a part of the product unprotected during functioning, producing early failures. These types of defects are an important part of non-functioning causes.

2.6. Biodegradation

This is a degradation process involving biofactors, such as bacteria or fungi. In order to study polymer degradation produced by bacteria, it is necessary to use advanced investigation means. In [10] the results of a study performed on a polyimide coating exposed to a fungal consortium was isolated, identifying the existing species: *Aspergillus versicolor*, *Cladosporium cladosporioides* and a *Chaetomium* species. Actively growing fungi on polyimides yield distinctive EIS (*Electrochemical Impedance Spectroscopy*) spectra through time, indicative of failure of the polymer integrity compared to the uninoculated controls. First, a decrease in coating electrical resistance was noticed correlated with a partial ingress of water molecules and ionic species into the polymeric matrices. This was

followed by further degradation of the polymer produced by the activity of the fungi. The relationship between the change in impedance spectrum and microbial degradation of the coating was established by SEM (*Scanning Electronic Microscope*) and an extensive colonization of polyimide surfaces by fungi was shown. EIS proved to be a sensitive tool for evaluating the polymer biosusceptibility to microbian degradation.

In order to detect the source of microbial contamination, research on metallic substrates covered by polymers was performed [11]. Long-term electrochemical test in aqueous NaCl produced from deionised water were performed for these structures. Microscopic inspection revealed that the surface of the polymer was heavily colonized by micro-organisms, which had developed naturally. The deionised water was considered as a possible source and, to establish the extent of contamination, samples were acquired from Italy, USA and UK. In all cases, the presence of biological contaminants, both bacterial and fungal growth ensued, thus reflecting the widespread contamination of deionised water systems. As a conclusion, the bacterian biodegradation of polymers seems to be a real and nocive phenomenon. To prevent it, decontamination with bacteria of deionised water must be accomplished.

3. BENEFICIAL DEGRADATIONS

In principle, polymer degradation is a destructive phenomenon, needing to be diminished. But there are situations when polymer degradation proves to be beneficial, becoming even the basis of the functioning principle of the micromachined device, incorporating the polymer. Some example will be relevant:

a) chemical sensors based on the degradation of polymer films in the presence of chemical substances
b) biodegradable sutures, avoiding the operation of string removing
c) drug delivery at “fixed point” in human body. The idea is a simple one: the drug is encapsulated in a polymer, resistant to normal environment, but degrading in the environment specific to a desired area of the human body.

In the following, some examples of such applications of polymer degradation are presented.

At the end of the 90s, researchers from Sheffield University [12] reported a biosensor based on capacitance modifying produced by polymer dissolving catalyzed by an enzyme. Thin films of a copolymer of methyl methacrylate and methacrylic acid were deposited onto gold-coated electrodes setting-up a capacitor. By the enzymatic action of urease on urea, a local pH increase, triggering the dissolution of polymer films was noticed. This was accompanied by an increase in capacitance of up to 4 orders of magnitude: a very sensitive sensor for urea in serum and whole blood was obtained. The degradation is reproducible, the degradation rate being proportional with enzyme concentration. Later, the group from Sheffield developed, on the same principle, sensors for other enzymes [13].

In March 2003, researchers from California University, San Diego reported the transfer of the optical properties of a semiconductor crystal to a plastic material (*Science*, March 28, 2003) [14]. This important achievement opens the possibility to use implantable devices for monitoring the "delivery" of drugs in human body or to manufacture biodegradable suture. Recently, the team led by Prof. Michael J. Sailor developed sensors on porous silicon able to detect biological and chemical agents (useful in the case of a terrorist attack), and optical sensors (on porous silicon) changing the colour in the presence of sarin or other toxic gases. Now this team reported a method to transfer the optical properties of such sensors (specific to nanostructured crystalline materials) to some organic polymers. The advantage is the biocompatibility and flexibility of new sensors, very useful in medical applications. Moreover, plastic materials have a much higher reliability and durability. The used method is similar to manufacturing plastic toys from a mold. First, a silicon chip containing an array of nanometer-size holes is manufactured, giving the chip the optical properties of a photonic crystal (a crystal with a periodic structure that can control precisely the transmission of light much as a semiconductor controls the transmission of electrons). Then, a molten or dissolved plastic was injected into the pores of the finished porous silicon photonic chip. The silicon chip mold is dissolved away, leaving behind a flexible, biocompatible "replica" of the porous silicon chip. The Sailor's team is now able to "tune" their sensors to reflect over a wide range of wavelengths, some of which are not absorbed by human tissue. In this way, the scientists can fabricate polymers to respond to specific wavelengths that penetrate deep within the body. A physician monitoring an implanted joint with this polymer would be able to see the changes in the reflection spectrum as the joint is stressed at different angles. A physician in need of information about the amount of a drug being delivered by an implanted device can obtain this by seeing how much the reflection spectrum of a biodegradable polymer diminishes as it and the drug dissolve into the body. Such degradable polymers are used to deliver antiviral drugs, pain and chemotherapy medications and contraceptives.

To demonstrate that this process would work in a medical drug delivery simulation, the researchers created a polymer sensor impregnated with caffeine. The sensor was made of poly(lactic acid), a polymer used in dissolvable sutures and a variety of medically implanted devices. The researchers watched as the polymer dissolved in a solution that mimicked body fluids and found that the absorption spectrum of the polymer decayed in step with the increase of caffeine in the solution. Hence, the drug was released on a time scale comparable to polymer degradation.

4. CONCLUSIONS

- Polymers are one of the most promising materials in microtechnologies.
- From the "traditional" application in microelectronics, valid also in microtechnologies (such as encapsulating material or photoresists), now

specific applications of the polymers have been developed: polymer-based sensors or polymer micromachining for microsystem manufacturing.
- The study of degradation phenomena in polymers becomes one of the key issues in microtechnologies.
- In this paper, the main degradation / failure mechanisms were identified, together with the methods to diminish these phenomena.
- A central role is played by the access to modern techniques for failure analysis, allowing the accurate identification of the involved phenomena.
- An important idea emerged from the paper: a closer co-operation between researchers in polymers and those in microtechnologies is needed.

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Bacterial Exocellular Polymers. Biosynthesis, Characterization, Applications

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Abstract. In natural habitats the cell surface is well recognized as being of paramount importance in the survival of the microorganism. These organisms adhere to or detach from various interfaces by the cell surface polymers. In addition to their importance in the ecophysiology of microorganisms, these polymers have also been the subject of intensive study due to their applied value. In some cases these molecules have been shown to be surface active, amphipathic biopolymers exhibiting high affinity for air/liquid, liquid/liquid and liquid/solid interfaces. The properties of amphipathic cell surface polymers make them interesting candidates for various industrial applications.

Where possible, we will present their chemical composition, some physical characteristics, and the biological functions. Finally, the results of several experiments illustrating the potential applications of both the biopolymers and the organisms, which produce them, are presented.

Many prokaryotic organisms secrete on their surfaces slimy or gummy materials (Figure 1). Bacteria in nature are surrounded by a thick, continuous highly-ordered hydrated polyanionic polysaccharide matrix that must be expected to influence profoundly the access of molecules and ions, including protons to cell wall and cytoplasm membrane. Bacterial exocellular polymers associated with the cell wall and membranes have been investigated extensively [1].

The exopolysaccharides are a common product of microbial cells, a universal genetical characteristic of bacteria, which is expressed differently depending on species, medium conditions, and precursors. *In situ* they could be synthesized by a large number of microorganisms, more than 70 species of bacteria, yeasts, fungi and microalges.

Microbial exopolysaccharides have generally been considered as secondary metabolites, not growth related, produced when a carbohydrate source is present in

excess. Some may be complex with various functional groups attached to the saccharides and some may have several functions, serve as physical barriers between the environment and the organisms.

Fig. 1. Bacterial capsules: negative staining with India ink [1].

To understand the function of a polysaccharide and how this is regulated, it is necessary to know the structure of the polymers, their relations with the cell wall, the reactions by which the polymer is synthesized and assembled and how metabolites regulate synthesis and assembly of the polysaccharide.

The relations with the cell wall are suggestively presented in the diagram from Figure 2.

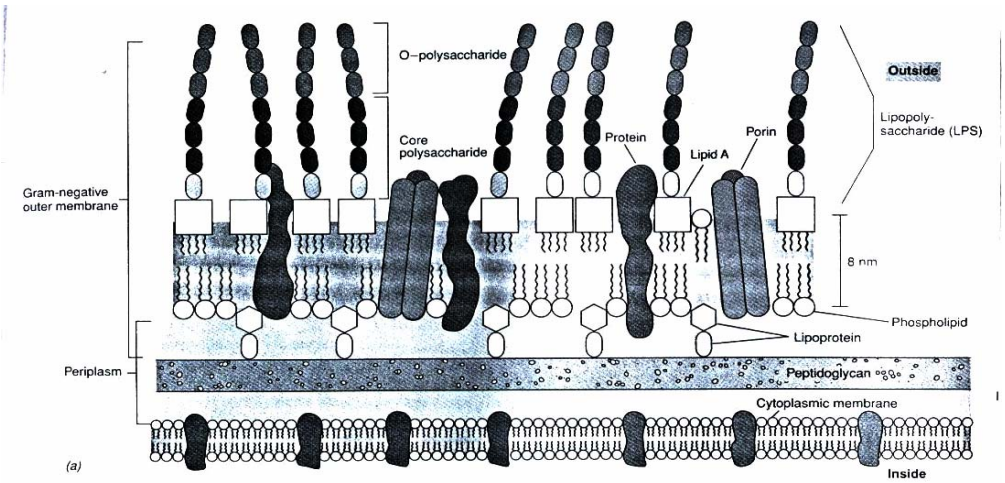

Fig. 2. The outer membrane of Gram-Negative bacteria [3].

Most exopolysaccharides are presumed to be synthesized by a cellular mechanism identical or similar to that involved in cell wall syntheses, but a few, however, are synthesized extracellularly. At each stage in exopolysaccharide synthesis, control mechanisms can operate and affect the production of polymer [4-

7]. The initial level of control is seen in the various mechanisms of substrate uptake. During or after the uptake, the substrate is phosphorylated prior to conversion to sugar nucleotides. The monosaccharides are transferred from the sugar nucleotides to an isoprenoid lipid intermediate. After the formation of the oligosaccharide subunits of the extracellular polymer, attached to the isoprenoid lipid, they may either be excreted directly or transferred to some acceptor molecule at or near the cell surface. The synthesis of these polymers is regulated by physiological factors that affect the synthesis of their components. Capsule formation is generally favored by a high C:N ratio, whereas synthesis that depends on extracellular glycosyl donors responds to the concentration of the disaccharides.

The carbon sources utilized for exopolysaccharides biosynthesis can be various [6, 8, 9] such as the following:

- glucides: glucose, sucrose, fructose, corn sugar, cereal grain hydrolyzates, molasses, soluble starch and flours, sugar-rich wastes);
- hydrocarbons and low-molecular-weight petrochemical substrates: n-alcanes, n-paraffin C_{12}-C_{17} mixtures, hard liquid paraffins, crude oil;
- lower polyhydric alcohols: 1,2-propandiol, ethanol, ethyleneglycol, n-propanol, trimethylglycol, glycerol, methanol;
- methane.

Microbial capsular polymers in the simplest sense are defined as those outermost components of the cell periphery that surround the bacterial cell [10]. This definition is itself controversial for it excludes those extracellular polymers found in the culture filtrate. Some authors prefer to differentiate between these structures and to define the latter type of polymer as "slime". The terms "capsule" and "slime layer" are used in the early studies to describe these polysaccharide layers, but the more general term *glycocalyx* is now accepted [11].

The bacterial glycocalyx is defined as a polysaccharide-containing material lying outside the cell wall. The morphological features and chemical composition vary in different organisms. The glycocalyx may be thick or thin, rigid or flexible, depending on the chemical nature of a specific organism. Glycocalyces are subdivided in two types [11]:

1. *"S" layers*, composed of a regular array of glycoprotein subunits at the cell surface as described by Sleytr [12].

2. *Capsules*, composed of a fibrous matrix at the cell surface that may vary in thickness and may accurately be described by the following nonexclusive descriptors:

a) rigid - a capsule sufficiently structurally coherent to exclude particles (e.g. India ink.);

b) flexible - a capsule sufficiently deformable that it does not exclude particles;

c) integral - a capsule that is normally intimately associated with the cell surface;

d) peripheral - a capsule that may remain associated with the cell in some circumstance.

The chemical composition of "S" layer has been reviewed by Sleytr [12], and that of *bacterial capsules* has been exhaustively reviewed by Sutherland [13].

Bacterial capsules have complex structures composed of saccharides that occur in a periodic manner [14]. These structures may be either homopolymers or very complex heteropolymers of a wide variety of monosaccharides among which neutral hexoses, 6-deoxyhexoses, polyols, uronic acids and amino sugars are prominent, and phosphate, formate, pyruvate and succinate may be present as substituents [11].

The physical nature of bacterial glycocalyx The bacterial glycocalyx is often a highly hydrated polymer matrix composed of 99% water (Sutherland 1977). In aqueous solution a polysaccharide chain may be in one of many feasible conformations, because of the relatively low-energy barrier that separates closely related conformers. However, if several non-bonded interactions (hydrogen bonding, dipolar and ionic interactions, solvent effects on the dielectric constant, and possibly Van der Waals interactions) occur and act cooperatively with water, the conformation of the polysaccharide will be considerably more stable.

The stability of the conformation assumed by the polysaccharide is determined by the number of interaction sites per glycosyl residue and the average interaction energy per site. Feasible conformations are dictated to a large extent by the glycosidic linkage [14]. The relationship of the bacterial glycocalyx to the cell wall is of pivotal importance, and the demonstrated role of divalent cations in the linkage of "S" layer glico-proteins to the cell wall may constitute a general mechanism of glycocalyx attachment.

Polysaccharide culture broths are typified as highly viscous. The *viscous nature* of the medium is due to the presence of the polymer, which is continuous with the water phase and, particularly in the case of bacterial cultures, the microbial cell contributes little to the viscosity. These fluids are distinct from fungal and streptomycetes culture medium in which the mycelium causes the broth to be highly viscous and is discontinuous with the water phase. Thus, although mycelia and polysaccharide media may show equivalent measured viscometric behavior, the heat and mass transfer characteristics of the broth may differ markedly.

Extracellular polysaccharides form two distinct groups depending on their chemical composition [8, 15]:

- *homopolysaccharides*, composed of a single structural unit, such as: Dextran, Levan, and Cellulose;

- *heteropolysaccharides*, containing several different monosaccharides, some of which may be present in more than one molar equivalent. Most microbial heteropolymers are composed of neutral sugars and uronic acids. Some may contain aminosugars instead of uronic acids or along with them. In addition, many contain acetyl groups, acyl groups such as formate and succinate, pyruvate in the form of a ketal, sulphate and phosphate inorganic anions. Most microbial exopolysaccharides are heteropolymers [16].

One group has studied extensively an extracellular polysaccharide xanthan, from *Xanthomonas campestris*. Their structural studies suggest that the xanthan contains repeating units composed of D-glucuronic acid, glucose and manose in the molar ratio of 1:2:2 with one acetate group and one pyruvate group per three repeating units. Morris [17] has shown that the polysaccharide undergoes a concentration independent, temperature induced transition from an ordered to a disordered state in the range of 70-85°C. H NMR, optical rotation spectroscopy and viscometric measurements showed a temperature-dependent change in the physical properties of the Xanthan.

Polysaccharides are currently recovered through precipitation with organic solvents. Some polymers are much more easily recovered than others. Those polymers which have a high content of acetyl or other lipophilic groups are more difficult to precipitate and require greater volumes of organic solvent. Because the presence of the acetyl groups doesn't improve the characteristics of the polymer, an alternative is to remove them, or to isolate the mutants producing non-acetylated polysaccharides.

According to the *ionic charge***,** microbial exopolysaccharides can be:

- *neutral polysaccharides*, such as: dextran, curdlan, levan;
- *anionic polymers*, for example: alginate, xanthan, rhizan.

Much of the research has been directed towards delineating the sequence and mechanism of reactions by which the major sugars are incorporated into a polysaccharide. Attention now needs to be focused on determining the structural microheterogeneity, the factors that influence the biosynthesis of various species and the role of each species in the biochemistry of the organism. Some of the structural microheterogenity may reside in the location and number of functional groups (methyl, acyl, phosphoric and others) attached to a polysaccharide. The percentage of the polysaccharide in each conformation could be controlled by regulation enzymes that remove and add the various functional groups without destroying the main polysaccharide chain, a mechanism that is energetically more efficient than degradation and synthesis of protein.

The fixed locations of bacterial polysaccharides on the cell and membrane surface and the relatively large number of saccharide chains per unit area, provide the bacterial cell with a system that may interact with its environment by complexing select small and macromolecules. When considered in this manner, each polysaccharide chain may serve as an acceptor of functional groups and the

conformation of each chain is dictated by the nature, location and number of functional groups attached to it.

The advantage of producing microbial polysaccharides rests in their assured production quality and variety. Polymer production can be controlled within precise limits, utilizing convenient or cheap substrates and the scale of production can be geared to the market [18].

The microbial polysaccharides such as Alginates and Xanthan are produced industrially. The industrial value of polysaccharides lies in their *rheological properties*, in their capacity to alter the rheological properties of aqueous solutions or their flow characteristics [6, 19-21]. The behavior of the polysaccharides in solution may be Newtonian, pseudoplastic or plastic. Many polysaccharides can exhibit thixotropy, such a characteristic having potential industrial application. The various possible results of interaction between polysaccharide molecules can also be utilized. The microbial exopolysaccharides are water-soluble polymer (hydrocolloids), with a good solubility in hot or cold water to give high viscosity neutral solutions at low concentrations.

These products can be used as alternatives to other synthetic or natural water-soluble polymers, or as novel polymers in thickening, suspending and gellification applications. Most polysaccharides can be used as stabilizers, leading to improved suspension or dispersion of particulate material in aqueous mixture, or as thickeners. Other major roles of the polymers are as film and fibre forming agents, or to assist water retention.

The microbial exopolysaccharides have a high stability in wide ranges of pH (3.0 - 9.0), temperature values, and salts concentration. Also they are compatible with acids and bases and exhibit a good synergistic with other polysaccharides, salts, surfactants, dyes. Molecular weight is highly variable (0.9 - 1.6×10^6 Dalton), it could be influenced by manipulating culture conditions [22].

Some exopolysaccharides, such as Emulsan, an anionic heteropolymer produced by *Acinetobacter calcoaceticus*, exhibit emulsifying and dispersion capacities for hydrocarbons and oil substrates. The microbial exopolysaccharides are not toxic and are biodegradable.

Some properties of exopolysaccharides referring to the colloidal properties, gel formation, surface film and fibre formation, thickening agent, found *applications in the following economical fields* [9, 20, 23-31]:

- *Oil industry*: mobility control agents to recover additional oil from waterloaded reservoirs, by reducing the flow capacity of the solution in the rock system, either by increasing the viscosity of the solution, or decreasing the permeability of the system (selective plugging).
- *Drilling mud, drilling and wellborn fluids*: polysaccharides introduced into these fluids add to their special features such as high viscosity with increased temperature resistance and a high degree of pseudoplasticity.

- *Textile industry*: thickening and stabilizer agent of textile printing pastes.
- *Remediation of wastewaters*: flocculant for water clarification, for metallic ion biosorption from wastewater.
- *Agriculture*: carrier for agrochemical, agricultural and herbicidal sprays; roots and seeds dipping to retain moisture; dipping Christmas trees.
- *Analytical and preparative biochemistry*: material for obtaining a range of stationary phases which can be used as ion exchanges, in chromatographic techniques, specific absorbents for affinity chromatographyc, support for enzymes and microbial cells immobilization.
- *Chemical industry*: stabilizer in emulsion paints; suspending agent to maintain uniform suspensions of particles such as solids in ceramic glazes, mica in wallpaper printing; priming porous surfaces; temporary binding of sintered products; ticketing of latex, adhesives, clay coatings for paper finishing; gelled detergents; gelled explosives; waterproof dynamite.
- *Pharmaceutical and cosmetic industry*: gel formation agents in pharmaceutical and cosmetic preparations; thickening of cosmetic creams, lotions, shampoos and pharmaceutical products; binding pharmaceutical tablets; hydrophilic barrier creams.
- *Medicine*: in dental impressions; substitute of blood plasma (Levan, Dextran); Fe-Dextran complex used in anemia treatment; immunomodulator agent; inhibition agent for malign processes.
- *Food industry*: stabilizer in food such as ice cream, salad dressings and fruit drinks; gel forming agent in milk desserts, jellies and animal foods; viscosifier for sauces and syrups; agent for control ice-crystal formation in foods which are frozen and thawed; in instant foods; incorporation into bread for improving its texture and other properties.

In Table 1 some examples of commercial microbial exopolysaccharides are presented, with their main properties and application fields [32].

The design of economically viable processes for the production of extracellular microbial polysaccharides presents several interesting challenges to the microbiologist, chemist, engineer and microbial technologist, some fruitful areas for research include: devising methods for altering and controlling the composition and molecular weight of polymers, design reactors with improved heat and mass transfer capacities at high product concentration, mutation and selection techniques, DNA- recombinant techniques, economic methods of product isolation and cell removal [33-37].

Table 1. Microbial exopolysaccharides of commercial interest

Commercial name	Microorganism	Characteristics of product	Applications
XANTHAN	*Xanthomonas campestris*	- high viscosity - pseudoplasticity - good suspending agent - good compatibility with acids, bases, salts, surfactants, polymers - low toxicity	- oil industry - drilling and wellborn mud and fluids - chemical, pharmaceutical, cosmetic, textile, food industry - agriculture - remediation of waste waters
ALGINATE	*Azotobacter vinelandii* *Pseudomonas aeruginosa*	- different degrees of viscosity - good compatibility with color reagents	- food and textile industry
ZANFLO	*Erwinia tahitica*	- high viscosity - pseudoplasticity - stabilized suspending and emulsifying agent - good compatibility with salts and cationic dyes	- chemical and textile industry
INDICAN	*Beijerinckia indicus*	- high viscosity - gel formation by heat - solubility in methanol - stabilized suspending and emulsifying agent	- gelling agent for mixture of water with ethanol, methanol, or ethyleneglycol
DEXTRAN	*Acetobacter* sp. *Leuconostoc mesenteroides*	- high viscosity - behavior almost Newtonian	- medicine: substitute of blood plasma and in Fe-dextran complex used in anemia treatment
CURDLAN	*Alcaligenes faecalis* *Agrobacterium* sp.	- irreversible gel formation by heat	- food industry - support for obtaining immobilized enzymes - tumoral inhibition agent
RHIZAN	*Rhizobium meliloti* *Agrobacterium tumefaciens*	- high viscosity - pseudoplasticity	- drilling mud and wellborn fluids - oil industry
PULULAN	*Aureobasidium pullulans*	- high viscosity - impermeable to O_2 film and fibre forming agent	- food industry - chemical industry: adhesive
SCLEROGLUCAN (POLYTRAN)	*Sclerotium glucanicum*	- high viscosity - pseudoplasticity - high stability in a wide ranges of pH and temperature values	- drilling and wellborn fluids - oil and chemical industry

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A Thermodynamic Approach to the Hydrothermal Synthesis of Hydroxyapatite-Based Nanocomposite Materials

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Abstract. The synthesis of hydroxyapatite (HAP) by hydrothermal procedure has been studied to establish the most suitable conditions for addition of tetragonal zirconia or polymer to HAP as reinforcing agent in order to obtain biologically active nanomaterials. Thermodynamic prediction has been used to anticipate the synthesis, pH, and temperature for the complex system. The validation of the synthesis route has been made on the basis of the structural and compositional characterization of composites. Density values were very close to the theoretical ones for HAP (2.76 g/cm^3 for the composite and 3.02 g/cm^3 for pure HAP). Hydroxyapatite crystallite sizes are in the nanometre range in all cases. Nanocrystalline HAP is expected to present high chemical and biological activity and high sorption capacity.

1. INTRODUCTION

Ceramic-based composite nanomaterials play an increasing role in the high-tech fields from structural (replacing traditional materials) to functional (from electronics to biomaterials) applications. Different physical, mechanical, chemical or mixed methods have been proposed to obtain the initial nanostructured powders with desirable characteristics for producing dense sintered materials (bulk, thick or thin films) with required properties.

Hydroxyapatite – $Ca_{10}(PO_4)_6(OH)_2$ – is one of the best known biocompatible materials due to its similar composition with the human bones (natural composite consisting of calcium phosphates like HAP and collagen) and high bioactivity. Its utilisation in orthopaedic implants and dentistry is, unfortunately, limited by its low mechanical strength. As a consequence, many efforts have been drawn towards the synthesis of HAP-composite nanomaterials with enhanced bioactivity and mechanical properties [1-16]. The hydrothermal method is a wet chemical process

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which presents some advantages, like: one-step process, low synthesis temperatures, obtaining of materials with nanocrystalline structure, controlled nucleation, homogeneous composition, versatility (oxides, sulphides, carbon nanotubes) and low pollution [17].

The main problems are related to hydroxyl bonding, which produces powder agglomeration. To solve these problems, different approaches have been proposed, like surface modification using adequate polymers or using external driving forces like electric field including deposition of nanocrystalline thin films. A convenient approach is to, firstly, predict the thermodynamic equilibrium in the complex water-ions system and then to verify the conditions to obtain powders with the desired characteristics.

The present paper gives some results on the thermodynamic predictions and their applications in the synthesis of HAP-composite powders from some definite systems.

2. THERMODYNAMIC CONSIDERATIONS REGARDING HYDROTHERMAL SYNTHESIS OF CERAMIC OXIDES

Generally, the hydrothermal processes may take place in two ways: hydrothermal reactions (reactions between species in hydrothermal solutions under the influence of temperature and pressure) and hydrothermal crystallization (transformation of amorphous species in crystalline ones under the influence of temperature and pressure). Figures 1a and 1b show that, by increasing temperature and electronegativity, the equilibrium goes toward oxide formation, the Gibbs free energy being higher in the case of hydrothermal reaction than for the hydrothermal crystallization. Calculations have been made using a special soft [18].

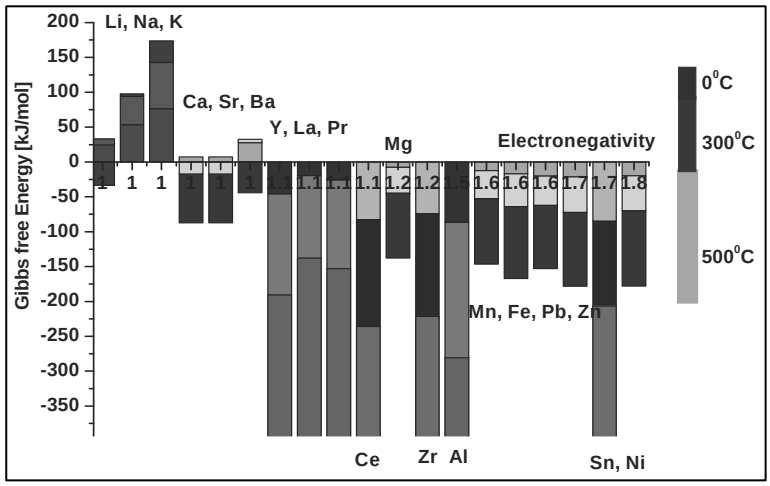


Fig. 1. a. Gibbs free energies for the synthesis of some oxides by hydrothermal reactions.

As a consequence, in most of our works we have synthesized different oxides starting from water soluble compounds using alkaline hydroxides as mineralizing agents. It appears that the role of solution pH should also be taken into account. A simple and reasonable prediction of species formed *vs.* solution pH at different temperatures consists in calculating the potential – pH (known as Pourbaix) diagrams.

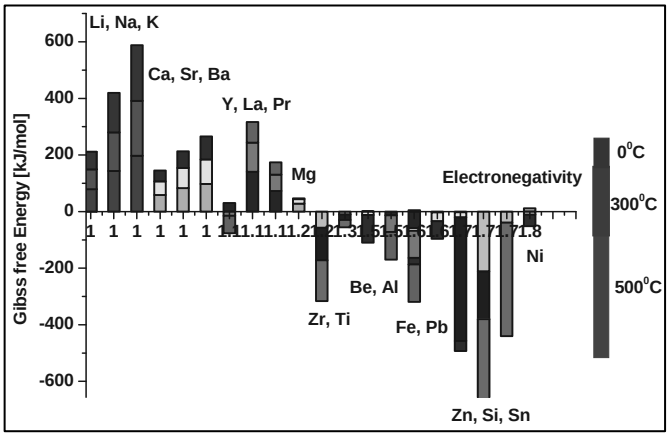


Fig. 1. b. Gibbs free energy for the synthesis of some oxides by hydrothermal crystallization.

3. EXPERIMENTAL

The precursor solutions were prepared by the dissolution of pure soluble salts (calcium nitrate $Ca(NO_3)_2 \times 4H_2O$, diammonium phosphate $NH_4H_2PO_4$ zirconium tetrachloride $ZrCl_4$, yttrium nitrate $Y(NO_3)_3$ and sodium maleate-vinyl acetate copolymer) under vigorous stirring into distilled water in the appropriate amount corresponding to the programmed ratio. The pH of the solution was adjusted to the desired value by mixing it with ammonium hydroxide solution. The composite powders were then obtained by hydrothermal treatment of the suspension in a 2L Teflon autoclave (CORTEST, USA) for two hours in the temperature range of 100-250^{0}C. The precipitates were separated by filtering, washed with distilled water to remove the soluble chlorides or nitrates and with ethanol to reduce agglomeration and finally dried for several hours in air at 110^{0}C. Phase composition of powders was investigated by X-Ray diffraction (XRD). The phase composition has been calculated according to Bragg-Brentano method using CuK_α radiation. Specific surface area has been measured according to BET method (Gemini 2360 Analyzer). The picnometric densities (AccuPyc 1330 device) were also measured using the inert gas adsorption method. Microstructural characterization of powders was made using FT-IR analysis (JASCO FT/IR-620 spectrometer and the Scanning Electron Microscopy (SEM) method (LEO 1530 microscope).

4. RESULTS AND DISCUSSIONS

4.1. Synthesis of Yttria-doped Zirconia Nanopowders

Yttria-doped zirconia materials with tetragonal symmetry are known to increase the mechanical properties of many ceramic matrix composites including HAP due to their intrinsic high toughness. A comparison of mechanical properties of alumina and YTZP mechanical characteristics are presented in Table 1. The synthesis of YTZP powders was consequently first addressed.

Table 1. Some characteristics of 96% Al_2O_3 and YTZP (tetragonal ZrO_2)

	Al_2O_3 (96%)	Y-TZP
Young's modulus E (GPa)	250-330	200
Bending strength (MPa)	300	800-1200
Fracture toughness (MPa.m$^{1/2}$)	3-3.5	6-8
Poisson's ratio	0.22	0.28
Hardness (VH) (GPa)	1600	1250

The calculated Pourbaix diagram of the system at normal temperature (Fig. 2) shows that complete precipitation of both ZrO_2 and Y_2O_3 takes place in basic pH (above 7). By increasing the temperature up to 200^{0}C and corresponding vapour pressure of the solution, the binary system is stable in a larger pH domain (starting from 4.5). The experimental verification of the chemical composition shows an increase of the yttria molar ratio with increasing pH and temperature, confirming the thermodynamic predictions. Consequently, an increase of the tetragonal phase has been observed in the XRD pattern presented in Figure 3 [19].

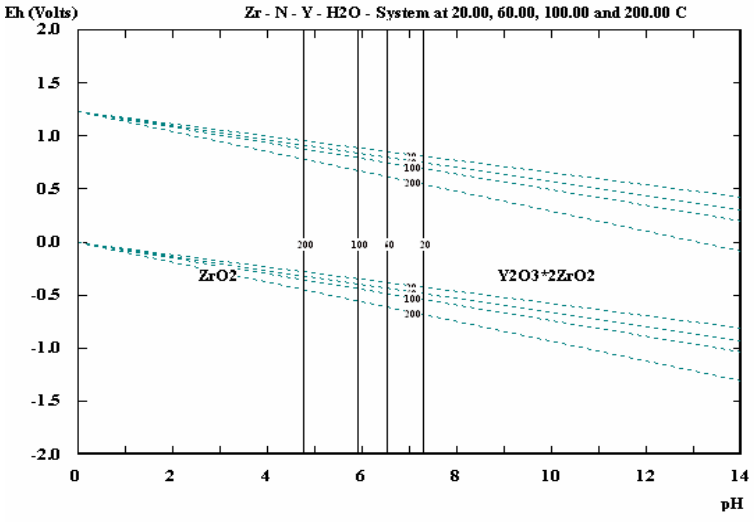


Fig. 2. Potential-pH diagram of the system Zr-Y_3-H_2O *vs.* hydrothermal temperature.

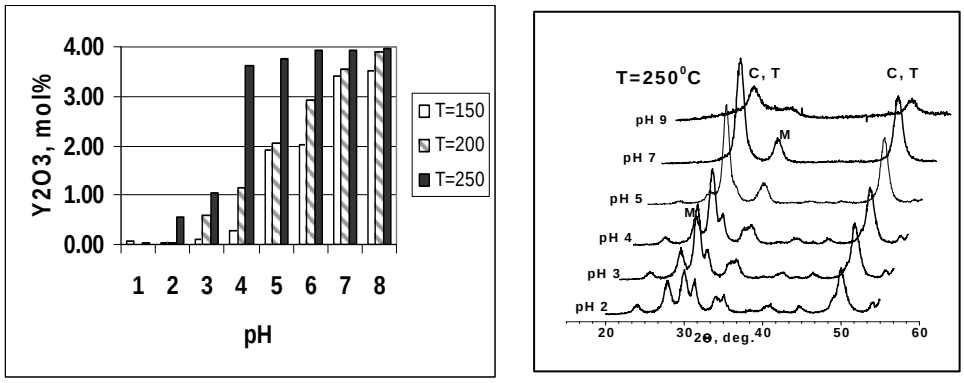


Fig. 3. Yttria molar content (left) and corresponding XRD pattern of YTZP powders obtained at 250^0C (right) *vs.* hydrothermal temperature and pH [19].

4.2. In situ hydrothermal synthesis of HAP-YTZP and HAP-polymer nanopowders

Sodium maleate-vinyl acetate copolymer (NaM-VA) was used in order to control the crystallization process of HAP composites. The selection was based on the previous experiments showing its good hydrophilic properties. Thermodynamic predictions were made using the same soft. Due to the fact that the existing database does not contain any information regarding thermodynamic values for polymeric compounds, an approximation has been made introducing the values of the monomers.

The main possible reactions in the proposed systems that were considered are:

Hydroxyapatite formation:

$$5Ca(NO_3)_2{\times}4H_2O + 3NH_4H_2PO_4 + 7NH_4OH = Ca_5(PO_4)_3OH + 10NH_4NO_3 + 26H_2O \quad (1)$$

Vinyl acetate units decomposition into acetic acid:

$$C_4H_6O_2(VACg) + NH_4OH = C_2H_5NO + C_2H_4O_2(ACAg) + H_2(g) \quad (2)$$

Formation of Y_2O_3 doped ZrO_2:

$$2Zr(+4a) + 2Y(+3a) + 14NH4OH = Y_2O_3{*}2ZrO_2 + 14NH_4(+a) + 7H_2O \quad (3)$$

HAP formation in the presence of organic monomer:

$$5Ca(NO_3)_2{\times}4H_2O + 3NH_4H_2PO_4 + C_4H_6O_2\ (VACg) + 8NH_4OH = Ca_5(PO_4)_3OH + C_2H_5NO + C_2H_4O_2(ACAg) + 10NH_4NO_3 + 26H_2O{+}H_2(g) \quad (4)$$

HAP-YTZP formation:

$$5\ Ca(NO_3)_2{*}4H_2O + 2Zr(+4a) + 2Y(+3a) + 3NH_4{*}H_2PO_4 + 21NH_4OH = Ca_5(PO_4)_3OH + Y_2O_3{*}2ZrO_2 + 14NH_4(+a) + 10NH_4NO_3 + 33H_2O \quad (5)$$

The calculated Gibbs energies of the reactions assumed before are presented in Table 2. It may be observed that reaction (2) is very close to the equilibrium while polymer addition in the system slightly increases the standard Gibbs thermodynamic potential of the HAP formation reactions in absolute value. *In situ* formation of HAP-YTZP nanopowders (reaction 5) is thermodynamically favoured.

Gibbs energy of reaction 5 is considerably higher than that of Y_2O_3 doped ZrO_2 formation (reaction 3) or HAP synthesis (reaction 1). From the thermodynamic point of view, solid solution of Y_2O_3*$2ZrO_2$ is formed in a first stage and it could be considered as a nucleation agent for HAP. Secondly, HAP is produced and YTZP substitutes Ca^{2+} ions in the crystalline lattice.

Table 2. Calculated Gibbs free energies

Temp., ^{0}C	Δ^rG_1, kJ	Δ^rG_2, kJ	Δ^rG_3, kJ	Δ^rG_4, kJ	Δ^rG_5, kJ
20	-591.563	-109.546	-1128.148	-701.108	-1719.710
60	-603.718	-110.784	-1181.572	-714.501	-1785.290
100	-620.893	-111.671	-1233.413	-732.564	-1854.306
200	-716.844	-112.531	-1362.149	-829.375	-2078.993

$\mathbf{\Delta^rG_1}$ = Gibbs energy of reaction 1 (HAP formation)
$\mathbf{\Delta^rG_2}$ = Gibbs energy of reaction 2 (vinyl acetate decomposition into acetic acid)
$\mathbf{\Delta^rG_3}$ = Gibbs energy of reaction 3 (formation of Y_2O_3 doped ZrO_2)
$\mathbf{\Delta^rG_4}$ = Gibbs energy of reaction 4 (HAP formation in the presence of organic monomer)
$\mathbf{\Delta^rG_5}$ = Gibbs energy of reaction 5 (HAP-YTZP formation)

Thermodynamic values of vinyl acetate decomposition to acetic acid (reaction 2) are almost constant with temperature while a slight increase is observed for the others (figure 4). Equilibrium compositions of inorganic phases are reached at a higher temperature (200-300^{0}C).

Comparing Gibbs energies for the reactions (1) and (4) it can be observed that a small amount of vinyl acetate units strongly increases the domain stability and the equilibrium constant in the favour of HAP precipitation. A similar behaviour is expected in real conditions in the presence of the copolymer.

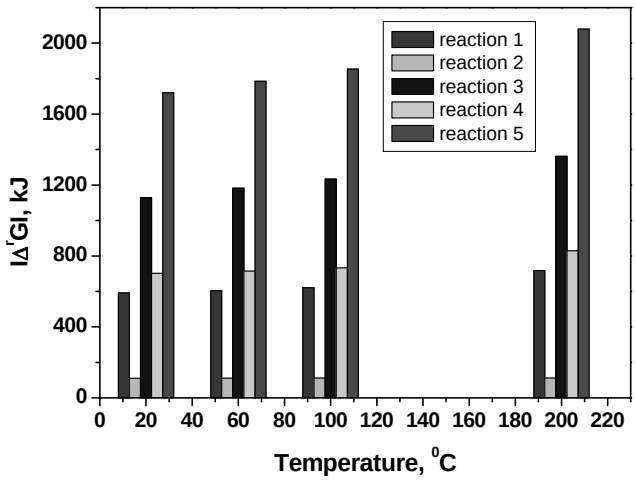


Fig. 4. Calculated Gibbs free energies in absolute value at different temperatures.

Figure 5 shows the influence of yttria-doped zirconia addition on HAP formation. ZrO_2 phase may appear at low pH and composite powder is stable above pH = 5. These predicted thermodynamic data were corroborated with the experimental ones. The influence of the NaM-VA/HAP ratio on the precipitation behaviour was followed by turbidimetric titration, presented elsewhere [20].

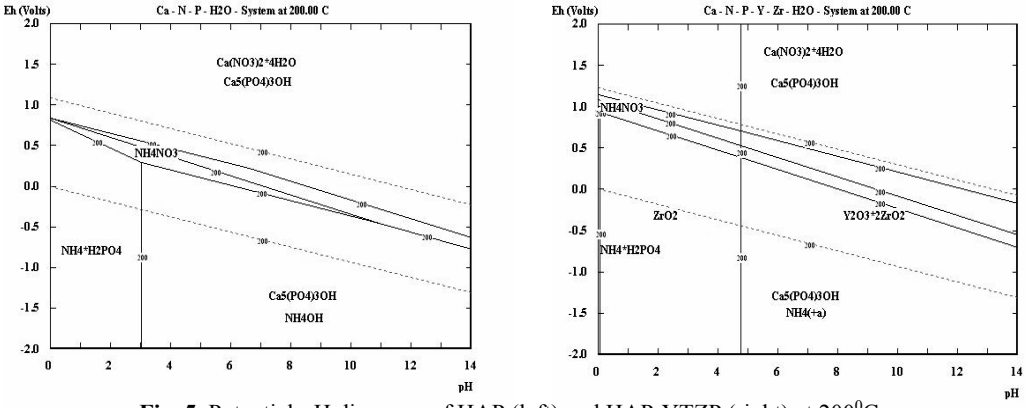


Fig. 5. Potential-pH diagrams of HAP (left) and HAP-YTZP (right) at 200^0C.

The nature of HAP/MAc-VA interactions was evidenced using the FT-IR analysis (Fig. 6). Based on the assignment of the observed bands (Table 3) it is suggested that physical interactions between pure or YTZP-doped HAP inorganic matter and polymeric MAc-VA matter take place *in situ* during the hydrothermal reaction [20].

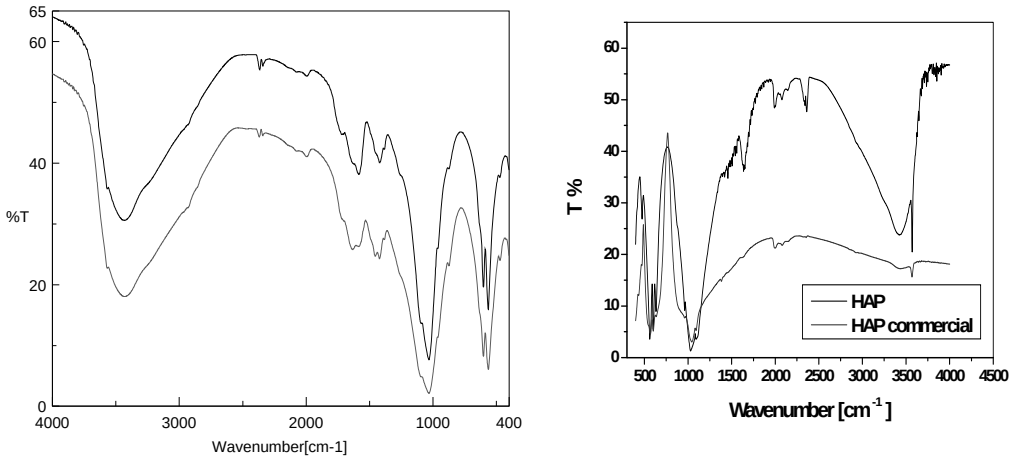


Fig. 6. FT-IR spectra [20] of HAP/NaM-VA (5% and 10%) powders (left) compared to pure commercial and hydrothermal HAP powders (right).

Table 3. FT-IR spectra of hydrothermal HAP, Commercial HAP and HAP/NaM-VA powders

Wavenumber [cm^{-1}]				
HAP/NaM-VA 5%	HAP/NaM-VA 10%	Hydrothermal HAP	Commercial HAP	Assignment
3572	3572	3570	3565	OH stretching
3443	3443	3450	3424	OH streching
1723	1723	-	-	Ester carbonyl stretching
1577	1577	-	-	C=O or C=O-Ca
-	-	-	-	CO_2 trace
1103	1103	-	1090	HPO_4 (1135) and asymmetric HAP (1090)
1033	1033	1030	1038	P=O
873	873	-	-	PO_4^{3-} substitution with CO_3^{2-}

The evolution of crystalline phases of composite HAP-ZrO_2 and HAP/NaM-VA powders (Fig. 7) evidenced that crystalline powders containing apatite (A) as single phase were obtained directly from the hydrothermal process. As thermodynamic calculation predicted, both pure ZrO_2 and YTZP substituted the Ca (II) ions in the crystalline lattice. Increasing polymer content had a very slight influence on the crystallization degree of the apatite phase.

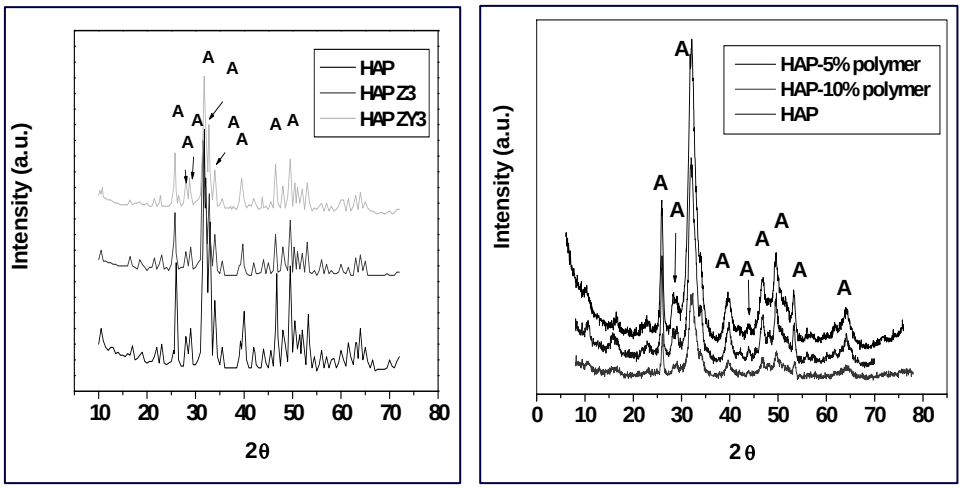
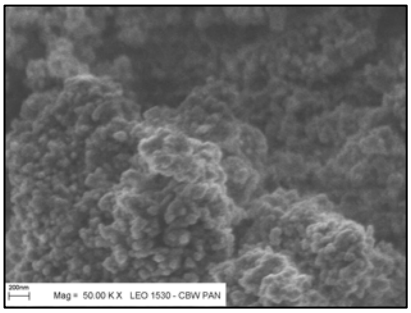
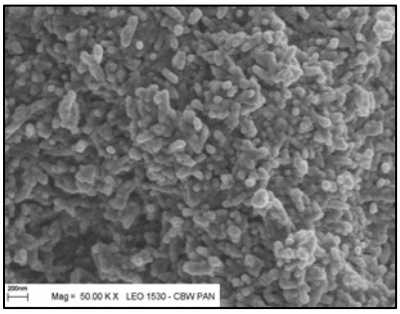


Fig. 7. XRD pattern of HAP - ZrO_2 (left) and HAP/NaM-VA (right) hydrothermal powders [20].

Microstructural characterization of composite powders using SEM is presented in Figure 8. It may be observed that the microstructure of powders is strongly

influenced by the presence of the NaM-VA polymer. Pure and YTZP-doped HAP powders consist of small agglomerated powders while NaM-VA powders present prismatic non-agglomerated crystals.

a) 



b)

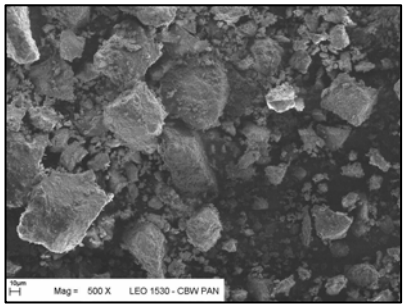
c) 

Fig. 8. SEM of pure HAP (a), HAP doped with 10% YTZP (b) and HAP 10% NaM-VA.

The morphologic and grain size analysis based on SEM micrographs were corroborated to some physical characteristics of the powders presented in Table 4. It is observed that NaM-VA/HAP composite powders obtained *in situ* by hydrothermal reactions have a larger surface area compared to both pure and YTZP-doped HAP powders [20].

As can be seen in Figure 8.c organic-inorganic composite powders are porous and this could be an explanation of measured S_{BET} values presented in Table 4. On the other side, calculated grain sizes for the same powders based on relation (6) are smaller and they are sustained by SEM micrographs.

$$S = \frac{6}{\rho \cdot d} \tag{6}$$

where: S is specific surface area (m^2), ρ is picnometric density (g/cm^3) and d is grain size (nm). Taking into account that relation (6) refers to spherical particles it could be presumed that the grain size values correspond to HAP particles in composite powder. Comparing the grain sizes of pure HAP, YTZP-doped HAP and NaM-VA/HAP powders, it is clear that maleic acid copolymer represents a better crystal growth regulator than Y_2O_3-doped ZrO_2.

Table 4. Physical characteristics of HAP powders obtained by hydrothermal route

Characteristic	HAP	HAP-YTZP	HAP/5% NaM -VA	HAP/10% NaM -VA
S_{BET}, m^2/g	63.66	119.67	166.30	156.81
Density, g/cm^3	3.02	3.09	2.76	2.73
Grain size, nm	31.20	16.19	14.01	13.08

5. CONCLUSIONS

During hydrothermal *in situ* treatment of HAP-maleic acid copolymer mixtures, an ionically crosslinked polymer-calcium phosphate network is formed. Maleic acid copolymers seem to be active crystal growth regulators for calcium phosphate, leading to powders with nanometric crystallite size, as calculated from the BET specific area. Density values were very close to the theoretical ones for HAP (2.76 g/cm^3 for the composite and 3.02 g/cm^3 for pure HAP). Hydroxyapatite BET diameter is in the nanometre range in all cases. Nanocrystalline HAP is expected to present high chemical and biological activity and high sorption capacity.

The results will be used in the near future to validate the biocompatibility of the system compared to various types of polymers for the hydrothermal synthesis of HAP-polymer nanocomposites as well as for obtaining HAP-polymer films using the electrodeposition method.

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Composite Biomaterials with Glass Nanofillers and Biocompatible Polymers with Applications in Dentistry

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Abstract. The biomaterial composites based on polymers and inorganic fillers appeared, for the first time, four decades ago and due to their properties: physiognomic aspect, good adhesion to hard dental tissues, lack of toxicity, high mechanical resistance, they have been imposed in the modern dental practice finding in the latest years applications in therapy, orthodontion, prothetics and dental prophylaxis. The changes that were brought in the making of composite resins regarding the initiation system, the obtaining of some new filler and also of some monomeric systems that confer higher properties to the composites, were reflected in the composition of the materials presently existing on the market. It can be affirmed that, along the years, a permanent interest was shown for the development of these materials. In this study, the *physico-chemical* and *mechanical characteristics* of four composites, formulated on the basis of dimethacrylic monomers and mixtures of fine fillers of glasses with Sr, Zr, Zn, La and colloidal silica, in proportions aiming the adjustment of different properties of the composite system, are determined.

1. INTRODUCTION

The existing studies [1, 3] are focused on finding some methods to improve the properties of the composites by changing the chemical nature and the size of particles, the monomers, the ratio between the base monomer and the dilution monomers, initiators, etc. Through these changes we wanted to improve the optical, physiognomic, mechanical properties, even though the results were not always the expected ones, leading to the improvement of some properties and to the prejudice of others.

Many dental materials which are commercialised at this time include only a few particles which have the size larger than 3–5 μm, the medium size of the particles being between 0.6 and 1.0 μm. Some of these composites have a uniform distribution of the particles and others have it in a larger area, which enhances consistency and plasticity characteristics. Nowadays, there are not any definitive studies to confirm the superiority of these fillers. Some *in vitro* studies were focused on identifying and evaluating the elements that are lost from the old dental composites and also if the radioopaque element glasses which contain Zr, Zn, La and Sr are more soluble than quartz or amorphous SiO_2 in aqueous solutions [4-6].

In this field, the literature mentions a large variety of values for the mechanical properties of dental composites used as restoratives for anterior teeth. Because of the different methods of obtaining and testing dental composites, there are contradictions concerning the reported values. The compressive strengths for conventional and microfilled composites reported in literature range between 140 and 310 MPa and the tensile strength values range between 25.5 and 53.5 Mpa [7, 8].

The purpose of this study is to evidence the coupling agent that was disposed to the synthesized glasses and to determine the water absorption, water solubility, compression diametral tensile strength and Vickers microhardness of the components of four composite biomaterials used for the restoration of the dental crowns morphology, realized in our laboratory.

2. EXPERIMENTAL

A. The synthesis of the Composite

1. The organic phase

A very important element of the organic phase of the composite materials, a mixture of three oligomers Bis-GMA_n (n = 1, 2 and 3), containing 83% Bis-GMA_1 monomer: 2, 2-bis-[4-(2-hydroxy-3-methacryloyloxypropoxy)-phenyl]-propane (the "real" Bis-GMA), 16 % Bis-GMA_2 (dimer) and 1 % Bis-GMA_3 (trimer) was used. Bis-GMA_n was diluted with triethyleneglycol dimethacrylate (TEGDMA). Bis-GMA is a large aromatic dimethacrylic monomer, which formes a crosslinked hard polymer, with greater chemical resistance, good marginal adoption because of a small polymerization contraction, good 3D stability and a lower toxicity degree due to its low volatility and also a lower penetration of the dental tissues.

2. The inorganic phase

The experiments pursued the goal of obtaining some vitrous masses that include a series of oxides with certain properties corresponding to the composites or the incorporation of some elements with a high atomic number in glass that constitutes a part or the total of the filler mixture. Oxide composition, temperature, melting time and surface area for synthesized glasses are shown in Table 1.

Table 1. Chemical composition of the filler (wt. %)

Glass	SiO_2	B_2O_3	Al_2O_3	SrO	ZrO_2	ZnO	La_2O_3	P_2O_5	NaF	AlF_3	CaF_2
G1	40	10	5	29	8	-	-	-	-	4	4
G2	35	-	10	-	-	-	20	10	5	5	15
G3	45	13	5	35	-	-	2	-	-	-	-
G4	45	12	5	-	-	30	-	-	-	4	4

	G_1	**G_2**	**G_3**	**G_4**
Melting Temp [°C]	1380	1150	1300	1450
Melting time [h]	4	3	4	5
Surface area [m^2/g]	10	12	14	11
Density [g/cm^3]	2,8	2,6	2,9	2,7

The chemical bond between the organic and inorganic phases was provided by silanation of nanofillers with 3-methacryloyloxypropyl-1-trimethoxy-silane (silane A-174). Silanation was made from an acidulated ethanol-water solution of the silane A-174. The ratio of ethanol to water was 90/10. The solution was acidulated at pH 3.5-4 using acetic acid to provide the hydrolysis of methoxy groups of the silane to silanol groups. The amount of silane coupling agent (X) used for the nanofiller treatment was determined using the relation proposed by Arkles:

$$X = A \times f/\omega$$

where X is the amount of coupling agent in grams needed to obtain minimum uniform coverage, f is the amount of nanofiller (g), A is the surface area of the nanofiller (m^2/g) and ω is the wetting surface of silane ($m^2/g.$, ω is 314 m^2/g for silane A 174).

The quantity of active double bonds attached to the nanofiller particle surfaces was determined by FTIR spectroscopy of the silane-coupling agent deposed on the synthesized powders.

3. The preparation of composite material

The use of light-curing composite material in therapeutic dentistry was formulated in a monocomponent system based on the mixture of monomers formed of Bis-GMA_{0-2} and TEGDMA (triethylenglycol dimethacrylate) and a mixture of silanized hybrid mixtures, colloidal silica (surface area 180 m^2/g) and strontium, zinc, zirconium and lantan glasses. The composite paste was obtained by the dispersion of the hybrid filler in the monomer mixture, where the photosensitizer, camphorquinone (CQ) was solved, in a concentration of 0,5% related to the

monomer quantity, and the photoreductor, dimethylaminoethylmethacrylate (DMAEM), in a concentration of 1% related to the monomers, the polymerization inhibitor BHT (tert-butyl hydroxytoluene) was added in an amount of 0,1%. Five light-curing composites based on hybrid fillers were synthesized. Their chemical composition is presented in Table 2.

Table 2. The chemical composition of a light-curing composite

Composite code	Composition (wt.%)			Observations
	Monomer mixture	Glass	Colloidal silica	
HC(G_2)	20	G_2 65	15	Good photo-polymerization at 2mm/40sec
HC(G_3)	20	G_3 65	15	″
HC(G_1)	20	G_1 70	10	″
HC(G_4)	20	G_4 70	10	″

4. Photochemical initiation system

Allen *et al.* [9] propose a graph to describe the effect of the reducing agent in the photochemically initiated polymerization of the acrylic monomers. The efficiency and the rate of the photoinitiation is a function of the acrylic (methacrylic) monomer ability to react with triplet-excited state of the benzoquinone (Ist way) as shown in Figure 1.

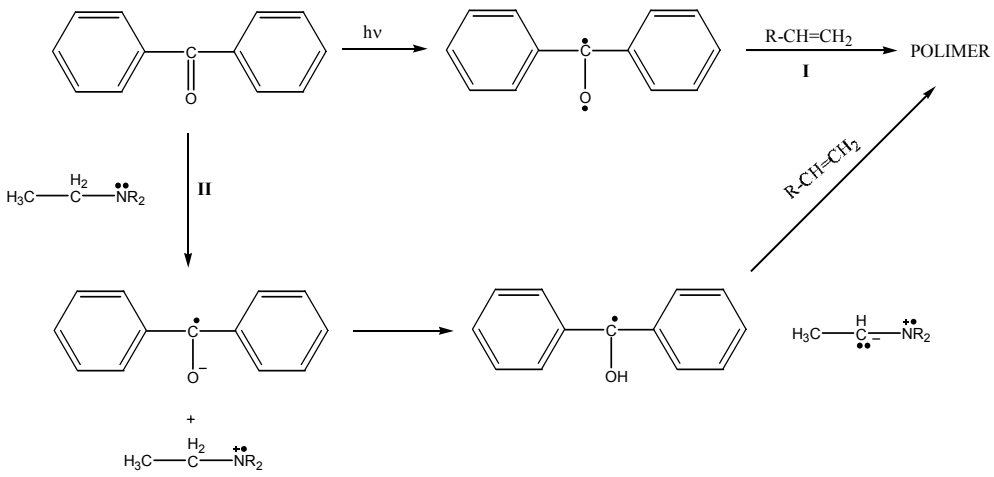


Fig. 1. Visible light photochemical initiation mechanism of acrylic monomers.

But if the excited state of the benzoquinone reacts preferably with the amine reductive reagent (IInd way), the capture of the monomer is much more efficient

because of the larger rate of the electronic transfer, and the photopolymerization rate has a significant growth. By measuring the rate of photopolymerisation with visible light of an unsaturated ester, N,N-dimethylamino-ethyl-methacrylate, with 2% camphorquinone, with and without 4% tertiary amine, Allen *et al.* [9] found that the presence of the amine reduces the gel time from more than 20 minutes to 20 seconds [10-11].

B. The characterization of the composites

1. Determination of mechanical properties

After preparing, the light-curing paste composites were hardened in the shape of standard bars, in Teflon moulds with a special form, by exposure to the light flux emitted by a CURING LIGHT XL 3000 lamp, in the visible domain 400-500 nm, for 180 sec. After three minutes of light exposure, the obtained bars were introduced in a water bath at 37°C where they were kept for seven days. Cylindrical bars were obtained in Teflon moulds, for *compressive strength* (CS) determinations (4 mm diameter and 6 mm length) and for *diametral tensile strength* (DTS), *Vickers Hardness Number* (VHN) and microstructure determinations (6 mm diameter, 3 mm length).

The compressive strength was calculated from the relation:

$$CS = 9.81 \times F / 0.785 \times d^2$$

where F is the load at fracture and d the diameter of cylinder.

The diametral tensile strength was determined from the relation:

$$DTS = 2F / \pi dt$$

where d is the diameter and t the thickness of the cylinder, respectively.

The tests for the mechanical properties (CS, DTS) were made on a universal mechanic testing instrument, INSTRONE brand of the VEB Thürignger Industrie Werk Rauenstein Company.

For the determination of Vickers micro-hardness, a Carl Zeiss Jena instrument equipped with a Nepophot 21 microscope that permits the measurements of the diagonal of the spot with a precision of 0.5 % was used. The Vickers micro-hardness HV is calculated with the expression given below, for F measured in [kgf]:

$$HV \quad \frac{2F \sin \frac{136^o}{2}}{d^2} \quad 1.854 \frac{F}{d^2}$$

2. Determination of water sorption

Water sorption was measured on disks of material of 20 ± 0.1 mm in diameter and 1.0 ± 0.05 mm in thickness, stored in distilled water at 37°C for

15 min, dried and placed in a desiccator over freshly dried silica gel. After constant weight was achieved, the samples were placed in distilled water at 37°C for seven days, after which they were removed, air dried for 15 seconds and weighed within one minute from removal. Water sorption is calculated as the weight of water sorbed divided by the total area of the sample and is reported as mg/cm:

$$\textit{sorption}\ (\mathrm{mg/cm^2}) = [\textit{weight after immersion}\ (\mathrm{mg}) - \textit{conditioned weight}\ (\mathrm{mg})]/\ \textit{surface area}\ (\mathrm{cm^2})$$

3. Solubility in water

Solubility represents the weight loss of some bars of composite caused by the disolving of the material in water, saliva, or other liquids. The test is made by the immersion of the bars (the dimension of the disks is the same as for the water absorbtion) in distilled water at the temperature of 37°C for 7 days. The solubilisation takes place through: the diffusion of the solvent in the polymeric matrix; the solving; the dispersion of the macromolecules in the solvent. A greater solubility may represent a large deficiency of the restauration materials.

4. The determination of the silane-coupling agent by FTIR spectroscopy

The IR spectra were registered on a FTIR Spectrophotometer JASCO–610. Information on the silane-coupling agent is obtained from the domain analysis 400 – 2000 $\mathrm{cm^{-1}}$ in KBr pellets. The silanation fillers were washed initially with acetone to remove the free absorbed silane, and the fraction that remains after this wash represents the chemosorbed silane.

3. RESULTS AND DISCUSSIONS

Starting from the necessity of obtaining materials with properties as good as possible: appropriate esthetic appearance; better physico-chemical properties; superior mechanical properties, *compressive strength and diametral tensile strength* are important parameters in the comparison of dental restorative composites. High compressive and tensile strengths are particularly important in the process of mastication, where the greatest loads are experienced by the tooth structure. After the tests made on the composites obtained in our laboratory, it can be seen that the mechanical properties depend on the nature and the concentration of the inorganic filler, based on glasses that include different oxides of elements with a big atomic weight: Sr, Zn, La.

In Fig. 2 the values of the mechanical properties of composites in the domain 250 – 281 MPa for the *compression strength* and 27 – 46,5 MPa for the *diametral tensile strength* are presented. The HC(G_2) composites which have filler with La glasses and colloidal silica have lower values of the mechanical properties. The HC(G_1) composite, which has the hybrid filler with 70% G_1 and 10% colloidal

silica, has the highest value of compressive strength (281 MPa) and diametral tensile strength (46.5 MPa). The analysis of the values regarding the compressive and diametral tensile strength of the four composites shows the fact that they are within the value domain recommended by the International Standards (ADA) for this kind of dental composites.

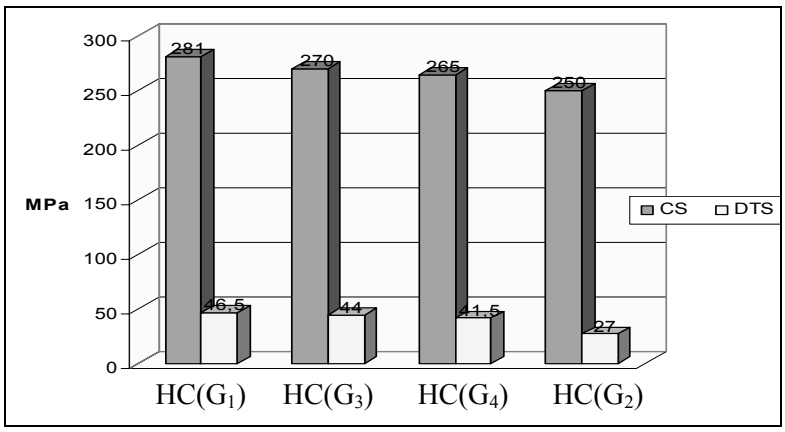


Fig. 2. Values of compressive strength and diametral tensile strength of the composites.

The Vickers micro-hardness (Fig. 3) values alternate in the range of 62-75 kgf/mm^2; the lowest value is recorded for the HC(G_2) composite and the highest value for the HC(G_1) composite. The small differences between the values of the four composites show that they are homogeneous and the polymerization has been completed. This parameter reflects the rigidity and the capacity of the materials to resist the mechanical stress, which ended with the deformation or breaking of the materials, offering, in this way, data upon the dimensional stability and on the rupture try-out of the adhesive restorations.

In the presence of water, the silicofunctional groups (OR) from the silane molecule can hydrolyze, forming hydroxy groups (OH) which assure the bond with the surface of the particles of fillers. The functional groups from another side of the silane molecule assure the bond with the unsaturated chains of the monomers. It is known that the inorganic particles with silicatic network have active OH groups dispersed on their surface. The frequency and the active power of these groups is a function of the structure of the inorganic mass, and thus of the surface. These groups are able to react with the functional silanoic groups resulted after the hydrolysis of the silanes through condensation reactions with water elimination, with the formation of some very strong siloxanic bonds, which are well included in the silicatic network of the inorganic phase.

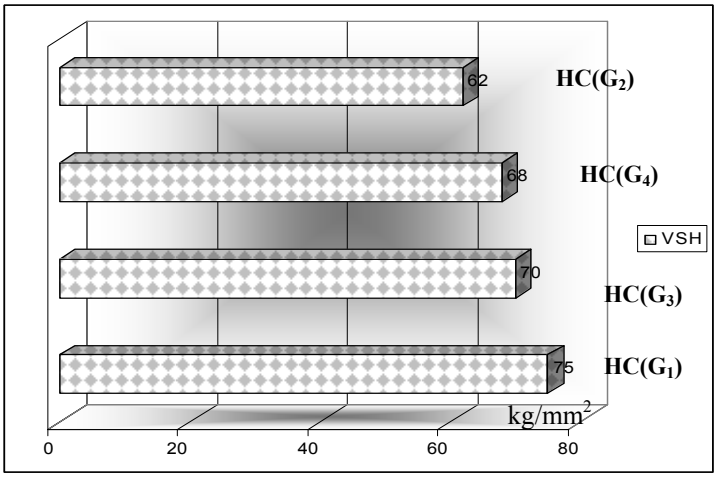


Fig. 3. Values of Vickers micro-hardness.

The interfacial bond between the silane A-174 and the surface of the synthesized fillers was qualitatively evaluated through FTIR spectroscopy. In Fig. 4 the IR spectrum of the silane A-174 is presented. Bands that show the presence of the organic rest of the methacrylic group can be observed. The bands at 1453 cm^{-1} and 1638 cm^{-1} correspond to the bond ν(C=C) from the methacrylic group. The intense absorption band at 1720 cm^{-1} is attributed to the bond ν(C=O) from the methacrylic group that enters the structure of the silane. The bands at 2800-3000 cm^{-1} are caused by the asymmetrical and symmetrical vibrations of the CH_3 and CH_2 groups.

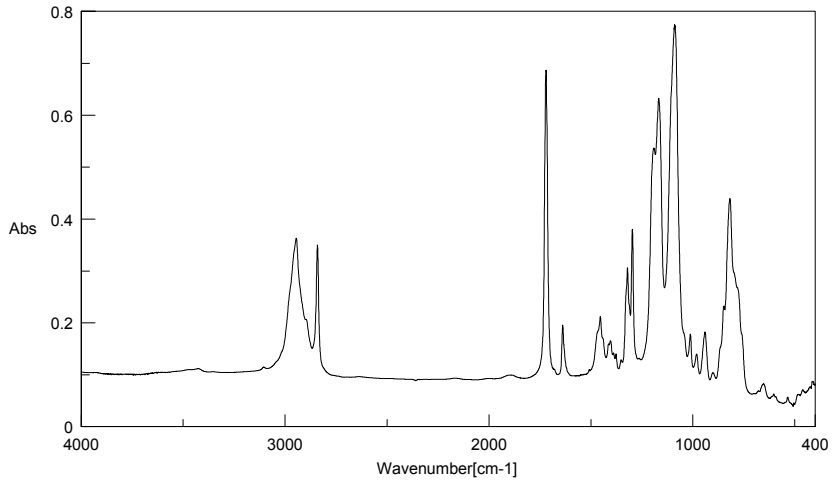


Fig. 4. IR spectrum of silane A 174.

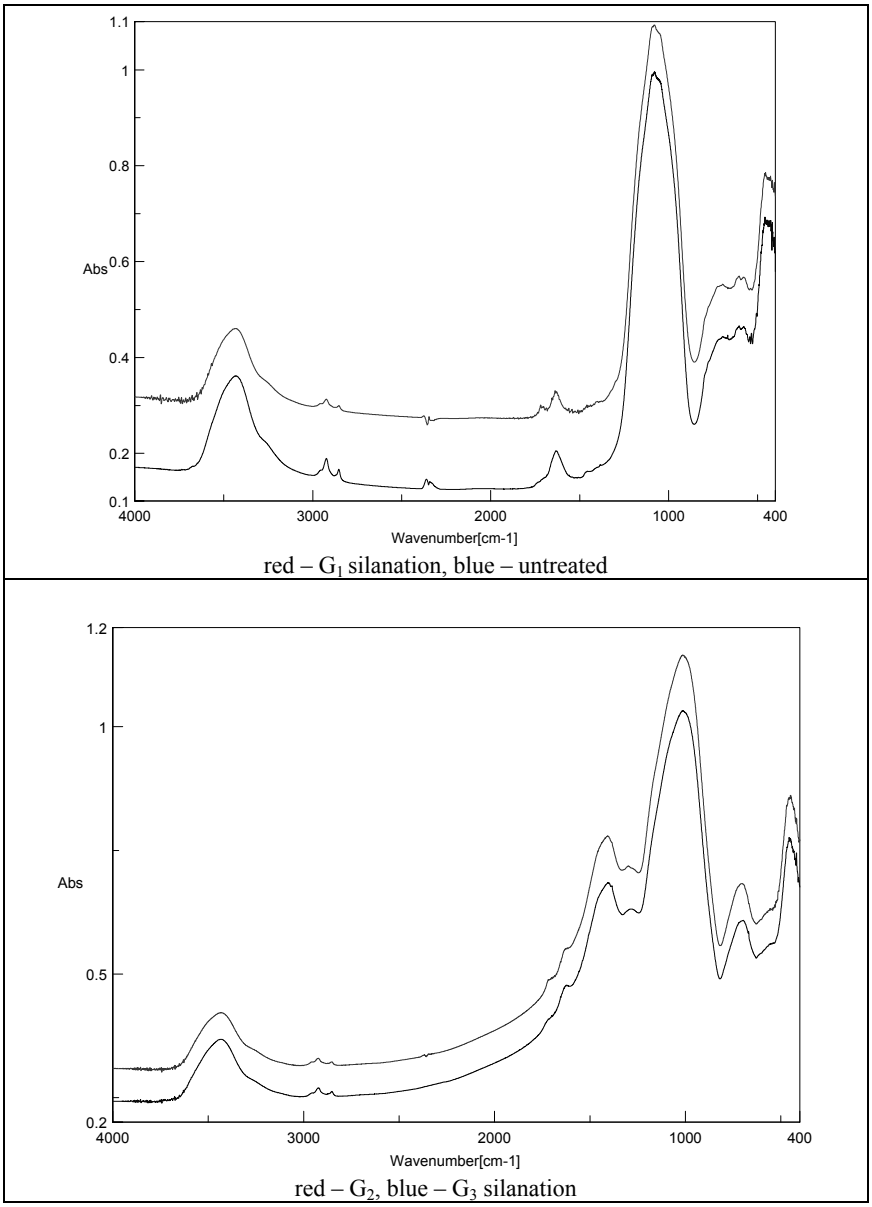
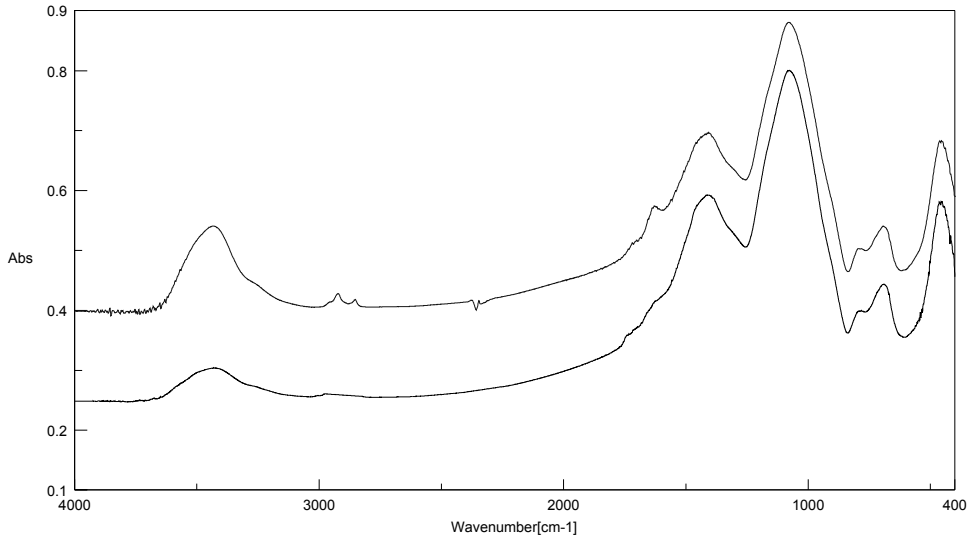


Fig. 5. The IR spectra of G_1, G_2, G_3 powders.

Important modifications in the 1000-1200 cm^{-1} range show the formation of some new types of Si–O bonds after the filler silanation. The growth in intensity of the δ(Si–O–Si) band at 470 cm^{-1} from the unsilanation powder shows a growth of the number of units Si_2O_5 and SiO_3 chains with oxygen that is not in the bridge. In

Figs. 5 and 6 the IR spectra show the presence of the silane on the probes for the vitreous filler G_1, G_2, G_3 and G_4 by very weak bands in the 2800-3000 cm^{-1} range. Absorption drops are present because of the ν(C-H) and ν(C=C) from A-174 silane.



red – G_4 silanation, blue – unsilanation

Fig. 6. IR spectra of the G_4 powder.

The best number of chemical bonds at the filler-matrix interface which are necessary to confer a durable resistance to the composition is not yet known. What is known is that, at low speeds of spreading the fissures, the determining factor is the strength and stability of the bond at the filler/polymer interface.

The insolubility of all the components of a composite resin is a basic condition to assure the full clinical success. The inorganic fillers are practically insoluble, but through the softening and the solving of the surface resin, they remain exposed and are easily removed by the outer agents. The solubility is increasing the marginal separation and the seepage, favoring chromatic modifications, due to the liquids that enter the marginal separation area. The composites which contain a larger quantity of compounds with low molecular mass, present a better solubility. The solubility of the formulated composite materials is of 0.35–0.5 mg/cm^2, value which corresponds to the internationally admitted limits of 0.10–0.68 mg/cm^2.

The value of water sorption by the composite depends more on the quantity of filler, on the treatment of the filler the coupling agent, and not least on the chemical nature of the filler. The value of water absorption for every experimental composite was considered as the average value of the five determinations and was graphically represented in Figure 7.

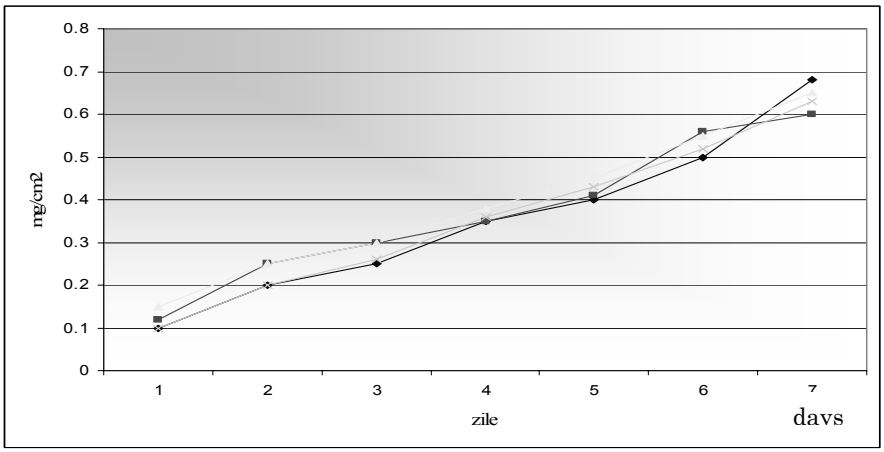


Fig. 7. Water sorption of the tested composite materials.

From the data obtained for the absorbtion of water it was observed indirectly that the organic matrix/filler interfacial bond is not affected, the values of water absorbtion for the presented composites were situated between 0.6–0.69 mg/cm^2. The value of 0.6 mg/mm^2 after 7 days at 37°C for the composite HC(G_1) is positioned in the accepted limits (maximum 0.8). It can be noticed that the hybrid composites we formulated have low water absorbtion (0.6–0.69 mg/mm^2), so that they will have a better stability in time.

4. CONCLUSION

The results of this study evidence the importance of the relationship between composition, filler/polymer bond and mechanical properties. The values of compressive strength, diametral tensile strength, and Vickers micro-hardness were determined. The highest ones have been registered for the photo-polymerizable composite HC(G_3) that has as filler glass with Sr+Zr and colloidal silica. The four light-curing composites in mono-paste system formed from an organic matrix that contains dimethacrylic monomers with a high molecular weight and an inorganic powder have high values of the mechanical properties.

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Heterocyclic Polymers for Micro and Nanotechnologies

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Abstract. The progress made in fluorinated heterocyclic polymers in which the heterocycle is 1,3,4-oxadiazole, imide, pyridazine, benzoxazole or phenyl-substituted quinoxaline is presented. These polymers have been synthesized by the polycondensatioin sisteme de surfactanti siliconicin reaction of various diacid chlorides containing hexafluoroisopropylidene groups with aromatic/heteroaromatic diamines, dihydrazides or bis(*o*-hydroxy-amine)s. They can be easily processed into thin films having the thickness in the micrometer range and very thin films and coatings with the thickness in the nanometer range, which exhibit high thermal stability, good electroinsulating and mechanical properties and some of them are photoluminescent in the blue domain. Such properties make the present polymers very attractive for various high performance applications, such as micro- and nanotechnologies, where the materials are required to maintain their specific characteristics while in service at a high temperature.

In the past two or three decades, immense changes in science and technology have placed increasing stringent requirements on polymeric materials. Extensive studies have been and are currently being conducted in order to find new macromolecular structures that are more useful for many new applications and maintain their performance at high temperatures. High performance polymers are those that possess a combination of ideal physical and mechanical properties and maintain these properties at extreme temperatures. The heterocyclic polymers were introduced at the beginning of the 1960s to meet new demands for heat-resistant plastics for space and military applications [1]. Now, these specialty polymers find many other applications in microelectronics, computer technologies and communication technologies, as dielectrics used in the production of integrated circuits, films, coatings and resins for assembly and packaging in microelectronics, membranes for gas separations, adhesives, matrices for laminates, and more recently as light- emitting materials in opto-electronic devices especially for display, printing, and data storage. Wholly aromatic polymers such as polyamides,

polyimides, polyoxadiazoles, polybenzimidazoles have already been noted for their high temperature resistance and excellent physico-mechanical properties. They are also known as difficultly processable materials due to their insolubility in organic solvents and infusibility or lack of glass transition before decomposition. Because such problems restrict the further applications of aromatic polymers, considerable effort has been made to improve their processing properties by structural modifications. Our approach to improving the solubility and lowering the glass transition temperature is the introduction of flexible bridges such as hexafluoroisopropylidene (6F) in the main chain. At the same time, such modifications of polymer structures are expected to provide a better balance of physico-mechanical characteristics, as well as new properties [2].

Thus, we have synthesized new heterocyclic polymers having high thermal stability, good electroinsulating and mechanical properties and some of them exhibiting photoluminescence ability in the blue range, together with easy processability, particularly into thin films (micrometer range) and very thin films and coatings (nanometer range) of high quality. The main procedure was the polycondensation reaction of aromatic/heterocyclic diamines, aromatic dihydrazides, bis(*o*-hydroxy-amine)s or dihydroxy compounds with diacid chlorides having flexible hexafluoro-isopropylidene groups, or with diester-dianhydrides. Some of these polymers were tested in industry for high performance humidity sensors, electron-beam resists and Schottky diodes fabrication.

1. MONOMERS

The monomers which have been used in the polycondensation processes are shown below. From these, the majority has been synthesized in our laboratory by using various methods and only very few have been provided by commercial sources.

– aromatic diamines containing a heterocyclic unit such as 1,3,4-oxadiazole, benzoxazole pyridazine or phenylquinoxaline; aromatic diamines containing a cyano-substituted benzene ring; aromatic diamines containing two ether bridges (commercial); aromatic diamines containing 6F groups (commercial);

– aromatic dihydrazides;

– bis(*o*-hydroxy-amine)s;

– bis(hydroxyphenylquinoxaline)s and dihydroxy compounds containing imide rings;

– diacid chlorides containing hexafluoroisopropylidene units;

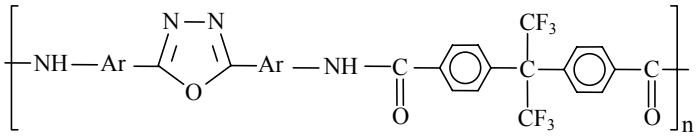
– aromatic dianhydrides containing ester groups.

2. SYNTHESIS OF THE POLYMERS

The following groups of polymers, shown below, were synthesized by polycondensation reactions of aromatic/heteroaromatic diamines, o-hydroxyamines, or dihydrazides with diacid chlorides of various structures or with diester-

dianhydrides; some polycondensations were also performed by direct use of certain dicarboxylic acids with hydrazine hydrate in polyphosphoric acid.

– Poly(1,3,4-oxadiazole-amide)s, poly(1,3,4-oxadiazole-imide)s and poly(1,3,4-oxadiazole-imide-amide)s, **I**, **II**, **III** [3-7]:



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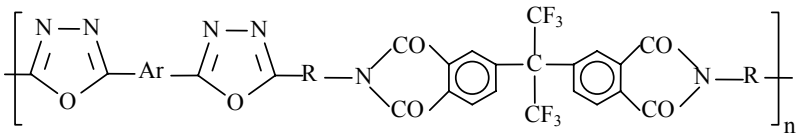

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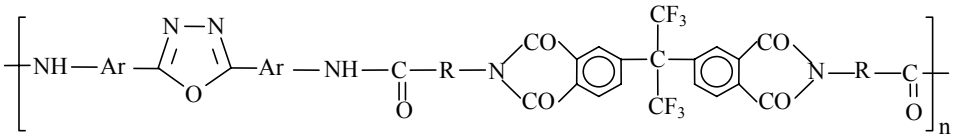
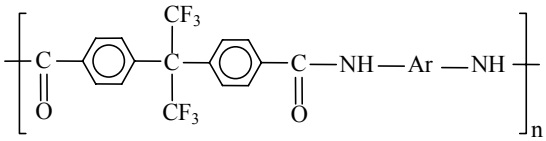
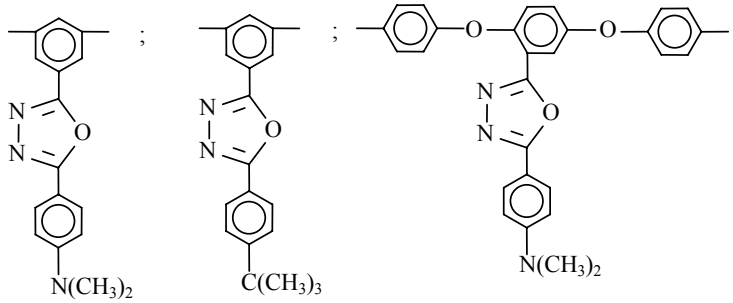


III

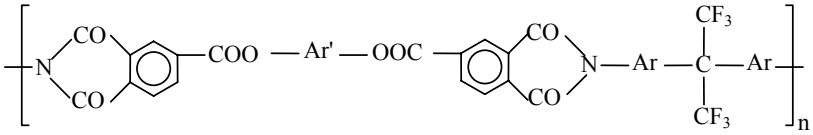
– Polyamides with oxadiazole rings in the side chain and hexafluoroisopropylidene in the main chain, **IV** [8, 9]:



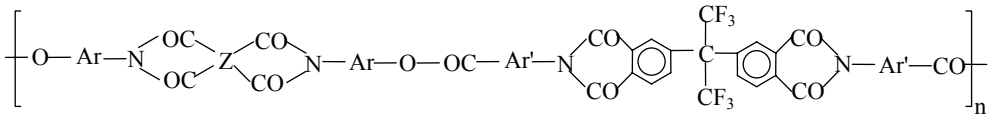
IV

Ar = 

– Poly(imide-ester)s, **V** and **VI** [10-12]:

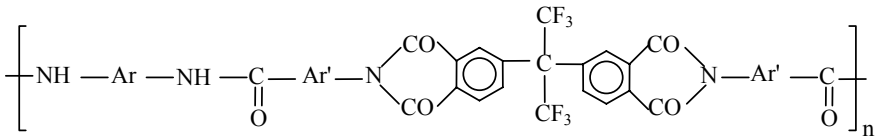


V



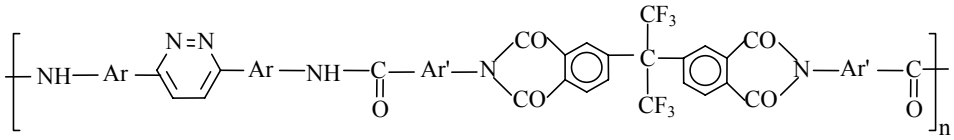
VI

– Poly(imide-amide)s, **VII** [13]:



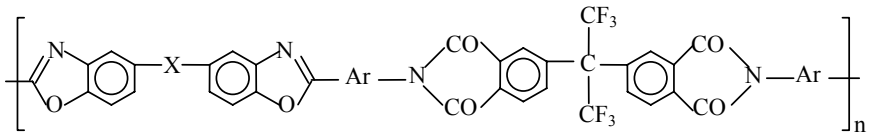
VII

– Poly(pyridazine-imide-amide)s, **VIII** [14]:



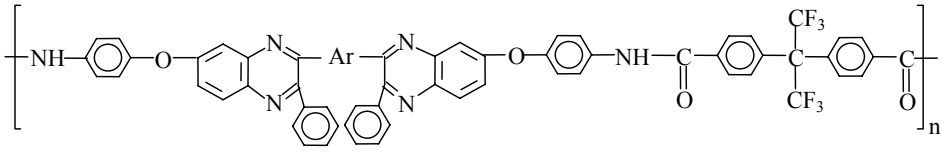
VIII

– Poly(benzoxazole-imide)s, **IX** [15-17]:

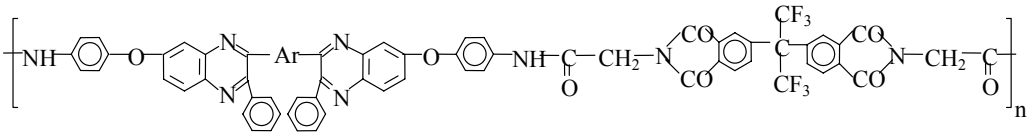


IX

– Poly(phenylquinoxaline-amide)s and poly(phenylquinoxaline-imide-amide)s, **X** and **XI** [18, 19]:



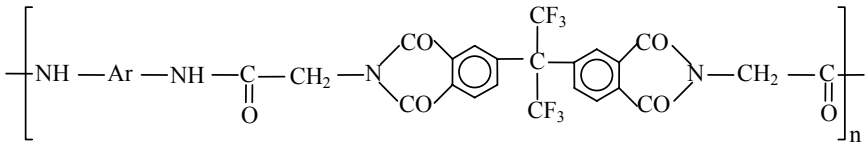
X



XI

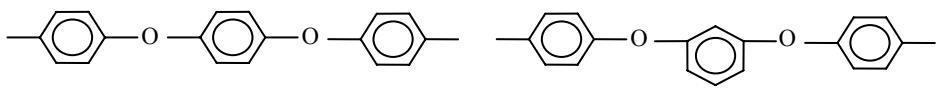
3. PROPERTIES OF THE POLYMERS

All these polymers have been characterized by infrared spectroscopy, measurements of inherent viscosity, molecular weight, solubility, film-forming ability, thermal stability, glass transition, electroinsulating properties and, for some polymers, the photoluminescence and electroluminescence were also studied. Most of the polymers exhibited relatively high molecular weight and narrow distribution, with very low amounts of unreacted monomers and oligomers. Typical curves obtained by gel permeation chromatography (GPC) are shown in Figure 1. For poly(imide-amide)s containing hexafluoroisopropylidene groups, **VII**, shown below, the weight-average molecular weight M_w is in the range of 12800 – 26700, the number-average molecular weight M_n is in the range of 4000 – 8200 and the polydispersity M_w/M_n is 2 – 5 [14].

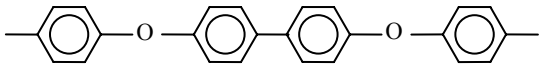


VII

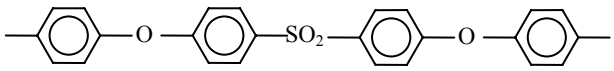
Ar =



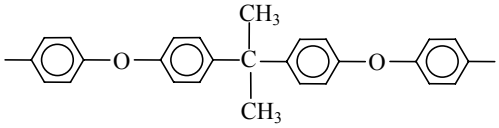
(VIIa) **(VIIb)**



(VIIc)



(VIId)



(VIIe)

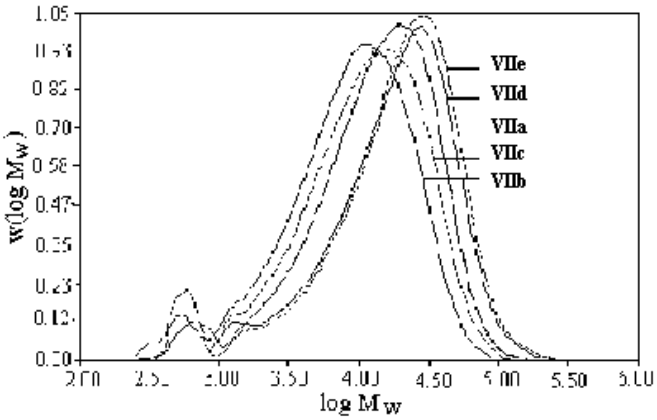
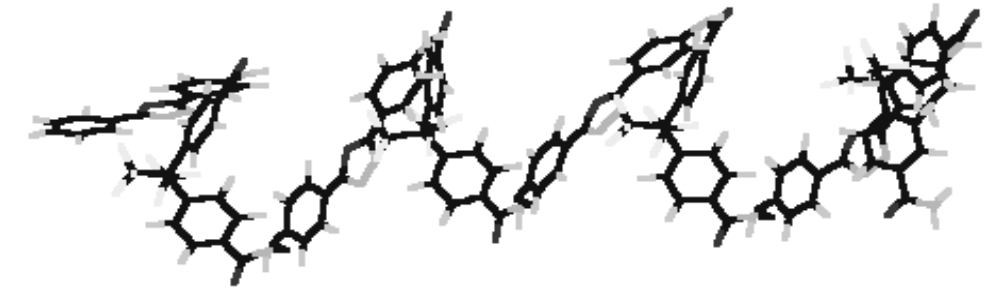
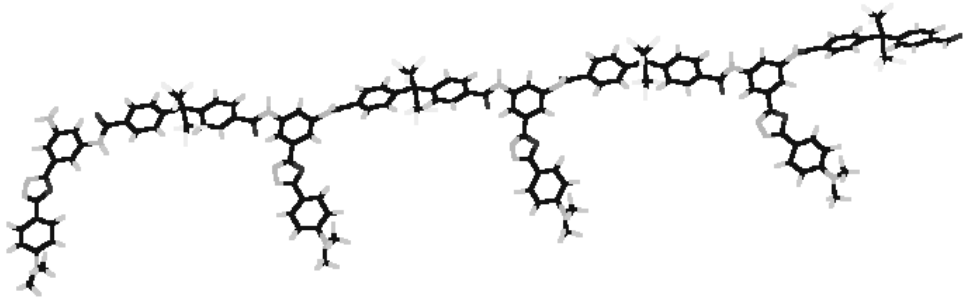


Fig. 1. GPC curves of fluorinated poly(imide-amide)s, **VII**.

All these polymers present good solubility in polar amidic solvents (N-methylpyrrolidinone, dimethylformamide and dimethylacetamide). Some of them exhibited good solubility even in less polar solvents, such as tetrahydrofurane or chloroform. The polymers were processed from such solutions into flexible films by casting or spin-coating techniques. The good solubility of most of these polymers was explained by the presence of hexafluoroisopropylidene groups. Molecular modeling showed that the shapes of the macromolecular chains are far from the rigid linear ones which are usually characteristic to wholly aromatic polyoxadiazoles, polyimides, polyamides or other polyheterocycles. Due to such shapes of the present polymers, the packing of their macromolecules is disturbed and the solvent can diffuse easily among the polymer chains and thus facilitate the solubilization. Typical model molecules are shown in Fig. 2.

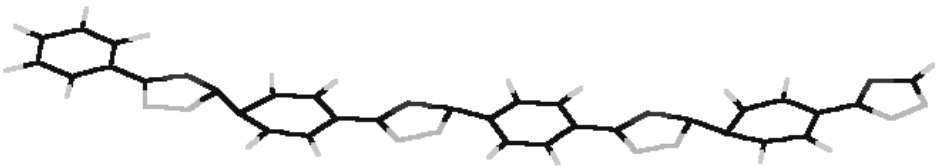


I



IV

Conventional aromatic polyamide



Conventional aromatic poly(1,3,4-oxadiazole)

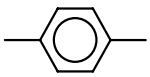
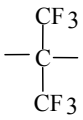
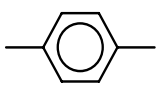
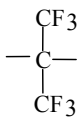
Fig. 2. Models of fragments having four repeating units of fluorinated aromatic polyamide with oxadiazole rings in the main chain **I** (top) and of aromatic polyamide with oxadiazole rings in the pendent groups **IV** (middle), compared with conventional aromatic polyamide and aromatic polyoxadiazole (bottom).

Most of these polymers possess remarkable film-forming ability. The free-standing films having a thickness in the micrometer range, 5 – 30 μm, were flexible and creasable and maintained their integrity after repeated bendings. Representative values of mechanical properties for a series of

polyphenylquinoxaline-amides containing 6F groups, **X**, are: tensile strength in the range of 59 – 78 MPa and elongation to break in the range of 34 – 55%, showing good mechanical properties, similar to those of related aromatic polyamides.

The electrical insulating properties of the free-standing polymer films were evaluated on the basis of the dielectric constant at different relative humidity levels. Most of these polymers exhibited low dielectric constant values, in the range of 3.1 – 3.6 at 0% relative humidity, being comparable to that (3.5) of Kapton film, made from a polyimide based on pyromellitic dianhydride and oxy-dianiline, which is one of the most preferred dielectrics for use in high performance applications. The lowest values of the dielectric constant were found for poly(benzoxazole-imide)s containing 6F groups **IX**: 2.77 – 3.09 (Table 1). The dependence of the dielectric constant on relative humidity is linear for certain of these polymers which makes them attractive for the manufacture of humidity sensors.

Table 1. Dielectric constant values of free-standing films made from poly(benzoxazole-imide)s containing 6F groups, **IX**

X	Ar	η_{inh} (dL/g)	Dielectric constant at relative humidity RH			
			0% RH	30% RH	60% RH	80% RH
—		0.73	2.77	3.05	3.42	3.76
—		0.60	3.04	3.44	3.85	4.06
		1.05	2.82	3.05	3.42	3.63
		1.00	3.09	3.55	4.00	4.19

Very thin films having the thickness in the nanometer range were made by the spin-coating technique from polymer solutions onto silicon wafers. Such films exhibited very smooth surfaces over large scanning domains (1 – 100 μm) when examined by atomic force microscopy (AFM). The value of root mean square roughness was 4 – 12 Å, being in the same range as that of highly polished silicon

wafers which were used as substrates. It means that the films are compact, homogeneous, without cracks or pinholes, practically defectless. In addition, the films had a strong adhesion to silicon wafers. Such properties of thin films are useful for potential applications in advanced microelectronics. Typical AFM images are shown in Fig. 3.

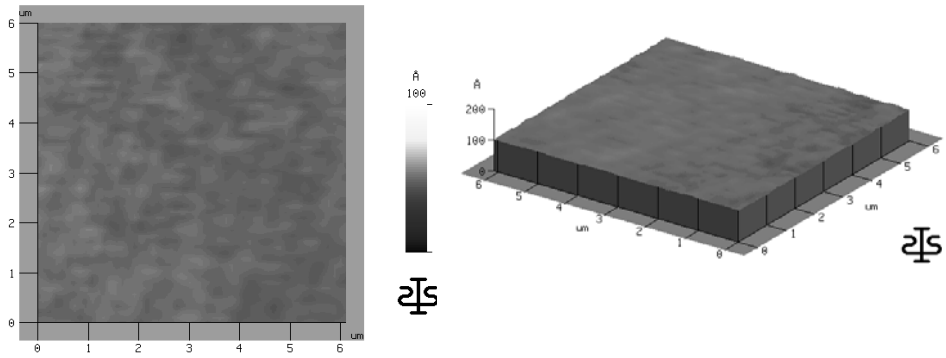


Fig. 3. AFM images of a thin film made from a poly(imide-amide) containing 6F, **VII** (left: top-view; right: side-view).

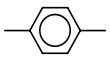
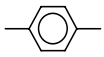
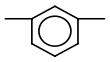
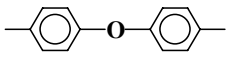
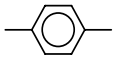
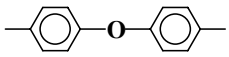
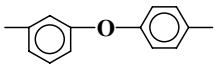
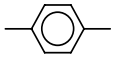
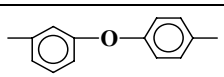
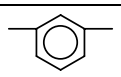
The thermal stability of the polymers was evaluated by thermogravimetric analyses. All the polymers which contain only aromatic/heteroaromatic rings and different flexible units in the main chain exhibited high thermal stability, with initial decomposition temperatures (temperature of 5% weight loss) above 400°C, and for some of them even above 450°C. The polymers which incorporated some methylene or ethylene units exhibited decomposition temperatures in the range of 350 – 400°C. As an example, Table 2 presents the thermal data of a series of fluorinated poly(oxadiazole-imide-amide)s, **III**. A typical TGA curve is shown in Fig. 4. Generally, it can be concluded that the thermal behavior of these heterocyclic polymers is very similar to that of related wholly aromatic/heteroaromatic polymers which do not contain any flexible groups, while their processability is significantly improved by the presence of these groups.

Another confirmation of the high thermal stability of poly(imide-amide)s containing 6F, **VII**, was obtained by recording the IR spectra of very thin films. The spectra remained unchanged after heating at 250, 300, 350 and 400°C, each for 15 minutes. After such thermal treatment the films were still compact and homogeneous, as evidenced by AFM investigation.

Most of the present polymers do exhibit a glass transition (T_g), usually high, in the range of 160-330°C, but still allowing for a large interval between glass transition and decomposition, which may be advantageous for processing by a thermoforming technique. A direct correlation can be seen between T_g and the content of *meta*-catenated phenylene rings. In poly(oxadiazole-imide-amide)s containing 6F, **III**, the polymer in which all the phenylene rings are *para*-catenated

has the highest T_g (313°C) while that containing two *meta*-catenated phenylene rings in one repeating unit, coming from each monomer segment, has the lowest T_g (245°C) (Table 2).

Table 2. Properties of poly(oxadiazole-imide-amide)s containing 6F, **III**

Polymer		η_{inh} (dL/g)	T_g (°C)	IDT (°C)
Ar	R			
		1.1	313	450
		0.9	304	440
		1.47	284	430
		0.68	268	420
		0.58	264	420
		0.46	245	420

η_{inh} = inherent viscosity; T_g = glass transition temperature;
IDT = initial decomposition temperature = temperature of 5% weight loss

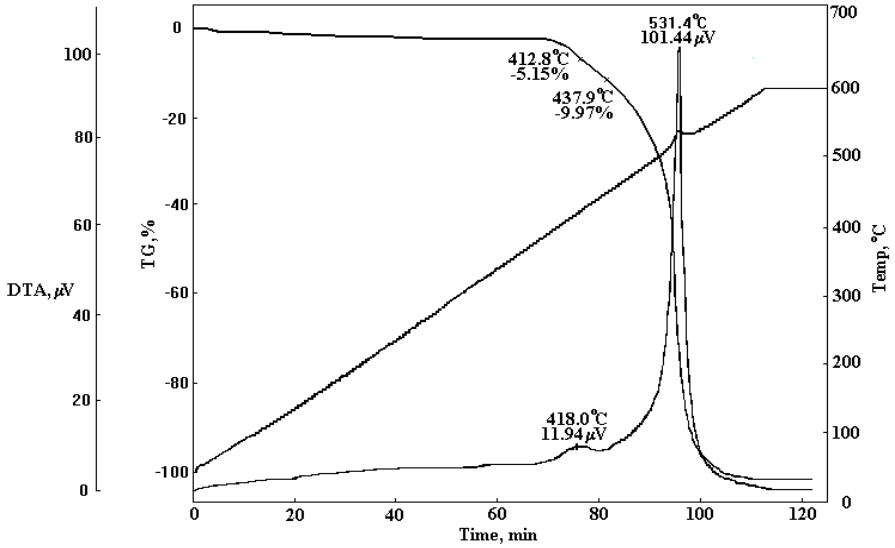


Fig. 4. TGA and DTG curves of fluorinated poly(oxadiazole-amide), **I**.

In the particular case of fluorinated poly(imide-amide)s, **VII**, containing a cyano substituent on the phenylene ring of diamine segment, it was found that, after heating at a high temperature, up to 400°C, the polymer films lost their T_g and became completely insoluble in any organic solvent. It is believed that, at a high temperature, some crosslinking takes place, presumably through the trimerization of the cyano groups to *sym*-triazine moieties. However, infrared spectra of the 400°C treated films showed only a very slight decrease in the relative intensity of the nitrile absorption at 2200 cm^{-1} (Fig. 5) which means that the percentage of crosslinking is very low, although enough to produce insolubility and disapearance of glass transition.

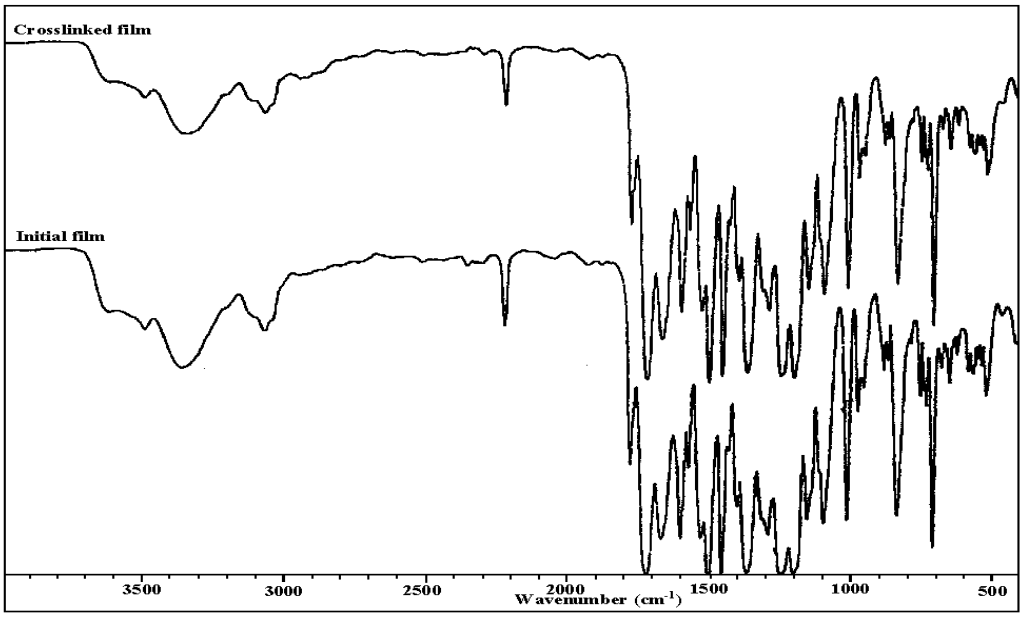


Fig. 5. FTIR spectra of a polymer film **VII** before and after crosslinking.

This behavior can be of interest for the advanced applications in which the polymer films are required to be extremely resistant to aggressive solvents. A slight decrease of dielectric constant was also observed, not significantly different from those of untreated films, although dielectric constant values as low as possible are very much desired. This showed that the dielectric constant is mainly influenced by the highly polarized carbonyl in amide groups which are not affected by the thermal treatment. Thus, the most important advantage of thermal treatment is to completely insolubilize the polymers and to determine the disappearance of T_g after their processing into thin films or coatings.

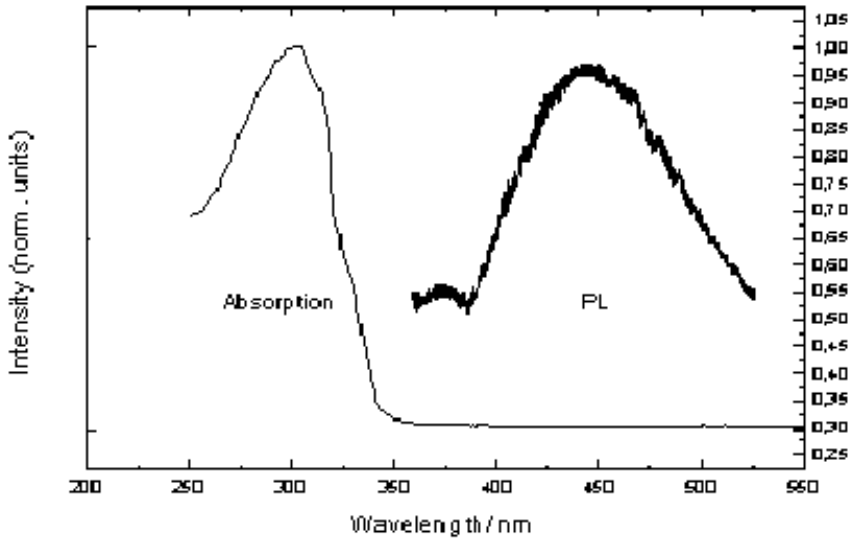


Fig. 6. UV absorption and Photoluminescence (PL) spectra of a poly(oxadiazole-amide) containing hexafluoroisopropylidene groups, **I.**

Electroluminescent devices based on organic thin layers have attracted much attention because of their academic interest and the potential utility of this technology for a wide variety of advanced applications such as flat-panel displays and light-emitting diodes (LED). It is desirable to develop new polymers which, along with high thermal stability and good processing ability into thin films, should also have predictable emission wavelengths, as much as possible in the blue region and should only require low-drive voltage. The light-emitting ability of certain polymers, namely those containing 1,3,4-oxadiazole ring in the main chain, **I** and **II,** or in the pendent group, **IV**, was evaluated on the basis of photoluminescence spectra. The polymer film **II**, deposited on silicon substrates, excited with UV light, showed strong blue photoluminescence, with a maximum at 475 nm. A light-emitting diode as single layer device has been made: the polymer was spin-coated from NMP solution onto an ITO (indium/titanium oxide) substrate. The film was dried and on top of it an aluminium electrode was evaporated through a shadow mask. From this single layer device electroluminescence was observed with a turn-on voltage in the range of 7 V. Such a behavior can be important for the use of some of these polymers in the construction of blue light-emitting devices. When studying the polymers containing oxadiazole ring in the side group, **IV**, it was found that those containing the dimethylamino-substituent in the *para* position of the chromophoric diphenyl-1,3,4-oxadiazole unit are the most promising candidates for the emissive materials in LEDs. These polymers showed intensive blue emission with the maximum between 460-480 nm (Fig. 6).

4. CONCLUSIONS

A series of heterocyclic polymers containing hexafluoroisopropylidene groups, in which the heterocycle unit is 1,3,4-oxadiazole, imide, pyridazine, benzoxazole, phenylquinoxaline, have been synthesized by using polycondensation reaction of a variety of monomers, mostly aromatic/heteroaromatic diamines, dihydrazides or bis(o-hydroxy-amine)s with diacid chlorides containing hexafluoroisopropylidene groups. In contrast to related fully aromatic/ heteroaromatic rigid polymers, which are completely insoluble in organic solvents, these polymers are easily soluble in polar aprotic solvents, such as N-methylpyrrolidinone, dimethylformamide and dimethylacetamide, and some of them even in less polar solvents, such as tetrahydrofurane and chloroform. This good solubility represents the key to a very important technological aspect: it facilitates the processing of polymers from solutions by casting or spin-coating techniques. Free-standing films in the micrometer range made from these polymers exhibited good mechanical properties, and very thin films having the thickness in the nanometer range exhibited very high quality being almost defectless. The majority of these polymers are highly thermostable presenting decomposition above 400ºC. Thus, the introduction of flexible hexafluoroisopropylidene groups did not significantly affect the thermostability when compared to related fully aromatic rigid polymers. Due to their flexible structures, the majority of the polymers do exhibit a glass transition, usually at high temperature, but still with a reasonable window between glass transition and decomposition, which may be useful for their processing by a thermoforming technique, as well. Most of these polymers exhibit low dielectric constant, of about 3.1 – 3.5, and a group of polybenzoxazole-imides containing 6F exhibited even lower dielectric constant values – below 3. That makes them attractive for applications in microelectronics as insulating layers. The linear dependence of the dielectric constant on relative humidity can be useful for the manufacture of high performance humidity sensors. From the polymers containing oxadiazole rings, certain structures exhibited photoluminescence in the blue range and experimental diodes constructed with them emitted blue light at a very low voltage, thus being very promising for future use in the manufacture of light-emitting diodes. All these properties combined with easy processability make the present polymers attractive candidates for various high performance applications, such as micro- and nanotechnologies, in which the materials are required to maintain their specific characteristics, such as chemical resistance, mechanical, electroinsulating and light-emitting ability while in service at a high temperature.

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Polymeric Chromophores with Variable Topology and Their Applications

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Abstract. This chapter reports a systematic study of the synthesis, characterization, and optical properties of a series of chromophore-functionalized polyurethanes prepared by attaching covalently/electrostatically azobenzene or stilbene moieties to polymer backbone. Key issues are how macromolecule architecture, chromophore-chromophore interactions, and photochemical processes are modulated by irradiation with UV light. The results indicated that the photochromic effect and fluorescent properties in polymer films of elastomer type are mainly controlled by the chromophore mobility.

1. INTRODUCTION

During the last two decades, there is an increasing interest in the introduction of photoactive moieties into a backbone as a modern trend for modification of tailor-made polymer properties for special applications [1]. Much of this interest has been centered on the synthesis and photochemistry of azo-polymers to elucidate the relationship between the chemical structure and their optical properties, taking into account the development of new specialized materials for optical information storage [2, 3]. Among currently used polymers, polyurethanes offer a set of advantages such as facile synthesis, structural and compositional flexibility, optical quality thin films, good stability, and solvent resistance [4]. By tailoring the polyurethane and chromophore structure, a variety of polymers with azobenzene [5, 6], stilbene [7-9], quinone groups [10] have been studied and developed for applications in liquid crystal displays, photochromic systems, non-linear optical and electroluminescent materials or as corrosion resistant metal recording tape.

Our program has been directed towards polyurethane ionomers, considered now one of the most active branches of polyurethane chemistry, whose interesting applications are related to the ability of polymers to form aqueous dispersions,

widely utilized as adhesives and coating materials [11]. In contrast with the scientific and commercial interest focused on these polymers, little work concerning the insertion of the dye structures or mesogenic azo units into the backbone was reported in literature [12-14].

In this context, we have developed a new family of polyurethane ionomers with photochromic, photodegradable, fluorescent, redox or UV/laser ablation properties induced by the presence of some specific chromophores anchored to the polymeric backbone as azobenzene [15-22], stilbene [23, 24], anthryl [25], quinone [26, 27] or triazene groups [28]. This paper will present a brief review on these photopolymers including the specific role of the chromophores in the developing of polymer properties with emphasis on new azo and stilbene ionomers.

2. CONTRIBUTIONS

2.1. Polyurethane Ionomers with Pendant Azobenzene

As described in our previous papers [15-22], azo ionomers may have a variety of chain structures introduced by means of new azo chain extenders, azo quaternizing (functionalizing) agents or azo polyol components (Table 1). Some of the most highly investigated polymers have been polyurethane cationomers based on polytetramethylene oxide diol (PTMO), polyethyleneadipate diol (PEA) of 1000 or 2000 average molecular weight, 4,4'-diphenylmethane (dibenzyl) diisocyanate (MDI, DBDI), 2,4-toluylene diisocyanate (2,4-TDI) and different chain extenders of ionic or non-ionic type.

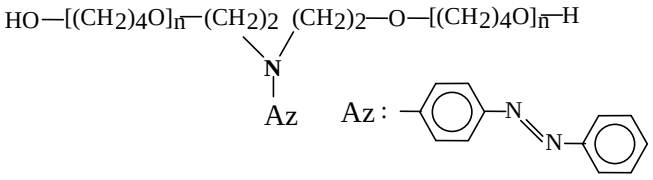
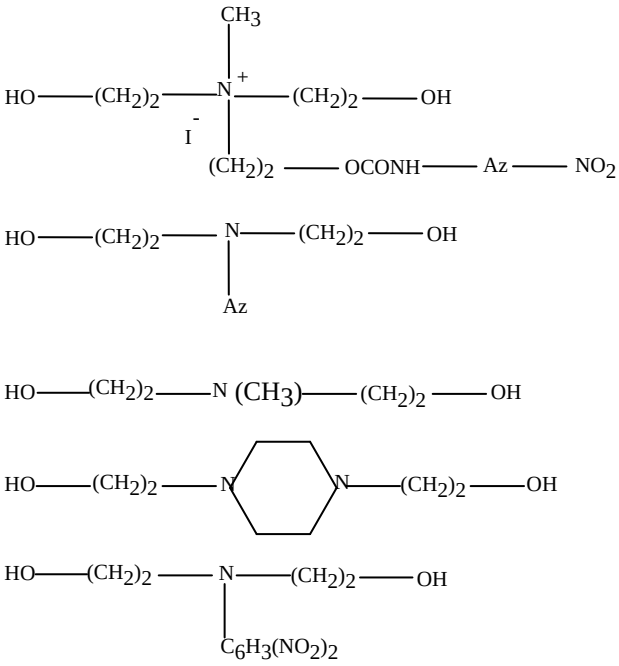
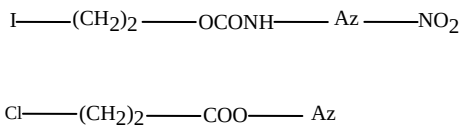
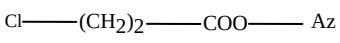
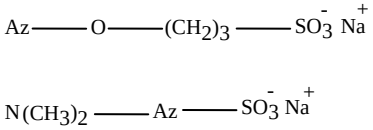
Therefore, the use of every azo component above mentioned was a route to afford azo-cationomers (Az-PUCs) with chromophore located in the ammonium quaternary structure, the non-ionic hard fragment, the polyeter chain or on the nitrogen atoms of urethane structure, as shown in Fig. 1.

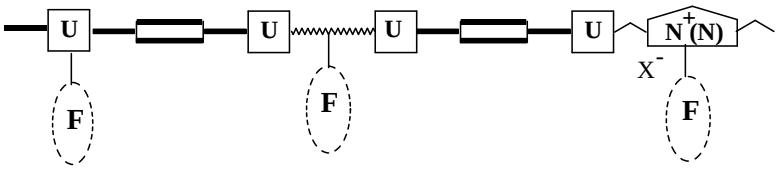
In order to investigate closely the influence of the ionic groups (usually under 1 meq. /1 g polymer) on photoreactivity of the chromophore, azoaromatic units as counterions of the ionic structure were also introduced into the polycations.

All azo polyether(ester)urethane cationomers are soluble in common solvents like THF, CH_3OH, DMF, DMAc and DMSO. Solutions from these red polymers were coated onto a glass substrate and dried to form colored and flexible polymeric films with typical elastomeric characteristics. Moreover, the optical clarity of these films is suitable for various applications.

The structure of all polymers was determined by elemental analysis, IR and UV-vis absorption spectroscopy. GPC analysis performed on some precursors indicated the absence of low or high molecular weight tails and reasonable number-average molecular weights. Such polymers contain azobenzene structures (between 5 and 30 wt. %) in varying compositions but the difficulty in treating azo polymers derived from the interchain interactions of polyurethane ionomers *via* Coulombic forces.

Table 1. Chemical structures used in the synthesis of azo polyurethane ionomers

Polyol:  	1. azo-polytetramethylene oxide diol
Chain extenders:  	2. 2-ethyl-N-methyldiethanol-ammoniu-N-[4(nitrophenyl-diazenyl)phenyl]amino-formate iodide 3. N-di-(β-hydroxyethyl)-4-aminoazobenzene 4. N-methyldiethanolamine 5. N,N'-di-(β-hydroxyethyl)-piperazine 6. N-(2,4-dinitrophenyl)-diethanolamine
Quaternizing agents:   	7. 2-iodoethyl-N-[4(4-nitrophe-nyldiazenyl)-phenyl]amino-formate 8. 4(3-chloropropionyl-oxy)-azobenzene
Azo salts:  	9. 3(p-oxyazobenzene)propane-sulfonic acid sodium salt 10. methyl orange sodium salt



where,

U : -NHCOO-

: Rest of MDI, 2,4-TDI, DBDI

: PTMO, PEA

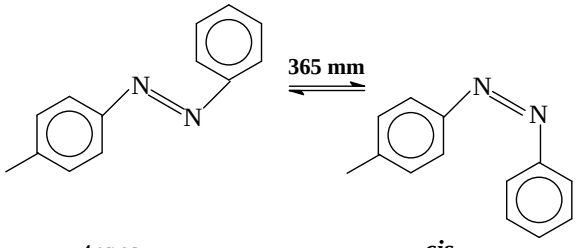
X^- : Cl, I, Az-

F : **Chromophore**

Fig. 1. Schematic representation of Az-PUCs.

2.1.1. Photobehavior of the azo chromophores in thin polymeric films

It is well known that a large number of chromophores used in polymer synthesis may undergo photochemical reactions when irradiated by UV light [29]. Normally, in every derivative, the azoaromatic chromophores are in the thermodynamically more stable *trans* configuration.



trans ***cis***

Photoexcitation of this structure induces a structural change of the *trans* conformer to *cis* isomer. Once the molecule is in the *cis* form, it often recovers to the initial *trans* configuration either by a back thermal reaction or by an inverse photoisomerization cycle. An important parameter for the determination of the spectral and temporal response of these polymers is the understanding of the complex properties of azobenzene in the polymeric films.

Obviously, the isomerization reactions of the azo chromophores are substantially slowed-down in polymer films compared to solutions, as a direct consequence of their reactivity sensitive to the local mobility of reactants and heterogeneity of reaction sites in the solid state. Our work has revealed some possibilities in the structural tailoring of such polymers capable to assure good photoresponse of the azo chromophores in thin films. Consequently, it was

confirmed that in thin films the isomerization rate and phototransformation degree of the azobenzene groups were affected by restrictions in the movement of the chromophores, imposed to the molecular chains by steric and shielding effects. An illustrative example is the ionomer film containing azobenzene as counterion of the ammonium quaternary structure (9, Table 1), whose *trans-cis* photoisomerization reaching equilibrium state in about 420 sec UV irradiation occurred with a molar fraction of *cis* isomer of 0.56 (Fig. 2, plot a). From the presence of the isosbestic points at 308 nm and 415 nm, one can draw the conclusion that the photoisomerization is the only chemical phototransformation suffered by the polymeric chain [19].

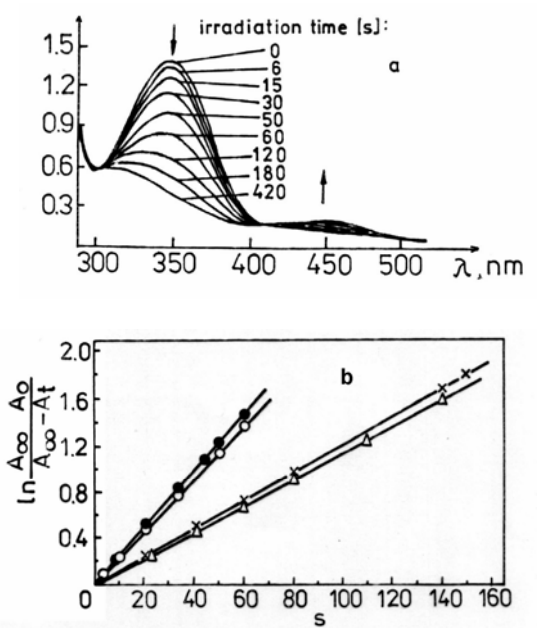


Fig. 2. *Trans-cis* photoisomerization of the azobenzene attached electrostatically to a polycation in film (a); (b) the *cis-trans* isomerization of two polycations with azo-soft segment in film (∇, x) and their corresponding non-ionic polymers (o, •) differing by the azo content.

Similar results were also reported on other polycations with azobenzene anchored in the polyether soft segment (1, Tab. 1) of the ionomeric backbone, when the photostationary state is reached in only 30 sec of UV irradiation and the molar fraction of *cis* isomer was about 0.34 [17].

Studies reported so far have mostly concentrated on the *cis-trans* isomerization of azobenzene in polymer films based on all polyurethane

cationomers. The principal driving force for the relaxation of chromophore is a large increase in mobility and free volume, sufficient to promote the return of the *cis* azobenzene structure to the initial *trans* configuration. These conditions are satisfied by a small number of polymers such as those described above. Evidence for this claim is that the spectral changes during the return of the chromophore can be easily observed within the thin polymeric films. The kinetics of *cis-trans* relaxation process of azobenzene in the previously irradiated films was followed by monitoring the changes of absorbances specifically to the *trans* isomer, appeared by storing the films at 80°C or at ambient temperature. In both cases, the return of the chromophores to the initial *trans* configuration occurred indeed, but with various rates. The first order plot for the thermal *cis-trans* isomerization of azo chromophore in the ionomeric films based on azo-polyether is shown in Figure 2 (plot b). Comparison of the rate constants of the ionic films (PUCAz, 7.2 wt % azo / $k_1 = 29.2\times10^{-3}$ s^{-1}; PUCAz, 9.1 wt. % azo / $k_2 = 25.9\times10^{-3}$ s^{-1}) with those found in the non-ionic ones (PUAz / $k_3 = 59.3\times10^{-3}$ s^{-1}, $k_4 = 57.8\times10^{-3}$ s^{-1}) evidenced the influence of the ionic interactions on the thermal recovery of the *cis* isomer to *trans* configuration. By contrast, for the ionic film having azo as counterion ($k = 8.46\times10^{-4}$ s^{-1}) the thermal recovery of the *cis* form is very slow (about 70 min).

Our findings sustain that the covalent introduction of the azobenzene chromophore as side group in the polyether segment of the polyurethane backbone seems to be a decisive factor of the reversible photo(thermo)reactions. An alternative approach should be the electrostatic incorporation of photoisomerizable azoaromatic structures into polyurethane cationomers as a convenient way for inducing photochromic properties to polymeric films intended for special applications.

2.2. Polyurethane Ionomers with Pendant Stilbene

Given the broad area of properties and applications of the stilbene polymers [8, 9], ionic polyurethanes with stilbene, considered more interesting than the nonionic ones, were prepared for further exploring and better understanding of the specific properties including fluorescence of such elastomers. For this purpose, polyetherurethane ionomers based on a new ionic diol bearing one side urethane-stilbene group (SD, Figure 3), MDI and PTMO were synthesized and characterized [23]. To explain the effects of ionic groups on the photoluminescence, we diversified the structure of polycations investigating functionalized polymers with stilbene (S-Cl, Fig. 3) either by a stepwise substitution of urethane hydrogen atoms or by a quaternization of a neutral polyesterurethane [24].

Some optical properties of the stilbene fragment located on the ionic structure or on the urethane structure of the polymeric backbone were studied comparatively with the parent derivatives. Additional information about the mobility of the stilbene inside polycations may be gained by measuring fluorescence. The stilbene ionomers (PUCSs) differ by the flexible segment length

and its nature, the concentration of urethane/ionic groups, and consequently by the stilbene content (between 13.6 and 24.7 wt. %).

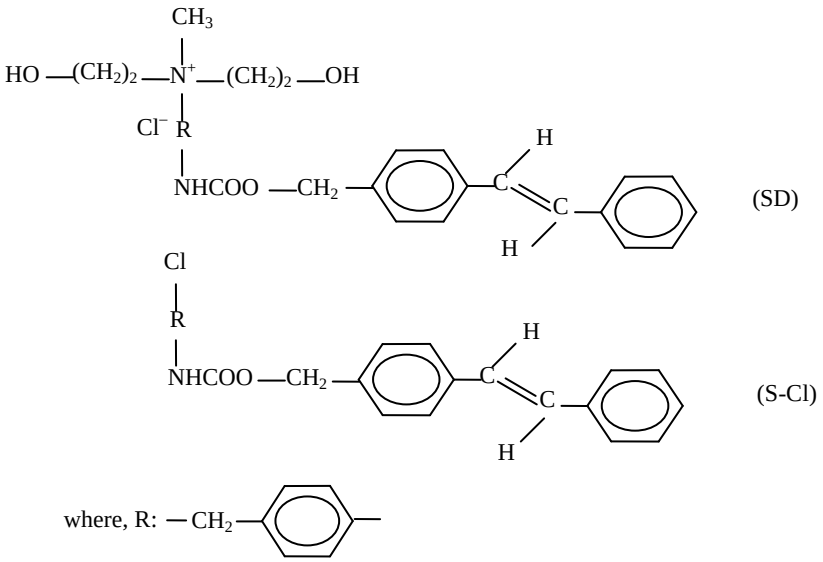


Fig. 3. The structure of stilbene derivatives used in the polymer synthesis.

The structure of these polymers was confirmed by spectral data and elemental analysis. Infrared spectra of all polymers exhibited typical absorption bands to the conventional polyurethanes. Although the double bond from stilbene molecule may be observed in the starting derivatives, the absence of the CH=CH absorption band in polymers could be due to overlap with the absorption maximum of the aromatic ring at 1600 cm^{-1}, as determined by infrared analysis. The stilbene compounds and polymers display a maximum at 970 cm^{-1} suggesting the *trans*-vinylidene formation [30].

In the ultraviolet-visible absorption spectrum, PUCSs in DMF shows three peaks corresponding to the *trans*-isomer absorptions centered at 305, 316, and 334 nm, with the maximum at 316 nm assigned to a π–π^* transition. Compared to the polymer, in the stilbene diol there is a slight hypsochromic shift of about 10 – 15 nm for absorption maximum positioned at 288, 296, 310, and 325 nm.

2.2.1. The UV induced trans-cis photoisomerization of the stilbene chromophore

Like azobenzene structure, the double bond in the stilbene molecule favors the *trans-cis* isomerization of stilbene derivatives resulting in the loss of planar geometry of the *trans* isomer in both ground and excited state [31]. Usually, the isomerization to *cis* configuration results in a loss of their fluorescence properties.

Therefore, exhaustive irradiation of both the stilbene derivatives and the corresponding polymers with monochromatic light (λ: 320 nm) induces a *trans-cis* photoisomerization with the formation of an equilibrium isomeric mixture, with the *cis* form predominating. Moreover, the *cis* isomer of SD is characterized by a different absorption maximum in the UV region.

Figure 4 (a) presents the absorption spectra for *trans* isomer before and after exposure to UV light of SD in methanol solution. Upon direct irradiation, its concentration gradually decreases with irradiation time, while that of the *cis* isomer increases until equilibrium is attained after about 180 s. As seen in solution, the *cis* form absorbs at 262 nm and the isomeric composition in the photostationary state was estimated at 65 % *cis* isomer. Accordingly, two isosbestic points at 340 nm and 266 nm appeared after exposing the solution to light, indicating the *trans-cis* photoisomerization of stilbene molecule as major reaction. Besides these peaks, the development of a new maximum at 220 nm suggested that the photochemistry of *trans*-stilbene combines characteristics of two photoprocesses, namely photoisomerization and photocycloaddition. In the latter case, the formation of *[2+2]* cycloaduct or photolysis product is possible [32].

The kinetics of the *trans-cis* photoisomerization of SD in solution as a first order reaction was monitored (Fig. 4, b). For the *trans* stilbene molecule in methanol, we found that the isomerization constant rate is 1.33×10^{-2} s^{-1}.

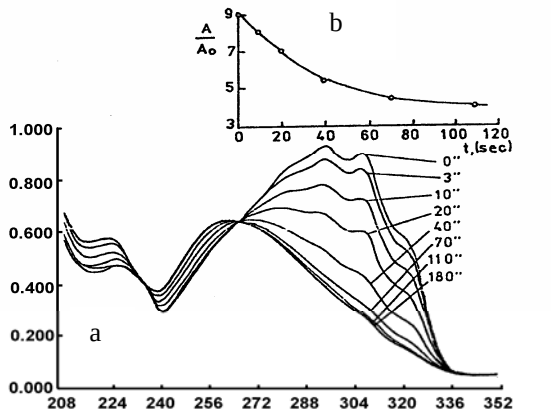
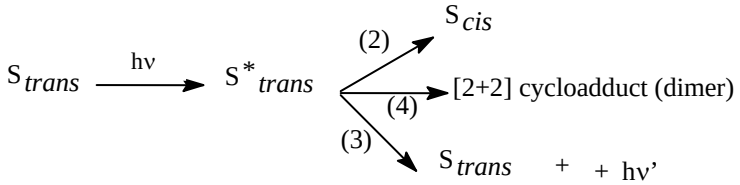


Fig. 4. Changes in the UV-vis. spectra of SD in CH_3OH during UV irradiation (a) and the dependence of the relative absorbance on the irradiation time (b).

As one may anticipate, the changes with time of the *trans* isomer in stilbene polymers were somewhat similar to the monomer behavior in solution, but owing to polyurethane competitive absorption at wavelengths less than 300 nm, no observation of either *cis* isomer or photoaduct was noticed. The value of rate constants and the longer times of irradiation required by the *trans* stilbene molecule to reach the equilibrium reflect differences in the structure and steric environments surrounding the chromophore in the dilute polymer solutions.

2.2.2. Fluorescence of the stilbene group in solution and solid state

The absorption of one photon into *trans* stilbene molecule has now created a singlet excited state which has four choices for returning to the ground state: (1) losing energy thermally, (2) undergoing a photochemical reaction with rotation of the stilbene molecule around the central ethylene bond, (3) losing energy in the form of a photon or (4) the formation of *[2+2]* cycloadduct *via* a singlet excimer. The electronically excited *cis* stilbene (2) is non-fluorescent and the luminescence process (3) is called fluorescence, according to the scheme:



The fluorescence spectra for irradiated samples with 365 nm were compared to the corresponding absorption spectra. The stilbene polymers absorb in the UV region (λ_A: 313–332 nm) and reemit the light as violet-blue fluorescent in the region 420–470 nm, while the stilbene derivatives absorb in the zone 286–328 nm and reemit at 416–449 nm (Fig. 5, Table 2).

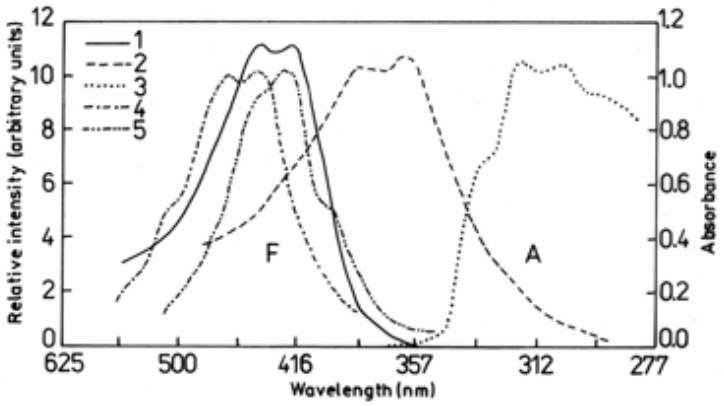


Fig. 5. Absorption spectrum of stilbene onic diol in DMF (3) and its fluorescence spectra in solution, λ_{ex}: 344 nm (1), 334 nm (2), 365 nm (5); solid state, λ_{ex}: 334, 344, 365 nm (4).

In all cases, the emision band was assigned to the formation of excimers between fluorophores. As seen from the data listed in Table 2, exciting at red edge with λ_{ex}: 334 nm (SD, Figure 5) and 328 nm for a non-ionic polymer (PUS1) with stilbene on urethane structure only "monomer" fluorescence at about 357 nm was observed in DMF solution (Figure 6).

Upon polymer quaternization, the excimer fluorescence peaks which arise at 422 nm (DMF) and 451 nm (film), respectively, do not depend on the photoexcitation wavelength. Moreover, the anchoring of stilbene onto the ammonium quaternary structure caused a red shift of the excimer because of the presence of aggregates in the polymers, more stable in the films.

Table 2. Physical and fluorescence data for the stilbene derivative and polymers in DMF solution and solid state

Sample	State	λ_A (nm)	$\lambda_{ex\,A}$ (nm)	λ_F (nm)	ϕ^a_F
S-Cl	DMF	286, 300, 314, 328	303, 328, 365	416	0.2
	Solid		328, 365	444, 470	0.22
S-D	DMF	303, 308, 324	334	357, 379	0.22
			365	416	0.16
	Solid	-	334, 344, 365	433	0.18
PUS1	DMF	313, 328	328	359, 384	0.14
			365	420, 438	0.12
	Film	315, 332	328, 365	450	0.06
PUCS1	DMF	313, 329	328, 365	422	
	Film	315, 333	334, 365	451	0.11

[a] - quantum fluorescent yield

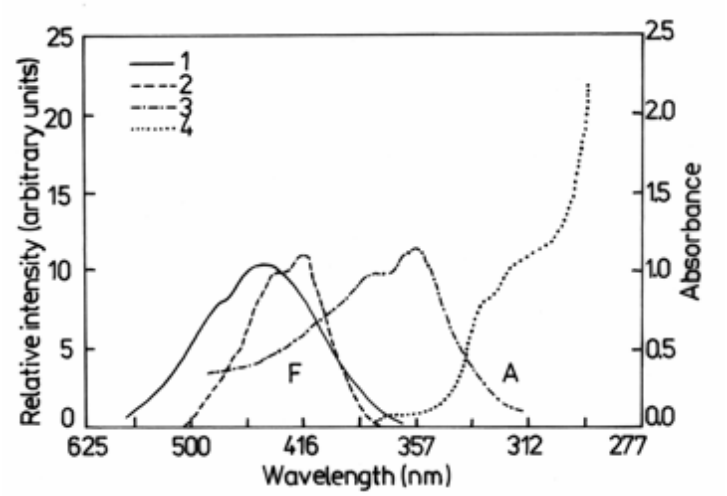


Fig. 6. Absorption spectrum of stilbene polymer in DMF (4) and its fluorescence spectra in film, λ_{ex}: 328, 365 nm (1) and in DMF, 365 nm (2), 328 nm (3)

From the result found on the model and polymers it can be observed that important steric effects are responsible for the increase of the quantum fluorescent yield (ϕ_F: 0.2), in comparison with that of pure stilbene (ϕ_F: 0.05) [33].

3. APPLICATIONS

The design of polymeric materials in which azobenzene moieties are attached in the main or side chains have been found to have great potential for emerging optical applications including dynamic and reversible holographic data storage, optical controlling process, optoelectronics and many other devices. Using the excited state of trans-stilbene from some polymers which can be quenched by electron-deficient aromatics, it is possible to develop a variety of vapor based "chemical" sensors of high sensitivity and selectivity.

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Silicon-Based Nanomaterials

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Abstract. Silicon is a widespread element in nanotechnologies, either as silica-filled polymeric nanocomposites, nanoporous silica, and magnetic nanoparticles or in various self-assemblies. The paper summarizes recent advances in silicon-based nano-sized materials and describes some results on micelle and nanoparticle formation promoted by functional polysiloxanes or by siloxane containing copolymers.

1. ORGANIC-INORGANIC NANOCOMPOSITES

Controllable growth of silica particles has been carried out at nanometric scale by the sol-gel process [1]. This is a useful technique to prepare *nanocomposites* of organic and inorganic materials. These hybrid nanocomposites are used as separation membranes or catalysts in automobile industry, microelectronics, optics, biology [2-6]. The highly crosslinked silicates are chemically and mechanically suitable matrices, and the addition of organic species makes them elastic or miscible with organic guest molecules [7]. Ordered inorganic silicates have been obtained using small surfactant molecules [8] or block copolymers [9] as templates. The subsequent removal of the organic compound leads to an inorganic solid of ordered porosity.

An interesting route in obtaining organic-inorganic hybrid nanocomposites is based on cubic silsesquioxanes [10, 11]. These are rigid crystalline, silica-like cores, perfectly defined spatially (0.5–0.7 nm). They can be bonded covalently to 8 R groups, thus forming octafunctional macromonomers, capable to homopolymerize or copolymerize with other functional cubes to provide nanocomposites whose length scales and interfacial interactions are exactly defined.

The importance of *mesopores* has been proven for polymer, dye or vitamin adsorption or for applications as electric double-layer capacitors [12]. Mesoporous silicas, i.e. with regular mesopore diameters between 20 and 500 Å, as defined by IUPAC, are of great interest in heterogeneous catalysis [13, 14], supramolecular assembly, molecular separation, optoelectronic technology [15]. Silica is used as support and functionalized by framework substitution or by post-synthesis surface modification [16].

Variously functionalized *nanoporous* silicas were obtained using tetraethoxysilane or variously substituted trialkoxysilanes as a silica precursor, and a large variety of amphiphilic or surfactant molecules as templating agents [7, 17-19]. The shape and size of the obtained silica can be controlled by the sol-gel reaction conditions [12] such as organic moiety, leaving group, solvent, catalyst, concentration, temperature, ageing time [20].

Due to the exceptional thermal and oxidative stability of silicates combined with the high optical quality of silica thin films [21], a wide variety of film coatings have been prepared by the sol-gel process. Sol-gel film coatings of *magnetic nanoparticles* have been of particular interest in recent years. Magnetic "nano-coatings" are designed to cover the particles with a nanometer scale layer. Most of the magnetic thin films are utilized in high-density information storage (recording tapes and disks) [22], but also for catalytic [23] and optical filter [24] purposes. Usually, magnetic nanoparticles are obtained starting from tetramethoxysilane, but the utilization of block copolymers containing functional groups in one block as surfactants has also been reported for preparing magnetic fluids [25, 26].

It is known that when a block copolymer is confined into a thin film, the chemical dissimilarity between the blocks results in a preferential segregation of one block to the interface. This segregation interacts with the connectivity of the blocks and orients the copolymer morphology parallel to the surface. Although this orientation persists only over a few layers for diblock copolymers in the disordered state, the orientations can propagate many lattice periods away from the surface when the block copolymer is ordered. These nanostructures can be of great relevance in the creation of porous media consisting of ordered pores and in the synthesis of *nanowires* with well-defined diameters and chemical structures [27].

It is also known that the extremely non-polar nature of PDMS structure together with the very low levels of intermolecular attractions lead to the formation of thermodynamically and mechanically incompatible blends with virtually all other polymeric compounds. The very low value of the solubility parameter of PDMS [$\delta = 7.3 – 7.5$ $(cal/cm^3)^{1/2}$] as compared to other polymers [$\delta = 8.5 – 14$ $(cal/cm^3)^{1/2}$] is the most important driving force in the formation of two-phase morphologies in PDMS containing copolymers. This produces microheterogeneous structures of colloidal dimensions [28]. Silicone micro- and *nanoparticle* dispersions with controlled silicone particle functionality and surface compatibility, prepared either by controlled phase separation of segmented siloxanes during the cure or by the

formation of prefabricated structured particles, are the key of novel silicone-toughened epoxy resins which exhibit substantially higher impact resistance without sacrificing high strength, stiffness, dimensional, environmental and chemical stability [29]. This was achieved using poly(siloxane-caprolactone) copolymers with OH functionalities as curing agents.

2. SELF-ASSEMBLIES

Molecules that possess both hydrophilic (polar) and hydrophobic (nonpolar) moieties are able to aggregate when dissolved in appropriate solvents. The structural incompatibility between the hydrophilic and hydrophobic groups of these molecules is the key of their properties. Surfactants are able to adsorb to the interfaces, thus modifying the interfacial energy. They can self-assemble in water, to form aggregates like micelles, lamellar phases and vesicles. Surfactants are used as stabilizers of interfaces or particles (emulsion formulations, particle dispersions, antistatics, foams, adhesion modifiers), as solubilization agents, enabling the water insoluble compounds to be concentrated into microdomains, or the orientation of chemical reactions. Depending on their chemical structure, there are ionic (anionic, cationic) and nonionic surfactants.

Silicone surfactants have a wide range of technological applications, including the rapid wetting of low energy surfaces, the stabilization of polyurethane foam, surface activity in organic and aqueous media, and their utility as coating additives. Generally, these applications exploit the high surface activity of these surfactants, including their ability to reduce the surface tension of liquids to about 20 mN/m. This extraordinary surface activity is the result of the intrinsic low surface energy of the siloxane backbone [30]. The siloxane surfactant structure includes a wide range of organic moieties linked to the siloxane backbone in order to solubilize the surfactant [31], namely nonionic, anionic, cationic and zwitterionic organic groups.

Extensively studied nonionic surfactants are PDMS/polyether block copolymers, in which surface saturation is achieved at quite low bulk surfactant concentrations [32]. The limiting surface area per molecule is controlled by the hydrophilic group and is essentially independent of the size of the PDMS segment. The relationship between the cmc and the hydrophilic/lypophilic balance (HLB) is similar to that of organic surfactants. Similar results have been observed for dimethylsiloxane esters of sulphonic acid and dimethylsiloxane substituted maleates and sulphosuccinates. The silicone surfactants are more surface active than their organic analogues [32].

Many polysiloxane–poly(alkylene oxide) surfactants are described in patents, due to their great applicative potential. The first siloxane–polyether copolymers were synthesized by the reaction of alkoxymethylsiloxane polymers with hydroxy–terminated polyethers. This reaction path led to Si-O-C bonds, which are subject to hydrolysis in the presence of acids or bases. Hydrolytically stable copolymers were prepared by hydrosilylation [33].

One of the major uses of polysiloxane–poly(alkylene oxide) systems is the stabilization of rigid polyurethane foams [28], since they are surface active in nonaqueous systems as well [33]. Even though the dimethylsiloxane–ethylene oxide copolymers may, in general, be less effective than certain fluorocarbon derivatives, they give remarkable reductions in the surface tensions of several organic fluids [34].

Poly(ethylene oxide) substituted trisiloxanes have been synthesized and their dynamics of surface and interfacial tension, concentration and temperature-dependent spreading performances have been investigated [35-37]. Cryo-TEM studies were undertaken in order to study the micelle and vesicle types in aqueous solutions [38].

Cationic siloxane surfactants bearing quaternary ammonium groups are also of great interest in corrosion protection, in fire-fighting foam formulations, bactericides and anticariogenic agents, or fabric conditioning agents [31, 39]. Siloxanes containing copolymeric surfactants also find applications in paint and cosmetic formulations, textile manufacturing or as agricultural adjuvants [38].

During the last two decades, the development of efficient drug delivery systems has attracted tremendous attention. In this context, a new field called "polymer therapeutics" emerged, referring to any polymer that is used as a component of a drug product. This includes biologically active polymers, polymer-drug conjugates, polymeric micelles, nanoparticles and polymer–coated liposomes [40].

Due to their high oxygen and moisture permeability, excellent blood compatibility (low interaction with plasma proteins) and non-toxicity [41, 42], siloxane-containing materials found a privileged place in biomedical applications (blood contacting devices, medical membranes, contact lenses, prosthetic devices) [43-45].

On the other hand, carbohydrates are highly hydrophilic, non-ionic polar compounds, with no toxicity. They were investigated and used as alternative raw materials for non-polluting, biodegradable and biocompatible products [46, 47]. Therefore, joining of polysiloxanes and saccharides in various macromolecular architectures offers interesting perspectives for many applications. Amphiphilic block copolymers containing carbohydrates can act as solubility enhancers for hydrophobic drugs and may facilitate the delivery of drugs to the target cell, based on biological recognition procedures [48-50]. Their use as transdermal penetration enhancers [51], cosmetic formulations [52, 53], surfactants [54-57] or self-assembling polymers [58, 59] have also been reported.

Differently shaped self-assemblies containing silica and/or siloxane polymers and copolymers have been reported. Depending on the processing conditions, self-assembled monolayers, micelle structures or nanoparticles were prepared.

2.1. Self-assembled Monolayers (SAMs)

Are defined as monomolecular films of a surfactant formed spontaneously on a substrate upon exposure to a surfactant solution [60]. The degree of order in

monolayers is the result of many factors, including geometric considerations, electrostatic and dipole-dipole interactions within the monolayers, affinity of the head group of the surfactant to the surface, etc. The proximity of adjacent chains in SAM makes it possible to perform chemical reactions between them, a phenomenon conceptually similar to intramolecular reactions in solution chemistry [60].

3-(Mercaptopropyl) trialkoxysilanes (MPS) were deposited and polymerized on the surface of gold and silver colloids to produce silica-coated nanometer-sized metal particles [61-63]. Water soluble semiconductor nanocrystals also known as quantum dots (QDs) have been obtained by the silica-siloxane coating technique [64, 65]. In this procedure, MPS is directly adsorbed onto the nanocrystals; a silica/siloxane shell is formed on the surface by the introduction of a base and hydrolysis of the silanol groups. Polymerizing silanol groups stabilizes the nanocrystals against flocculation and renders them soluble in solvents such as methanol and dimethyl sulfoxide. After further reaction with aminopropyl trimethoxysilane or trimethoxysilyl propyl urea, the particles become soluble in aqueous buffers.

Repetitive deposition of 1,2-bis(trichlorosilyl)ethane and 1,8-octanediol on the hydroxyl-terminated surface led to the formation of multilayers possessing horizontal evenly spaced crosslinked planes of siloxane polymer [66–68].

2.2. Micelle Structures

Micelle structures are the most common and studied type of self-association. The concentration at which micellization begins is called *critical micelle concentration* (cmc) [69]. Below cmc, only isolated molecules are found in solution, in equilibrium with a monolayer of surfactant at the air–solution interface. Above cmc, micelles are present, in equilibrium with isolated molecules in the solution and molecules adsorbed at the surface. Generally speaking, micelle formation occurs when diblock or triblock copolymers are introduced into a solvent which preferentially solvates one block in the copolymers. The dissolution of block copolymers in selective solvent results in aggregation of the non-solvated blocks [70].

In water micelles, hydrophilic groups are oriented towards water and hydrophobic moieties towards the interior. Thus, cavities are formed, in which water insoluble compounds can be transported, or even synthesized. Since the micelles exist on a nanoscopic scale, they can be considered nanoscopic reaction vessels or carriers. For example, PDMS microemulsions, i.e. aqueous dispersions exhibiting particles in the range of 5–60 nm, can be obtained by polymerizing octamethylcyclotetrasiloxane (D4) in microemulsions stabilized with ionic and nonionic surfactants [71]. They are actually “nanolatexes” made of kinetically rather than thermodynamically stable particles, exhibiting transparency and very large surface area. Polymeric micelles formed by amphiphilic block copolymers have been evaluated in multiple pharmaceutical applications as drug and gene delivery systems, in diagnostic imaging, as carriers for contrasting agents [40].

Amphiphilic poly(dimethylsiloxane–methacrylic acid or –N-vinylpyrrolidone) (PDMS-PMAA or PDMS-PNVP) block copolymers (Figure 1, Table 1) were synthesized by radical polymerization of methacrylic acid or N-vinylpyrrolidone in the presence of siloxane azoester macroinitiators [72].

The critical micelle concentrations in water (Table 1) were determined by surface tension measurements, using the plate method (Fig. 2) and/or by fluorescence spectroscopy in the presence of pyrene as a probe (Fig. 3) [73]. The minimum surface tension for all analyzed copolymers was situated around 40 mN/m, showing a high efficiency in reducing the surface tension of water (for distilled water, $\gamma = 72$ mN/m), even though not as pronounced as in the case of cationic siloxane surfactants [39]. As one can see from the data in Table 1, the cmc values determined by these two methods are in good agreement and lower as compared to those of PMAA homopolymer of a similar molecular weight (Mn = 100 000) (5.62×10^{-3} at pH = 8), denoting the influence of PDMS hydrophobic sequence. The values for the methacrylic acid containing copolymers seem to decrease as the lengths of both methacrylic and siloxane sequences are increasing. However, the cmc results are difficult to correlate with the structural differences in the copolymers. This conclusion may be the result of the hydrophobic interactions between the methyl groups of PMAA and siloxane groups and the formation of the core aggregates, which consist of siloxane repeating units (Fig. 4). The cmc values are higher at pH = 8 as compared to those at pH = 3, typically by an order of magnitude.

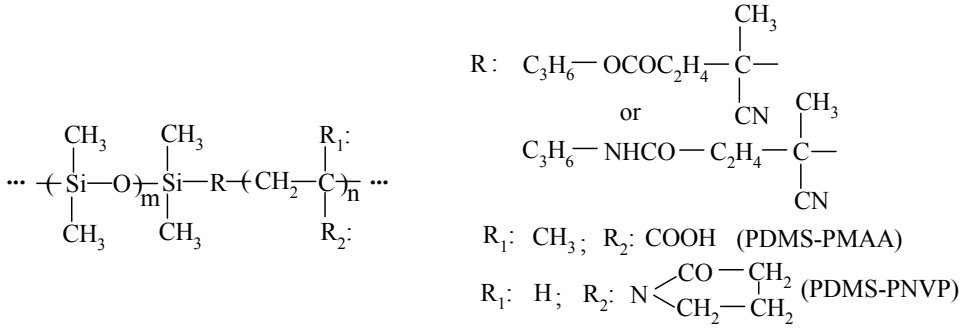

Fig. 1. Structure of amphiphilic siloxane block copolymers.

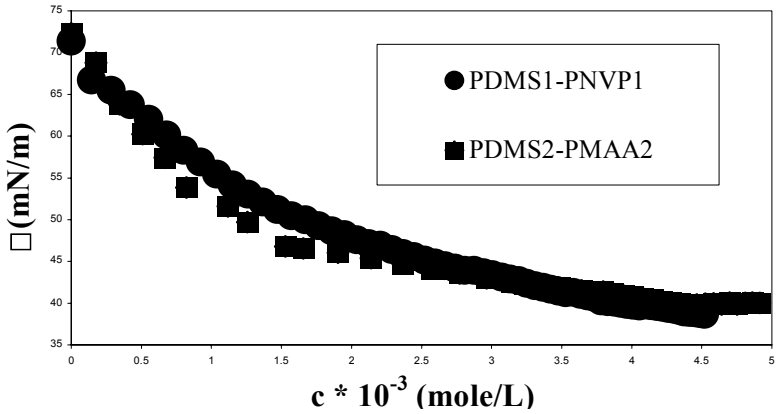

Fig. 2. Surface tension *versus* concentration for amphiphilic siloxane copolymers.

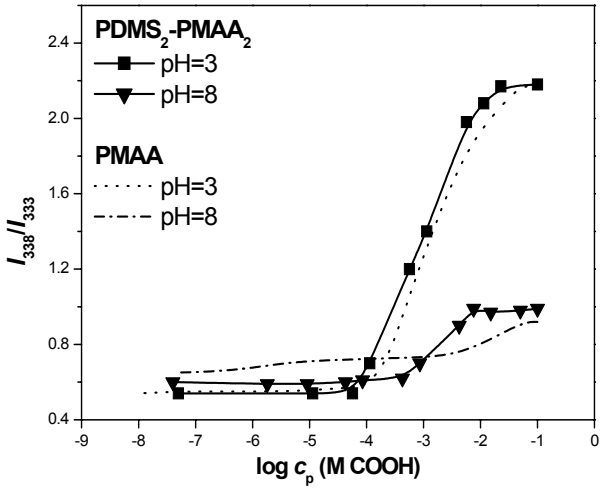

Fig. 3. Variation of the intensity ratio I_{338}/I_{333} in the excitation spectra of pyrene with polymer concentration and pH.

Table 1. Amphiphilic siloxane copolymers and their physico-chemical characteristics

Nr. crt.	Sample code	DP_{PDMS}	Vinyl / Siloxane (molar ratio)[a]	Mv[b]	Mn[c] (GPC)	cmc (mol vinyl/L x 10^{-3})		
						(from surface tension)	(from fluorescence spectroscopy)[d]	
							pH=3	pH=8
1	$PDMS_1$-$PMAA_1$	2	38	189 800		4.44	4.50*	-
2	$PDMS_2$-$PMAA_2$	5	73	-	52 500	-	0.06	0.62
3	$PDMS_3$-$PMAA_3$	12	10	121 400	-	1.24	-	-
4	$PDMS_4$-$PMAA_5$	22	42	95 300	-	-	0.10	3.20
5	$PDMS_4$-$PMAA_6$	22	157	350 800	-	-	0.06	1.70
6	$PDMS_1$-$PNVP_1$	2	36	26 600	27 100	2.03	0.89*	-

[a] As calculated from the integral ratios of the characteristic peaks in ^{1}H-NMR spectra
[b] Determined in methanol or water for MAA and NVP containing copolymers, respectively; Mv was calculated with the relations $[\eta] = 0.242 \times Mv^{0.51}$ for PDMS-PMAA and $[\eta] = 0.064 \times Mv^{0.58}$ for PDMS-PNVP copolymers, respectively [74]
[c] Determined by using polystyrene calibrating standards
[d] As determined from I_{338}/I_{333} ratio in the excitation spectra
* Values obtained at natural pH, i.e. 3.6 for $PDMS_1$-$PMAA_1$ and 5.1 for $PDMS_1$-$PNVP_1$

Telechelic oligomers, copolymers, as well as cyclic siloxanes bearing monosaccharide groups were also obtained by a procedure involving heterogeneous ion exchanger catalysis, combined with hydrosilation, using allyl–functionalized sugars (Fig. 5). Depending on the hydrophobic/hydrophilic ratio, water-soluble compounds were obtained. The critical micelle concentration was determined by superficial tension measurements, using the plate method**.** The obtained values, measured at 27°C, are in the range of 10^{-4}–10^{-5} M (about 0.2 g/l), which is in good agreement with the reported values for nonionic surfactants [46]. The values of the

minimum surface tension were found to be in the range 26–30 mN/m, lower than those corresponding to amphiphilic siloxane copolymers [73], but higher than those of cationic siloxane surfactants [39].

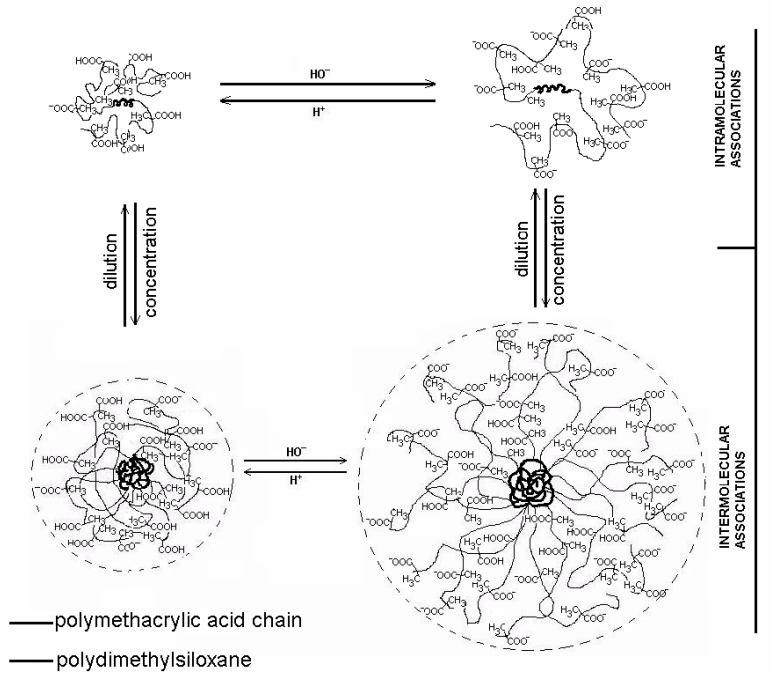

Fig. 4. Schematic representation of intramolecular (top) and intermolecular (bottom) interactions in PDMS-PMAA copolymers with increasing pH and concentration.

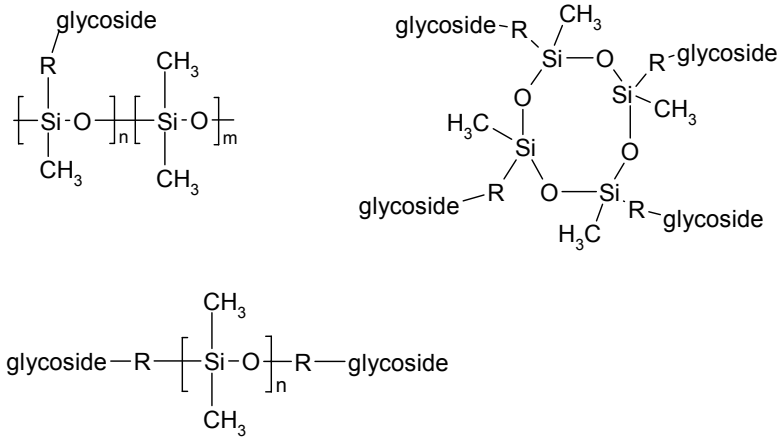

Fig. 5. Saccharide functionalized siloxanes.

3. NANOPARTICLES

Nanoparticles are defined as homogeneous particles or monolitic capsules, usually spherical, with dimensions situated in the range of nanometers. The preparation of nanoparticles can be performed by a large number of methods including both those starting from monomers (polymerization and polycondensation) and those involving – usually functional – preformed polymers (suspension crosslinking, solvent evaporation, coacervation, chelatization, nanoprecipitation, etc.).

Different types of functional polysiloxanes [75] and siloxane copolymers [76] were synthesized and used as blend compatibilizers and surface modifiers [77] or in different pharmaceutical and biomedical applications (contact lenses, implants, transdermal penetration enhancers) [78–80]. On the other hand, for biomedical purposes, poly(ε-caprolactone) (PCL) and its copolymers seem to be interesting synthetic substitutes of natural polymers in applications as vehicles for slow release of drugs [81–83] or as long term biodegradable – biocompatible ceramers appropriate for the repairing of skeletal tissues [84]. Nanoparticles based on amphiphilic copolymers containing poly(ethylene oxide) and PCL sequences have been proved to encapsulate various bioactive principles [85, 86] or even to present a stimuli (temperature)–responsive drug release behavior [87].

Two different systems based on PDMS and PCL were used to obtain unloaded or loaded particles with bioactive compounds. The first one contained a siloxane surfactant and PCL, the other one was composed of hydrophobic PDMS-PCL copolymer and poly(ethylene oxide-b-propylene oxide) surfactant.

3.1. Nanoparticles prepared in the presence of siloxane surfactants

Perhaps the most important component in nanoparticle formulations is the surfactant. Two types of silicone surfactants were tested in nanoprecipitation experiments to obtain unloaded or indomethacin (IMC) loaded nanoparticles, i.e., amphiphilic block copolymers (Figure 1, Table 1) or monosaccharide functionalized siloxanes (Figure 5). Polycaprolactone was used as core hydrophobic material. The average dimensions of the particles depend on the structure of the siloxane surfactant and on the preparation parameters. Particles with dimensions under 200 nm were obtained for initial concentrations in PDMS-PNVP block copolymer or monosaccharide functionalized siloxane surfactants as low as 2 or 1 g/L, respectively. The use of PDMS-PMAA surfactants in 2% concentration allowed the preparation of nanoparticles with dimensions between 200 and 300 nm. Even though a tendency of coalescence was observed during the concentration of water medium, the nanoparticles could be re-dispersed. Furthermore, their size was practically unchanged after three months of storing at room temperature. TEM micrographs (Figure 6) were taken after the sudden

evaporation of water and a pronounced coalescence was observed, probably due to very strong intermolecular H-bonding.

Preliminary tests were also made in order to study the stabilization of a high molecular weight monosaccharide functionalized polysiloxane. The obtained nanoparticles sizes were greater than in the case of PCL at the same initial concentration of the surfactant (350–500 nm). The best results were obtained with surfactants having the smallest hydrophile/hydrophobe ratio.

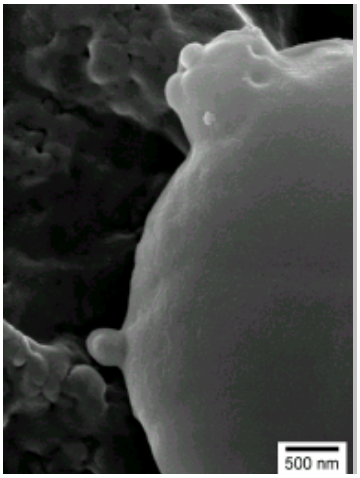

Fig. 6. TEM micrograph of PCL nanoparticles after water evaporation.

3.2. Encapsulating nanoparticles based on siloxane-caprolactone copolymers

PCL-PDMS di- and triblock copolymers (Fig. 7, Table 2) were obtained by coordination anionic polymerization of CL in the presence of triethylaluminum catalyst and excess of hydroxyalkyl mono- or difunctional PDMSs as chain transfer agents [88].

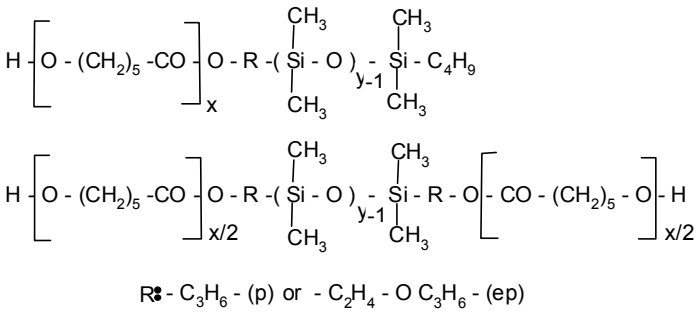

Fig. 7. PCL-PDMS di- and triblock copolymers used for the preparation of nanoparticles.

Stable unloaded and loaded (with indomethacin (IMC) or vitamin E (VE)) nanoparticles of low dimensional polydispersity were prepared through nanoprecipitation in water from dilute acetone solution of PCL-PDMS copolymers, in the presence of Pluronic emulsifier [poly(ethylene oxide) (PEO)-poly(propylene oxide) copolymer] (Table 2). For all used copolymers, the dimensions of unloaded particles ranged between 124 and 194 nm. Particle dimensions and size distribution (PSD) do not increase by loading small amounts of IMC (10% *versus* polymer weight in the nanoprecipitation feed). The nanoparticles loaded with a relatively higher amount of VE present larger dimensions and increased PSD as compared to the unloaded homologues.

Table 2. Characteristics of PCL-PDMS copolymers and of nanoparticles prepared therefrom

PCL-PDMS copolymer				Unloaded particles		DLE[d] (%)			
Sample code[a]	PDMS transfer agent[b]	Mn, $_{PCL}$	Mw/Mn (SEC)	Size (nm)	PSD[c]	VE		IMC	VE
						Size (nm)	PSD[c]		
D	ep_1PDMS_{800}	1x3200	1.19	-	-	343	0.65	-	60.80
T1a	p_2PDMS_{1500}	2x4800	1.38	194	0.09	264	0.52	-	54.73
T1b	ep_2PDMS_{1500}	2x4700	1.18	130	0.10	350	0.43	-	54.75
T2	ep_2PDMS_{1500}	2x2850	1.11	131	0.07	-	-	10.05	-
T3	ep_2PDMS_{3000}	2x5000	1.13	130	0.14	249	0.57	-	52.80
T4	ep_2PDMS_{4000}	2x7100	1.22	140	0.18	260	0.54	-	53.20

[a] D and T mean diblock and triblock PCL-PDMS copolymers

[b] p and ep mean propylene and ethoxypropylene spacers between OH groups and the siloxane chain; 1 and 2 refer to mono- and difunctional polymers; subscript numbers after PDMS indicate the average number molecular weight of the siloxane chain

[c] PSD represents the width of the distribution as determined by dynamic light scattering measurements on a laser Coulter LS apparatus

[d] DLE represents drug loading efficiency determined by UV analysis and calculated according to DLE = [drug amount/(drug amount + polymer amount)] x 100

There is no reliable correlation between particle dimension and the molecular characteristics of CL copolymers. However, the lowest molecular weight PCL–PDMS copolymer, with a higher content of OH terminal groups, able to interact with PEO–PPO–PEO emulsifier, yields the highest dimension of the nanoparticles.

^{1}H-NMR spectrum (Fig. 8, top) of nanoparticles solubilized in $CDCl_3$ show the characteristic peaks of the constituents (δ, ppm: PCL: 1.65, 2.62, 4.17; PDMS: 0.1; IMC: 3.69, 3.81, 6.40–7.50; Pluronic: 1.13, 3.10–3.90, 3.63). However, in water, the stable dispersion of nanoparticles shows only the peaks of Pluronic emulsifier (Fig. 8, bottom), suggesting a core-shell structure composed of a PCL-PDMS/IMC hydrophobic core and a Pluronic hydrophilic shell. The nanoparticles with a PEO-like surface are expected to have a good mobility in water and to resist protein absorption and cellular attachment.

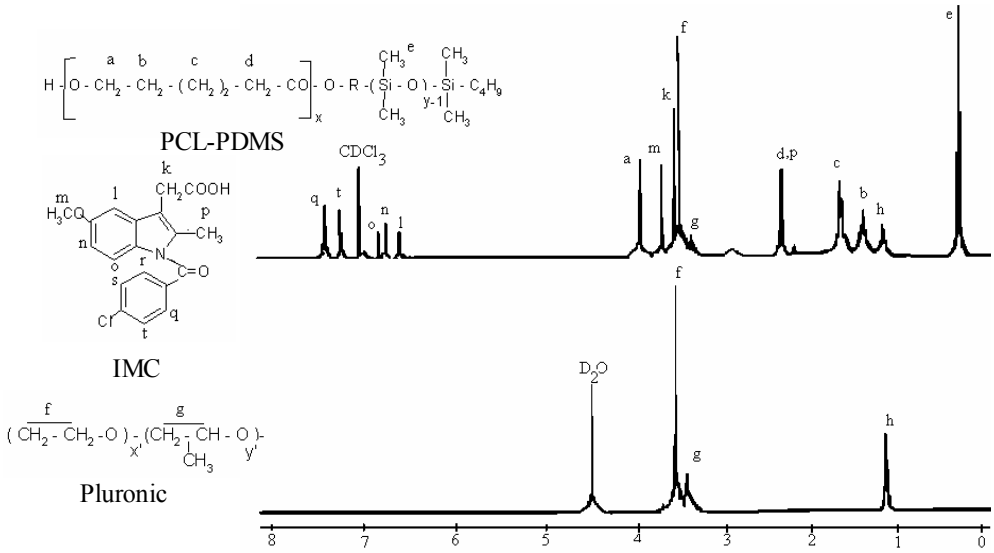

Fig. 8. ^{1}H-NMR spectra of indomethacin loaded nanoparticles: solubilized in $CDCl_3$ (top) and dispersed in D_2O (bottom).

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Ionic Polyurethanes with Biomedical Applications. Trends in Nanostructuring

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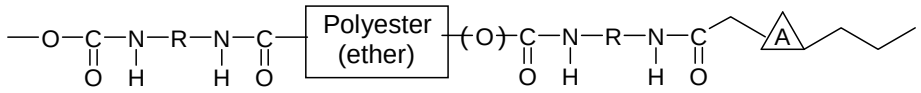
Abstract. We report a short review concerning some polyurethanes with specific functional groups incorporated in the macromolecular backbone by means of cholesteryl diol, dihydroxamic acids and/or 2,6-bis(hydroxymethyl)pyridine, N,N,N,N-di(β-hydroxyethyl)didodecylmethylammonium moieties. The elastomers investigated are constructed of poly(caprolactone) diol alone or together with poly(ethylene oxide) diol of 2000 molecular weight, as soft segment, and hard segments derived from aliphatic diisocyanate and the above-mentioned diols. The characterization tests for all polymers included IR and NMR spectral data, viscosity measurements, GPC, thermal and elemental analysis. The polymeric films, prepared from polyurethanes with urethane-cholesteryl and alkylammonium moieties exhibited in appropriate conditions an enzymatic degradation process. The opposite optical rotation of the cholesteryl-polycation compared to that observed for the starting monomer suggested a chiral perturbation of the ordered conformations in solution. Attempts to obtain polyurethanes based on dihydroxamic acids resulted in biocompatible materials with a good antitumoral activity against Walker 256 Carcinoma cells. Comparative studies showed that polymers with a minor concentration of pyridinium or ammonium groups could inhibit the growth of a bacterial culture (*E. coli, S. aureus, B. subtilis, Proteus, E. coli/Proteus*).

1. INTRODUCTION

The development of biomedical polyurethane materials continues to be motivated by the notable results of the production of surgical implants with controlled properties [1-3] and the proliferation of a vast array of nanostructures for creating unique systems [4, 5]. The main approaches to achieving desired materials can be divided into four categories: firstly, polymers with complex functionality such as phosphatidylcholine analogues [6, 7], secondly, the use of aqueous dispersions capable to form micro/nanospheres [8], thirdly, the composites/ nanocomposites based on polymers and metals, silica, organosilicates [9, 10], and fourthly, amphiphile gels [11-13]. Some example applications, including separation

membranes, actuators, cardiovascular and soft tissue engineering, biosensors or drug delivery, provided further impetus to design more efficient polymers concerning specific properties such as biocompatibility, antythrombogenicity, longer/shorter duration of actions and less toxic side effects, higher specificity of actions, mechanical characteristics in the biological environment. To date, although a variety of commercial biopolyurethanes do exist, only a few have been applied extensively.

One of the polymers targeted for use in biomedical applications is based on polyether(ester)polyol, a diisocyanate and a chain extender of ionic or non-ionic type. A schematic diagram of the segmented polyurethanes is presented in Figure 1.



where R is a rest of diisocyanate (MDI, IPDI, HMDI) and
A is a rest of diol, diamine, diacid

Fig. 1. Molecular structure of segmented polyurethanes.

Starting from this structure, several polyurethanes were investigated along with some well-characterized model systems in order to relate better the time-dependent changes to the actual chemistry and structure of the material. In brief, these polymers can be described as a chain made up of a soft flexible segment connected together with short hard segments including urethane groups and non- or hydrophilic sites (ionic groups such as alkylammonium, acetate or sulfonate salts). Consequently, the properties of the polyurethane block copolymers can be adjusted and balanced by variations of the relative percentage of the components and its nature. As a result of the diverse chemistry that can be used in producing specific polymers, much effort has been placed on understanding how changes in structure may be related not only to the initial properties but also to their variation in time when placed within a physiological environment. The solution of these basic problems should include the biological and physicochemical approaches, which must harmonize with one another. The application of these polymers involves both stable materials, which can serve as prostheses, and materials with limited stability, which undergo degradation after some time and are replaced with tissue. Accordingly, two trends of creating polymeric materials used in medical practice appeared: (a) materials resisting the influence of the living organism media and (b) materials resisting only for a definite period of time.

Recent investigations have revealed that during the exploitation of some implanted devices [14] there is an important degradation of the polymers which can be avoided by incorporating non-ether polyol chain segments such as poly(butadiene), poly(isobutylene), poly(carbonate) and/or poly(dimethylsiloxane). Furthermore, the structural and compositional flexibility as well as the relationship between blood contacting properties and the interfacial chemistry of these block copolymers of AB type can influence the different manifestation of each structure

and its antithrombogenicity, surface morphology, and surface properties. Additionally, due to the dissimilarity in the chemical structure of the constituent segments, there is generally thermodynamic incompatibility between these segments so that the formation of a microphase-separated domain structure consisting of hard-segment-rich and soft-segment-rich domains can contribute to the antithromogenic properties of ionic polymers. The potential driving force for the microdomain formation is a combination between hydrogen bonding and the electrostatic interactions between the ionic groups (under 1 meq/g polymer), as well as a possible crystallization of both phases [15].

The morphology of a non-ionic polyetherurethane with 30% hard segment content revisited by complementary AFM and TEM exhibited a multi-phase segregation on two levels (micro and nano) of structural organization [6, 16]. Visualizing the structure of phase-separated domains, microdomains of 20 nm length for soft segments and 5-10 nm for hard segments, were recently evidenced (Figure 2). At higher hard segment content, a larger scale structure was found consisting of both hard and soft segments. A significant advance in this area has been the synthesis of nanocomposite where the structural order within the material can be controlled on a nanometer scale. In particular, the inclusion of well-defined polymers into inorganic substrates, for instance silica, is of significance, because the functionality, composition and dimensions of these macromolecules enable the design of specific properties into the resulting hybrid.

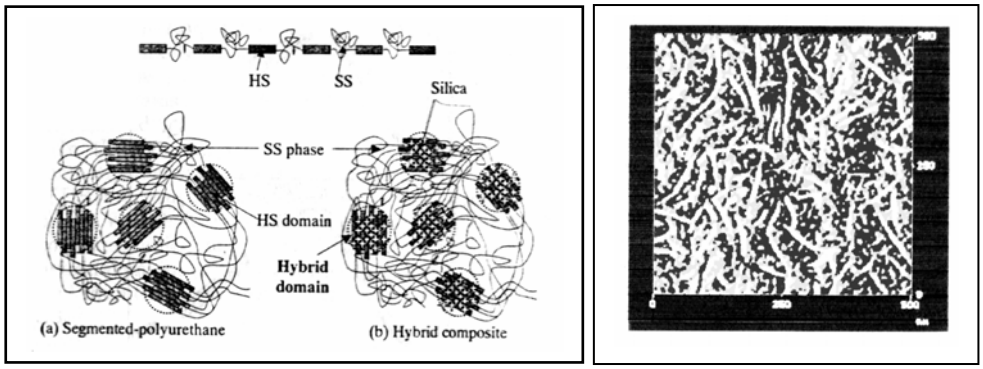


Fig. 2. The domain structure in polyurethane or a composite hybrid.

The first nanometers of the surface samples were also investigated by the XPS surface characterization of novel ionic perfluoropolyurethanes from the aqueous dispersions, as well as by ion mass spectrometry analysis [17]. It resulted that a clear surface enrichment in fluorine and its stratification in relation to the ionic character and film forming ability provided an interesting system to evidence nanostructuring of these structures intended for coating or surface treatments.

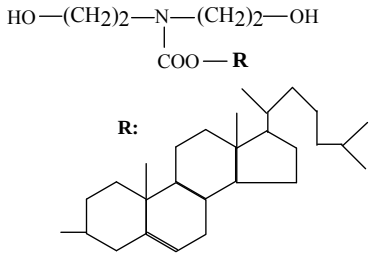
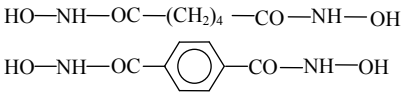
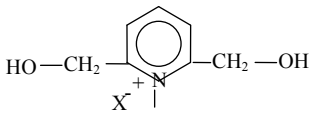
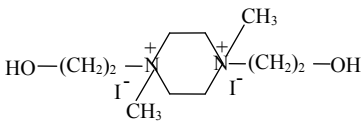
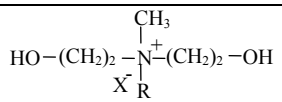
Therefore, the synthesis of new materials with improved properties and performance is a continually expanding frontier at the interface of chemistry and materials science. Such a task often requires complex synthetic pathways, modern investigation methods and a wide range of testing techniques. In the following, we

first review the preprogrammed properties of new amphiphilic polyurethanes based on polyester(ether) diol, isophorone diisocyanate (IPDI) and chain extenders differing in structure with emphasis on some biological aspects of the polymers.

2. PROSPECTS AND APPLICATIONS

As a part of our program, corollary work has been undertaken in our group to obtain novel polymers, in which the introduction of specific units (Table 1) into the main or side chain by means of a chain extender has proven to be significant in view of preparing biomaterials.

Table 1. The effect of chain extender on the polymer behavior

Structure	**Property**
	Biocompatibility
	Antitumoral (*in vivo*)
	Antibacterial
	Antibacterial
 R: Alkyl $C_{10,12}$; Chol., benzyl	Biocompatibility

2.1. Enzymatic hydrolysis of the polymers with cholesteryl and alkylammonium groups

One approach to preparing biopolymers has been the incorporation of cholesterol, whose important role to modulate the structural and dynamic properties of phospholipid double-layer membranes is well-known [18]. Except the polyurethanes with a zwitterionic structure of phosphatidylcholine, there is no information about the influence of the cholesteryl fragment on the properties in the ionic polymers possessing such groups, susceptible to promote a stronger interaction between the main backbone and pendants. Therefore, it is of particular interest to explore a way of preparing the cholesteryl-containing ionic polymers. Thus, polyurethane cationomers (Chol-PUC) based on cholesteryl diol toghether with N,N,N,N-di-(β-hydroxyethyl)didodecylmethylamonium as chain extender, poly(caprolactone) diol (PCL) and isophorone diisocyanate (IPDI) were synthesized and characterized (Figure 3). As expected, attaching long alkyl side chains on the quaternary ammonium structure into a polyurethane backbone can improve the biocompatibility of blood-contacting surfaces [19].

The structure of Chol-PUCs was confirmed by spectral data and elemental analysis. The characterization tests for polymers also included DSC, GPC and viscosity measurements. All polymers dissolved in polar solvents such as DMF, DMA, DMSO and the increasing content of hydrophilic sequences did not improve their solubility in other common organic solvents or in a mixture of DMF/H_2O. One major feature of these polymers is that polymer solutions can yield transparent and soft flexible films of elastomer type, with a good adherence on different substrates. With the current increased interest in the elastomer polymers to satisfy a diverse range of physical properties, a preliminary study of Chol-PUCs subjected to hydrolytic degradation was initiated.

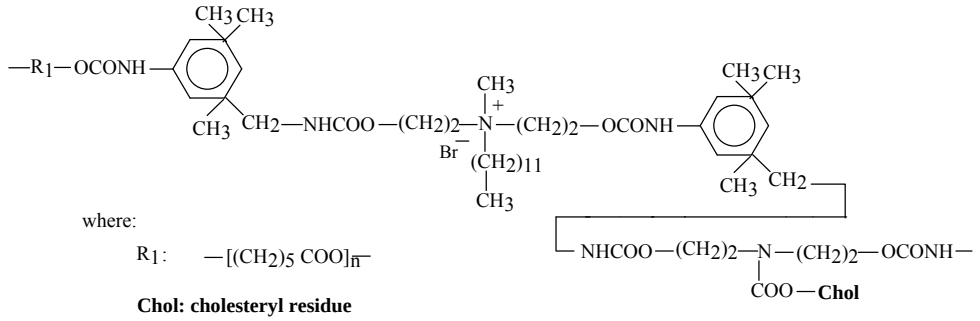


Fig. 3. The structure of polyurethane cationomers with a cholesteryl fragment and alkylammonium groups.

As a rapid method to evidence the degradation of PCL sequences in the corresponding polymers, the enzymatic process in the films subjected to a

phosphate buffer solution containing *Pseudomonas* (Ps) lipase at pH 7 and 37 ^{0}C [20, 21] was chosen. As a companion sample, a polymer film containing poly(tetramethylene oxide) sequences (PTMG) was also assessed. The enzymatic degradation of these films followed by the weight loss in the above conditions is shown in Figure 4 (Plot a, b). A comparison between these polymers immersed in phosphate buffer solution in the absence of lipase and exposed to the action of lipase suggested that only by subsequent enzymatic treatment a progressive degradation of the polyesterurethanes was indeed promoted. Moreover, the films showed a complete degradation in about 6 days. GPC measurements also sustain that the average molecular weight of the poly(esterurethane)s started to decrease slowly during the first two days of keeping in a solution with lipase.

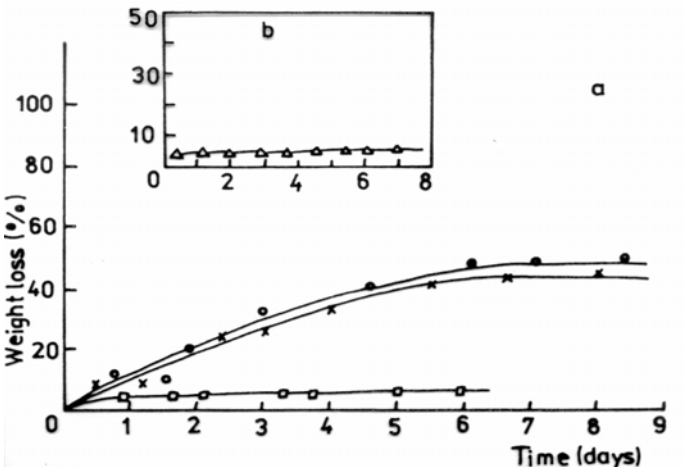


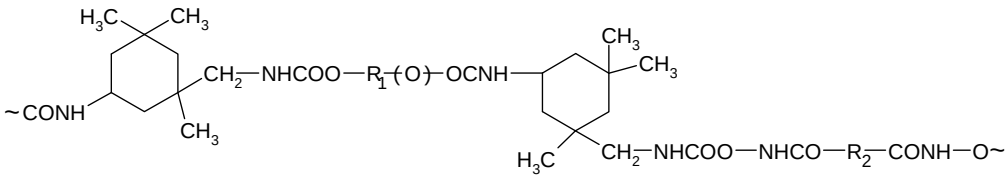
Fig 4. The weight loss of films of phosphate buffer solution: (a) in the presence of lipase, PCL-polymers (•), (×) PTMG-polymer (o) and (b) in the absence of lipase, PCL-polymer (Δ).

By contrast, the PTMG-containing film did not undergo any change in weight under working condition [22]. These briefly discussed data of biodegradability of the cholesteryl cationomers will be a starting point in further exploring such structures, relevant as coating materials for potential biomedical applications or in the detection of enzyme concentrations and the construction of biosensors.

2.2. Assessment of antitumoral effect in polymers containing dihydroxamic acids

In the framework of an ongoing research line, it appeared rather interesting to investigate some polyurethanes incorporating dihydroxamic acids into polymer chains that were anticipated to exhibit biological activity. The selection of dihydroxamic acids as novel chain extenders is not by chance, because a large variety of monohydroxamic derivatives are known as antimicrobian, antiinflammatory

or antitumoral agents [23, 24]. To demonstrate the biological properties of some dihydroxamic acids, we have initially chosen the terephtaloyl dihydroxamic acid (for PUT-1,2) and adipoyl dihydroxamic acid (for PUA-1,2), whose *in vivo* antitumoral activity was previously evidenced [25]. The preparation of the polymers (Figure 4) implied the use of the polyol mixture, namely PCL, poly(ethylene oxide) diol (PEO), isophorone diisocyanate and one dihydroxamic acid [26].



R_1 : PCL, PCL : PEO (1:1, 1:4)

R_2 : $-(CH_2)_4-$

Fig. 5. The structure of polyurethanes based on dihydroxamic acid.

The above polyurethanes were *in vivo* tested, according to well-known pharmacological methods. Upon contact of animal blood with polymer suspensions, some biochemical parameters such as cholesterol, glycemia, proteins and albumin were determined. Table 2 illustrates the difference between average values recorded on Wistar rats treated with polymers comparatively with control groups. Low amounts of polymer can induce a pronounced hypoglycemia, while the values of cholesterol, proteins and albumin remain within normal limits. A similar response of some hydroxamic acids as hypoglycemic agents has also been reported [27].

On the other hand, PUA and PUT produced a decrease of the gamma globulin fraction from the normal values, suggesting that there are marked differences in the interaction of blood with polymers based on aliphatic dihydroxamic acid comparatively with the samples possessing aromatic amide-urethane groups. Subsequently, we determined the hematological values recorded on the rats treated with all polymers (Table 3).

The effect of the administration of these polymers *in vivo* comparatively with control groups was observed. The experimental results seem to indicate that our polyurethanes used in a daily dose of 62.5 mg polymer/kg body weight for a period of 5 days, lead to a serious anemia reflected by the decrease of erythrocyte number and hematocrite, while the leucocitary series remains unmodified.

Table 2. Effects of the administration of polyurethanes on some biochemical parameters of Wistar rats

Code of groups	Control	PUT-1	PUT-2	PUA-1	PUA-2
Cholesterol, mg/ dL	65.93 ± 1.72	65.25 ± 4.87	69.68 ± 0.03	64.76 ± 3.45	66.58 ± 2.49
Glycemia mg/ dL	78.33 ± 2.51	67.50 ± 3.53	69 ± 2.82	56 ± 4.24	61 ± 2.82
Total proteins, g $^0/_{00}$	73.33 ± 1.15	70.6 ± 1.21	71.33 ± 3.05	70 ± 2.82	67 ± 4.44
Albumin %	31.80 ± 2.17	30.2 ± 1.30	30.33 ± 3.26	31.5 ± 1.27	28.16 ± 1.47
α_1	4.7 ± 0.5196	4.6 ± 0.30	5.1 ± 0.75	5.2 ± 0.28	5.5 ± 0.25
α_2	8.10 ± 0.0577	7.7 ± 0.43	8.2 ± 0.26	8.5 ± 0.63	7.5 ± 0.35
β	15.40 ± 1.5011	13.9 ± 0.55	14 ± 0.80	13.1 ± 2.54	13.3 ± 1.20

Table 3. Hematological values recorded on Wistar rats treated with polyurethanes

Code of Groups	Control	PUT-1	PUT-2	PUA-1	PUA-2	PU-0	Solvent DMF/ H_2O
H × 10^{-6}/ mm^3	9.0 ± 2.1	5.0 ± 0.7	5.0 ± 0.3	57 ± 0.4	4.1 ± 0.8	2.0 ± 0.6	7.5 ± 4.3
Hb, g %	13.06 ± 0.80	9.11 ± 0.28	9.58 ± 0.62	11.53 ± 1.11	10.83 ± 0.56	5.49 ± 1.56	12.96 ± 1.39
Hct, %	49 ± 3.46	38.5 ± 12.02	51.5 ± 7.78	45.5 ± 6.36	39 ± 1.41	31 ± 4.24	43.75 ± 7.1
L / mm^3	11600 ± 1833	12300 ± 5798	11050 ± 353	10400 ± 5091	5200 ± 848	11900 ± 4949	12325 ±7637
MCH, $\mu\gamma$	26.65	18.22	19.16	23.06	27.08	21.95	21.11
MCHC, %	14.44	23.66	18.60	25.34	27.78	17.52	31
MCV μ^3	54.44	77	103	91	97.5	126.65	74.87

Where: H, number of erythrocytes; Hb., hemoglobin; Hct., hematocrite; L, number of leucocytes; MCH, mean corpuscular hemoglobin; MCHC, mean corpuscular hemoglobin concentration; MCV, mean corpuscular volume

Compared to these polymers, a reference polyurethane (PU-0 prepared from PCL, IPDI and N-methyldiethanolamine) and the binary solvent DMF:H_2O (4:1 v/v) were administrated to rats. It was found that some modifications of the hematological values, in particular hemoglobin decrease, were also induced. The first observation yielded surprising results concerning the interaction of blood with all polyurethanes with or without biologically active segments as well as amide-urethane model or solvent.

Some attempts on the antitumoral activity of all polymers comparatively to a model were carried out *in vivo* too. The average tumor regression (ATR) values,

defined as higher than 35%, according to literature data [28], provides a useful picture of the sensibility of Walker 256 carcinoma cells against tested polymers. By studying the behavior of polyurethanes (Figure 6) we observed that the polymers based on aliphatic dihydroxamic acid (PUA-1, PUA-2) with a relatively higher ATR of 59% and 46.5%, respectively presented a good antitumoral activity.

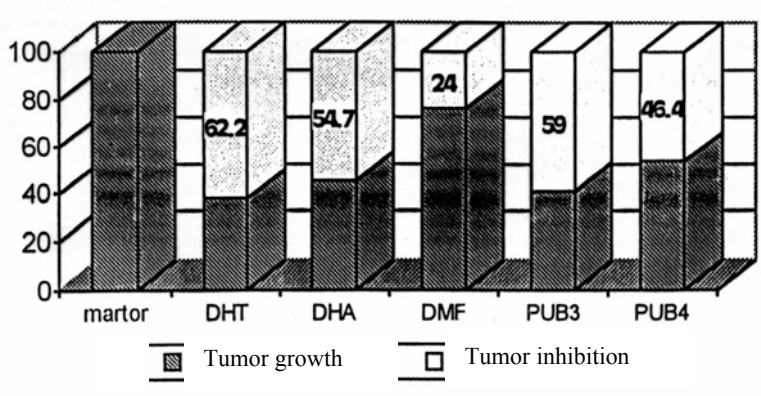


Fig. 6. Average tumor regression (ATR, %) values for tested samples.

A substantial deviation from the expected behavior has been found in experiments using polyurethanes with aromatic segments (PUT-1, PUT-2), the activity of whose (especially for PUT-2) was negligible. Compared to the corresponding monomers (DHT, DHA) with ATR values reaching 62% and 54% respectively, the studied polymers showed a lower activity which was generally expected. Following then the biological changes in the antitumoral response that occurred by the administration of PU-0, it could be concluded that only polymers chemically modified with some active moieties of amide-urethane type have shown any therapeutic effect. Unlike the DMF, recognized for its acute toxicity, after injection of binary solvent it is seen that the ATR value (25.6%) is equivalent with that obtained for ordinary polymer. By incorporating ionic groups similar results were obtained [29]. The observations accumulated during our study are only the beginning but the question why the polyurethanes differ in their biological activity so widely remains. Much additional work will be needed to see whether these new polymers are truly promising leads as cytodifferential agents for human treatment.

2.3. The antibacterial response of the polymers with pyridinium groups

In recent years, a lot of studies have reported data on the distinctive bioactivity of the pyridinium-type polymers and consequently, their bactericidal ability against some bacteria, viruses and other negatively charged species [30, 31]. This provides an opportunity to recommend them as potential candidates for applications in biotechnology, microbiology, environmental protection or

biosensors [32]. We have recently reported the preparation of new segmented polyurethanes based on PCL with or without PEO, IPD and 2,6-bis-(hydroxymethyl)pyridine. By a quaternization of the pyridine rings with benzyl bromide (about 85% quaternization degree) cationomers of pyridinium type were obtained (Figure 7) to examine their antimicrobial activity [33].

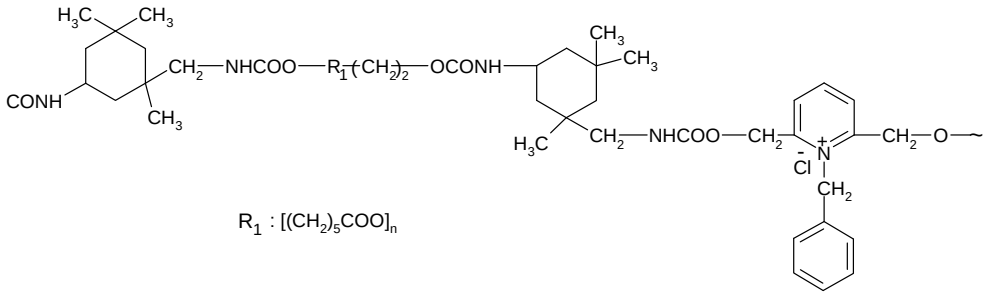


Fig. 7. The structure of polyurethane cationomers with pyridinium rings.

Therefore, Gram-positive and Gram-negative bacteria of type *Escherichia coli*, *Staphylococcus aureus* and *Bacillus subtilis* were put in standard conditions of cultivation (cultivation medium, inoculation, incubation time) in the presence of a determined quantity of polymer solutions in DMAc. The antimicrobial activity was evaluated in terms of suppression of the colony growth. The results listed in Table 4 show the ability of the polyurethane cationomers to kill different bacteria. It can be seen that these species of bacteria have a significant influence upon the bactericidal ability of the testing samples.

Table 4. Antimicrobial activity of the pyridinium polyurethane cationomers

	Suppression of the growth, R_i (mm)*								
	E. coli			*S. aureus*			*B. subtilis*		
	0.8	0.4	0.2	0.8	0.4	0.2	0.8	0.4	0.2
Polymer	(mg poymer×mL^{-1})								
Py-PUC-1	8	6	4	12	6	3	7	5	3
Py-PUC-2	6	4	3	10	4	2	6	5	3
Py-PUC-3	5	4	2	7	4	3	5	3	2
Py-PUC-4	5	3	2	6	4	2	4	2	2

- *- radius of the inhibition zone

Following the effect of the polymer concentration it was observed that all polycations exhibited a certain activity against *E. coli* and *S. aureus* at concentrations of about 0.8 mg mL^{-1}. As the polymer concentration decreases to 0.4 mg×mL^{-1} and 0.2 mg×mL^{-1} respectively, the antimicrobial action of all polycations on bacteria consequently diminished. Moreover, the introduction of

hydrophilic segments into a polyurethane backbone can not be considered an advantage for the bactericidal activity of these polymers. In a similar way, other polymers with a higher content of ammonium quaternary structures introduced on the macromolecular chain by means of Menschutkin synthesis were also tested [34, 35]. It was appreciated that the sensitivity of the tested bacteria (*E. coli, S. aureus, Proteus, E. coli/Proteus*) at low concentrations of polycations in ethanol: water (80:20 v/v) is comparable with that shown when some drugs were used (Negram, Nitrophurantoine). Antimicrobial properties evidenced during our study will demand further investigations concerning the biocompatibility of the polymers to be applied to the infected area. With future efforts it should be possible to produce polyurethane coatings with high bactericidal ability as a new generation of polymeric antibacterial agents.

3. CONCLUSIONS

A novel series of aliphatic polyurethanes containing cholesteryl and alkylammonium groups, pyridinium rings or ammonium quaternary structures on the macromolecular chain was prepared and characterized. Depending on the nature of the anchored functions, the physicochemical properties, as well as biological activity can be drastically affected. Introducing dihydroxamic acids into a polymer backbone improved the compatibility of polyurethanes so that compatible polymers with antitumoral activity may be obtained. The examination of the effect of the polyol component on the degradation of the cholesteryl-PUs revealed the susceptibility of polymeric films with polycaprolactone sequences to enzymatic degradation. *In vitro* comparative tests demonstrated that polycations of pyridinium and ammonium type inhibited the growth of a bacterial culture (*E. coli*, *S. aureus*, *B. subtilis*, *Proteus*, *E. coli/Proteus*). It was found that the antimicrobial activity of some polymers depends on the chemical structure of the principal backbone, the molecular weight, the concentration of ionic groups and the counterion nature. Such polymers with a well-defined number of biologically active segments and a small concentration of ionic groups exhibiting good film-forming ability as well as a typical elastomeric behavior might be used as coatings or surface-active additives on or in conventional polyurethanes, textiles. The quality of one of them to respond to an enzyme could be exploited in the construction of biosensors.

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Multifunctional Materials Based on Maleic Anhydride Copolymers

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Abstract. We are interested in maleic anhydride/acid based polymers that can be prepared from easily accessible commercial monomers and display a broad range of hydrophobicities and functionalities. By appropriate choice of the comonomer or by chemical transformation, multi-functional polymers are obtained which offer a variety of effects and applications. From the results already obtained or in progress we will present here: layer-by-layer deposition from maleic polyelectrolytes and dyes (Rhodamine G); synthesis of new maleic copolymers derivatives containing dyes or chromophores for optical applications; organo-inorganic composites or hybrids based on maleic acid copolymers and phosphates/hydroxyapatite; systems for controlled delivery of bioactive substances; synthesis of new MA copolymers with bulky/hydrophobic comonomers such as vinylnaphthalene, N-vinylcarbazole, N-vinylcaprolactame.

1. INTRODUCTION

Maleic anhydride copolymers are largely used, as antiscale agents, phosphate substitutes in detergent compositions, dispersants, flocculants, soil conditioners and others [1]. The interest for the biomedical application of maleic anhydride/acid copolymers as drugs, drug carriers, or biomaterials is continuously growing [2]. Maleic anhydride (MA) is not easily homopolymerized, but will readily copolymerize with a great variety of other comonomers when binary as well as ternary copolymers or multipolymers are obtained with the general

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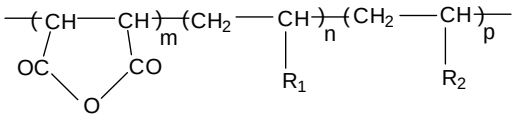
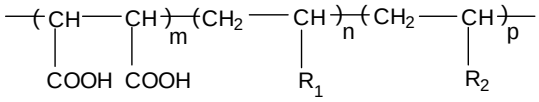
chemical structure, shown in Scheme 1, where m,n≠0, m=n or m≠n and p=0 or p≠0 and R_1 and R_2 are different substituents.



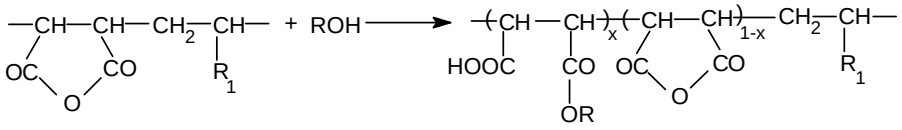
Scheme 1. Chemical structure of a ternary maleic anhydride copolymer.

These substituents can be more hydrophilic or more hydrophobic, allowing the design of the copolymer according to the requirements of the application. The copolymerization mechanism of MA is different from the classical one because MA, which is an electron acceptor, can form charge-transfer complexes (CTC) with donor monomers. Depending on the comonomer, the CTC will participate more or less in the chain propagating reactions so that the most MA copolymers have a predominantly alternating, easily reproducible structure. By the hydrolysis of the anhydride ring, maleic acid copolymers are obtained having the general formula presented in Scheme 2, with m, n, p as above.

Scheme 2. Chemical structure of a ternary maleic acid copolymer.



The chemical transformation of MA copolymers is another way to obtain new maleic copolymers with tailored properties. Besides the hydrolysis, many other reactions can be performed on MA copolymers with low molecular compounds having OH or NH_2 groups, such as alcohols or amines [3, 4]. When the reaction with alcohols or amines is performed in mild conditions, the monoesters or monoamides are obtained. In Scheme 3, the reaction with alcohols is exemplified.



Scheme 3. The reaction of MA copolymers with alcohols.

If the chemical transformation of MA copolymers is performed with low molecular compounds having different groups/functions, multi-functional polymers can be obtained, as presented in Figure 1:

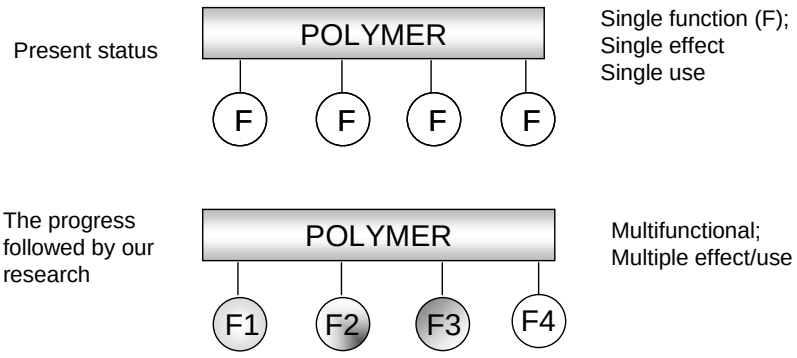


Fig. 1. The structure of multi-functional polymers having multiple applications.

The properties of maleic copolymers as multi-functional materials were less developed, but it can be easily seen that they are particularly suitable for this purpose. Their chemical structure can be tailored either by the appropriate choice of the comonomer (hydrophilic or hydrophobic) or by the chemical transformation with suitable low molecular compounds bearing different functions: charged groups (by hydrolysis), which result into polyelectrolyte behavior, dyes or chromophores, bioactive molecules and others [5, 6]. Moreover, they can be obtained from easily accessible commercial monomers which are relatively cheap, by radical copolymerization in organic solvents using common initiators such as benzoyl peroxide or azobisisobutyronitrile [AIBN – 2,2'-azobis(2-methylpropionitrile)]. So they are good candidates for various applications in which they can interact with small organic or inorganic ions or molecules, synthetic or natural, neutral or charged macromolecules. In this paper we will present some applications where these properties of maleic anhydride/acid copolymers or their derivatives were exploited. The neutral co-monomer units which we currently use, were N-vinylpyrrolidone (NVP), vinyl acetate (VA), methyl methacrylate (MMA), and styrene (St), given in the order of increasing hydrophobicity. From the results already obtained or in progress we will present here:

- layer-by-layer deposition from maleic polyelectrolytes and dyes;
- synthesis of new maleic copolymer derivatives containing dyes or chromophores for optical applications;
- organo-inorganic composites or hybrids based on maleic acid copolymers and phosphates/hydroxyapatite;
- systems for controlled delivery of bioactive substances;
- synthesis of new MA copolymers with bulky/hydrophobic comonomers such as vinylnaphthalene, N-vinylcarbazole, N-vinylcaprolactame.

2. LAYER-BY-LAYER DEPOSITION OF RHODAMINE 6G FILMS USING MALEIC ACID COPOLYMERS AS ANIONIC PARTNERS

Layer-by-layer (LbL) growth of polyelectrolytes (PE) is an effective way of preparing ultrathin polymer films that provide a high degree of control over structure, composition and thickness. Since the alternated deposition of polyanions and polycations onto surfaces was developed a few years ago by Decher [7], the research effort on such ordered PE complexes (LbL films) increased rapidly. It is believed that adsorption occurs through the interaction of a charged substrate with an oppositely charged polyion changing the surface charge. Alternating exposures of the surface to polycations and polyanions lead to multilayer formation. As an important extension of this technique other charged species can replace one of the polyions so that low-molecular-weight-charged compounds, such as dyes, can be incorporated into these layers [8-12]. Assemblies, including dyes or pigments, have received great interest in recent years due to their applications in coatings, printing, information storage and display technologies.

We exploited the layer-by-layer technique to produce dye-containing multilayer films with Rhodamine 6G which is used as an active medium for a large variety of dye lasers. Maleic acid copolymers could be suitable partners in LbL technique due to the presence of two carboxylic groups in each maleic unit which can dissociate in two steps depending on external conditions [13]. Additionally, the hydrophilic/hydrophobic balance can be varied by the appropriate choice of the comonomer(s) which is an advantage taking into account that the hydrophobic forces can contribute to LbL assembly [14]. To our knowledge, only few attempts have been made to use maleic acid copolymers as partners in the LbL technique [15-17]. In the following, recent results regarding the assembly of the Rhodamine 6G and maleic acid copolymers as cationic and anionic partners, respectively, will be reported, using poly(allylamine hydrochloride) as cationic partner for coating the substrate's surface. Maleic partners were obtained from MA copolymers with VA (NaM-VA) or MMA (NaM-MMA). The synthesis of the copolymers was described elsewhere [18, 19]. The corresponding maleic acid copolymers in sodium salt form were prepared by hydrolysis with NaOH aqueous solution for 24h.

Binary multilayers were prepared by alternately dipping the substrate into solutions of anionic polyelectrolytes and cationic dye R6G, the LbL deposition being monitored by UV-Vis spectroscopy. In Figure 2 the spectra of a glass alternately dipped in a NaM-VA solution and R6G solution is presented. The zigzag curve displayed in the inset of Figure 2 shows the changes of the absorbance at 540 nm corresponding to the adsorption and desorption process, as noticed already by other authors [8, 9, 20, 21]. The adsorption of R6G could be dependent on some hydrophobic forces taking into account the chemical structure of R6G. For this reason we have used another copolymer - NaM-MMA. The multilayers were prepared in the same manner as the previous assemblies and monitored by UV-Vis spectroscopy (Figure 3).

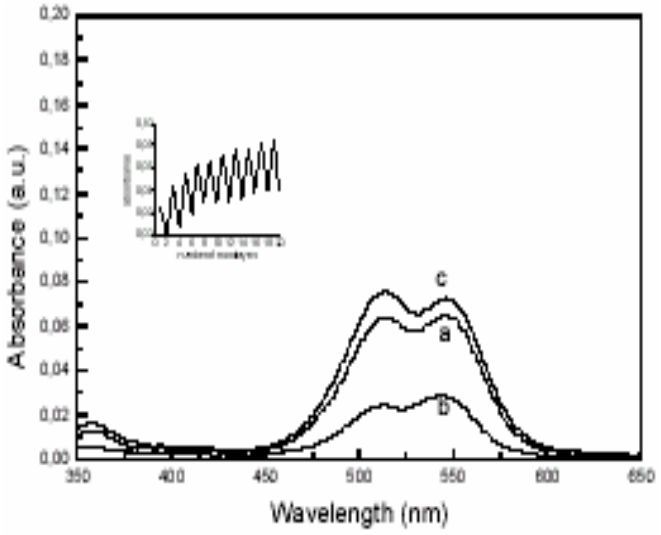


Fig. 2. UV-Vis absorption spectra on glass substrate of multilayer NaM-VA/R6G film: a) the fifth deposition in R6G solution; b) the following immersion in NaM-VA solution after a) deposition, and c) the sixth immersion in R6G solution. Inset shows changes of the layer absorbance at 540 nm with the number of deposited layers.

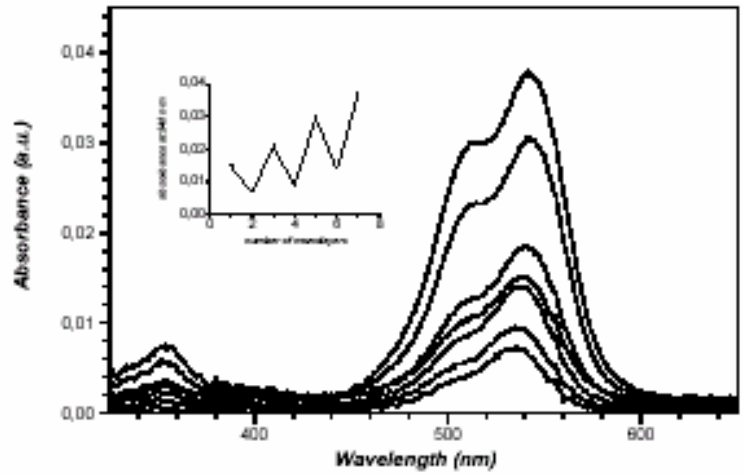


Fig. 3. UV-Vis absorption spectra of a glass substrate sequentially dipped in NaM-MMA solution (15 min) followed by R6G solution (15 min). This dipping cycle was repeated 7 times in order to build up thick multilayer films. Inset shows changes of the layer absorbance at 540 nm with the number of deposited layers.

Atomic Force Microscopy (AFM) can provide further detailed information concerning the surface morphology and the homogeneity of the LBL films down to the nanometer scale. Figures 4 a and b show the AFM images of (NaM-VA/R6G)2

and (NaM-MMA/R6G)4 multilayer films respectively, both prepared on silicon wafers.

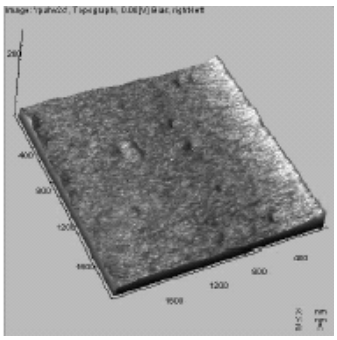
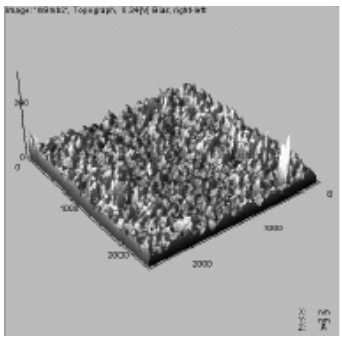
a)  b) 

Fig. 4. (a) AFM 3D image of 2 bilayers of NaM-VA/R6G and (b) 3D image of 4 bilayers of NaM-MMA /R6G, using 2mg/mL solution of polyanionic partner.

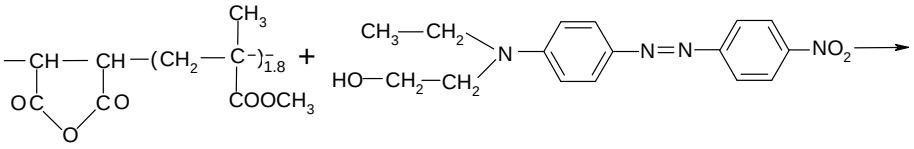
From the first image it can be sed that the multilayer films prepared from NaM-VA and R6G were fairly smooth and uniform, while they may in fact consist of a multitude of small domains. These domains are probably composed of complex ion pairs formed by association of R6G cation with NaM-VA polyelectrolyte chains via electrostatic interactions. Films prepared from NaM-MMA and R6G had a granular texture, making the surface rough. The average surface roughness estimated by AFM was 8 Å for multilayer films prepared from NaM-VA/R6G and 25 Å for multilayer films prepared from NaM-MMA/R6G, respectively.

In conclusion, we performed the successful assembly of Rhodamine 6G and maleic acid copolymers as cationic and anionic partners, respectively, using poly(allylamine hydrochloride) as cationic partner for coating the substrate surface or as a cationic co-partner [22]. The influence of the comonomer in the maleic anionic partner, of the presence of a polycationic partner and the effect of the polyanion concentration were checked in order to improve retention of the dye in the solid phase. At this stage no critical effect of these factors was observed.

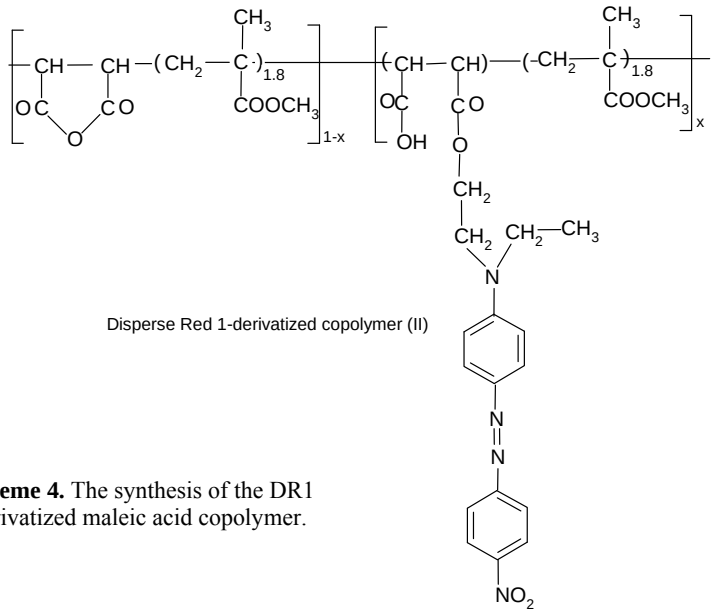
3. CHROMOPHORE FUNCTIONALIZED MALEIC ANHYDRIDE COPOLYMERS FOR LBL DEPOSITION

One of the fastest growing areas in the LbL technique is the incorporation of electro-optical moieties into the films. For this reason, there has been an increasing interest in the use of these films for non-linear optical devices, hole and ion transport, and other applications in which the ordering of the chromophore itself can be critical with respect to the final properties. Maleic anhydride copolymers were used only scarcely in this type of application [15]. For this reason we have synthesized new maleic acid copolymers containing N-ethyl-N-(2-hydroxyethyl)-4-

(4-nitrophenylazo)aniline (so-called Disperse-Red-1 - DR1) moieties by the reaction of MA-MMA copolymer with Disperse Red in mild conditions [23], according to Scheme 4. The DR1 content in copolymer was estimated by UV-Vis spectrometry in acetonitrile and confirmed by FTIR spectra. 27mol % of DR1 structural units in copolymer was reached. The corresponding sodium salt of the copolymer **II** was prepared by hydrolysis and neutralization with NaOH aqueous diluted solution for 24 h at 40°C and used as anionic partner in the fabrication of non-centrosymmetric multilayer films using the LbL deposition process in which the anionic partner was the polyallylamine [15].



Maleic anhydride-methyl methacrylate copolymer (I)



Disperse Red 1-derivatized copolymer (II)

Scheme 4. The synthesis of the DR1 derivatized maleic acid copolymer.

The deposition process was monitored by UV-Vis absorption spectroscopy and the morphology of the films deposited was visualized by Atomic Force Microscopy. Figure 5 shows the absorption spectra of the $(PAH/M\text{-}DR1)_{1\text{-}5}$ multilayer films. The absorption peak of M-DR1 is located at 488 nm and increases linearly with the addition of each bilayer, as typically shown in inset. This plot indicates that layer-by-layer deposited film could be fabricated with PAH/M-DR1.

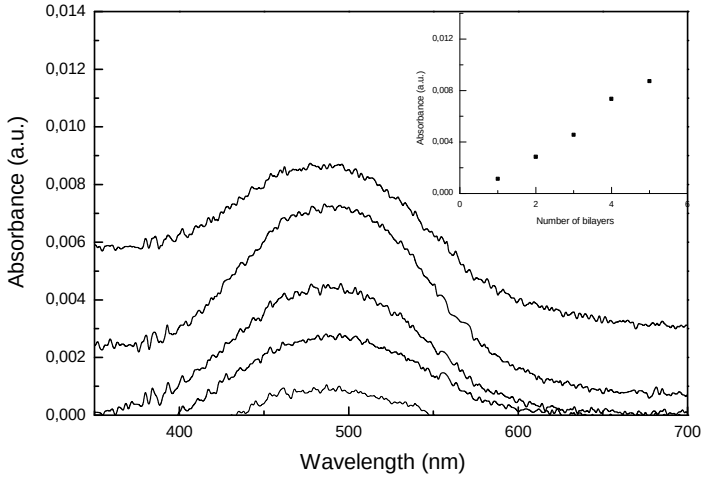


Fig. 5. UV spectra of the (PAH/M-DR1) multilayer films. The curves from bottom to top are corresponding to spectra of 1, 2, 3, 4 and 5 bilayers. Inset shows the dependence of the absorbance on the number of layers deposited.

The kinetics of the alternating deposition of DR1-containing polymer and the polycation PAH was followed also by optical second-harmonic generation (SHG). SHG was clearly observed from the films prepared using maleic acid copolymer containing DR1 (Figure 6). The SHG signal increased with the number of chromophore containing polymer layers up to 5 layers, while further assembly reduced the signal. Other maleic copolymer derivatives containing chromophore moities were obtained by appropriate chemical transformation, presented in Table 1. Work is in progress concerning the characterization of their electro-optical properties.

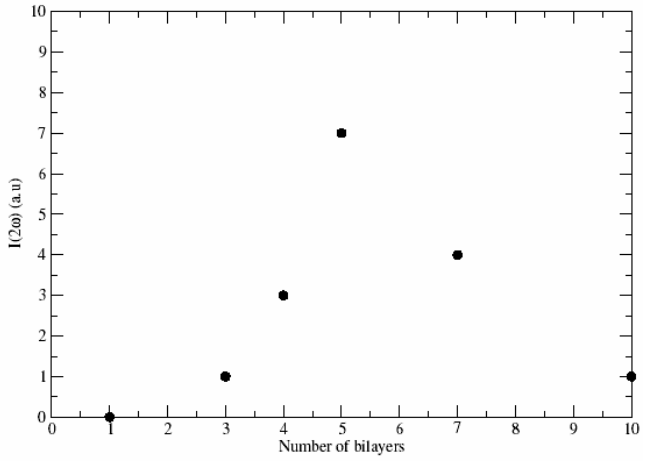


Fig. 6. Dependence of the SHG signal on the number of bilayers deposited on the substrate.

Table 1. Reaction conditions for modification of maleic anhydride copolymers with different chromophores

Sample code	Copolymer	Reactant	Time h	Temperature °C	Chromophore units, mol%
S-3AC	S-MA	3-amino-ethyl-carbazole (3AC)	24	50	56
P-3AC	NVP-MA	3-amino-ethyl- carbazole (3AC)	24	50	85
S-9EC	S-MA	9-ethanol-9-carbazole (9AC)	24	50	6
P-9EC	NVP-MA	9-ethanol-9-carbazole (9AC)	24	80	9
S-1AP	S-MA	1-amino pyrene (1AP)	48	60	2
P-AP	NVP-MA	1-amino pyrene (1AP)	48	80	25

4. ORGANO-INORGANIC COMPOSITES/HYBRIDS FROM HYDROXYAPATITE AND MALEIC ACID COPOLYMERS

In nature, structures of complex shape are often formed in processes, where the self-asembly properties of complex organic molecules are combined with the rigidity of inorganic compounds. Such „bio-inspired" concepts can be applied to the synthesis of artificial organic-inorganic hybrid materials. Hydroxyapatite (HA) is the main mineral constituent of vertebrate skeletal systems. Ceramic hydroxyapatites are widely employed in various biomedical applications. The fabrication of such a densely sintered ceramic almost always starts with the synthesis of a HA powder of desirable particle characteristics. For this purpose a number of novel processing routes were developed, such as hydrothermal reactions.

The role of polyelectrolytes as crystal growth regulators was already demonstrated [24]. Maleic acid copolymers were demonstrated as active crystal growth regulators for calcium carbonate or other sparingly soluble low molecular salts [25, 26]. Conversely, their effect in the HA crystallization was not yet investigated. We have checked the interaction between calcium nitrate and dihydrogen phosphate promoted by the addition of ammonia in the presence of a maleic acid copolymer as a model of the hydrothermal synthesis of hydroxyapatite. The formation of HA in the presence of various amounts of NaM-VA copolymer was followed by potentiometric, conductometric and turbidimetric measurements [27]. In Figures 7 a) and b) are presented some typical results obtained by turbidimetric and conductometric titration with ammonia of a calcium nitrate and dihydrogen phosphate mixture added with a maleic acid copolymer. The amount of added maleic copolymer influenced the phase separation, as shown in Figure 7 a). Good concordance between the two kinds of methods was observed, the discontinuity of the measured property taking place at the same volume of added ammonia regardless of the method (Figure 7 b).

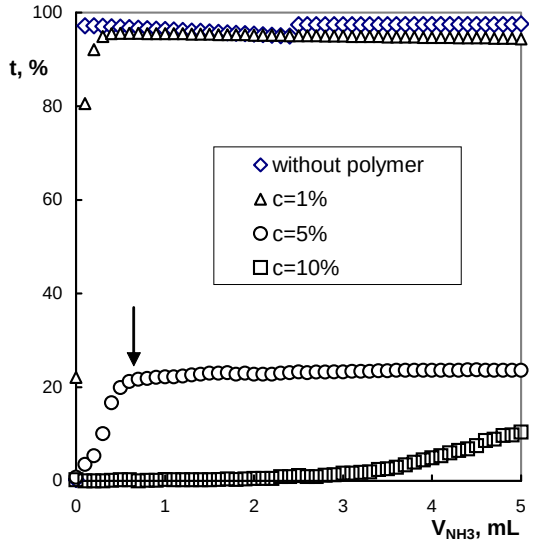


Fig. 7. a) Influence of the amount of added maleic copolymer on the phase separation (turbidity) of the system.

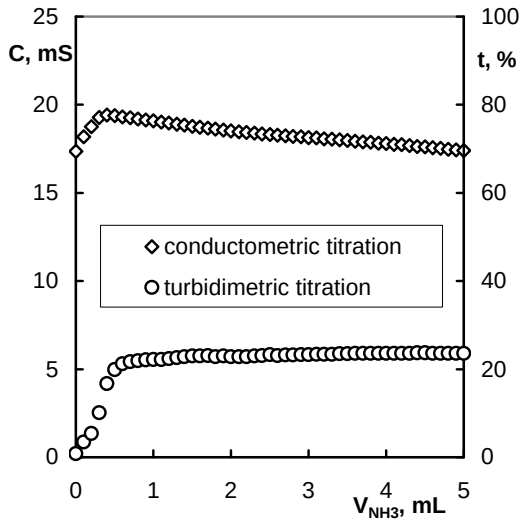


Fig. 7. b) The comparison between conductometric and turbidimetric measurements on the organo-inorganic system.

In Figure 8 the FTIR spectra which confirm the interaction between calcium phosphate/hydroxyapatite and the maleic acid copolymer with hybrid formation are shown.

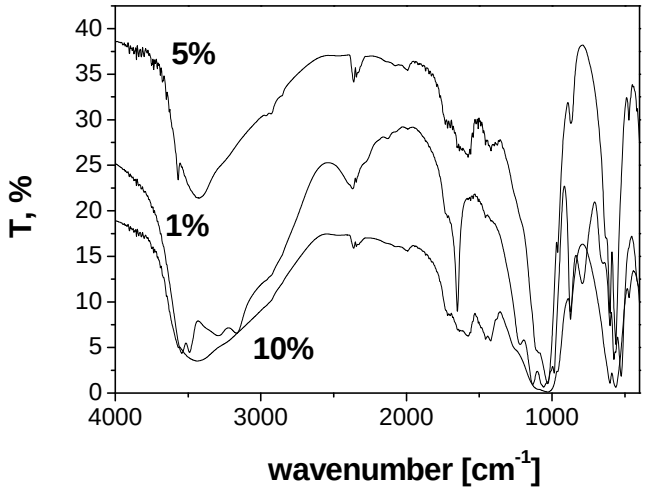


Fig. 8. FTIR spectra of calcium phospate separated in the presence of 1%, 5% or 10% of maleic acid copolymer (MC). Band assignment: 3545-3570 cm^{-1} – OH stretching from both CP and MC; 1709-1723 and 1572-1579 cm^{-1} – esteric or acidic carbonyl stretching from MC; 1135 and 1109 cm^{-1} – HPO_4/CP; 1032-1040 – MC and/or P=O from CP.cm^{-1}.

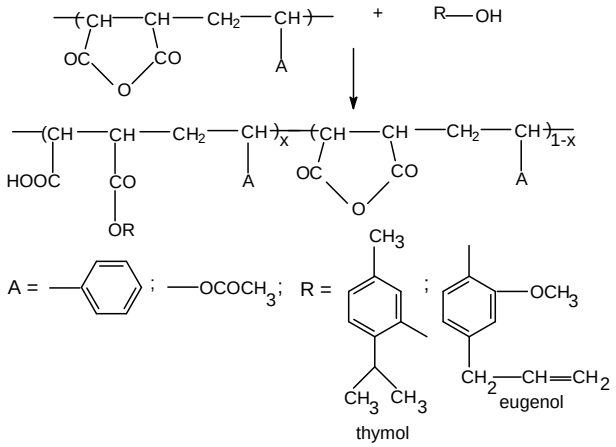
The HAP-polymer composites have lower production costs and are being tested as filling materials in dentistry. Another potential application would be the use in the coating of metalic implants in the medical field.

5. SYSTEMS FOR CONTROLLED DELIVERY OF BIOACTIVE SUBSTANCES. CONJUGATES OF MALEIC ANHYDRIDE COPOLYMERS WITH PHENOLIC DERIVATIVES AS MACROMOLECULAR DISINFECTANTS

Controlled-release technology is an interdisciplinary science that deals with the delivery of bioactive agents such as pharmaceutics, pesticides, proteins, or enzymes. One of the most important ways to achieve this goal is the use of so-called macromolecular conjugates which involve small molecules (drugs, etc.) chemically bounded to a polymer backbone. Until now there are only few papers related to the synthesis and characterization of polymer conjugates with disinfectant and/or odorant molecules. The synthesis of perfumed aldehyde Schiff bases with aminostyrenes followed by copolymerization in order to obtain controlled release systems was reported [28]. Thymol was reacted with methacrylic acid or p-styrenesulfonic acid and then polymerized to obtain macromolecular disinfectants [29]. Another way to increase the efficiency of these compounds was the release from glucosides [30]. The synthesis of polymeric systems containing

some disinfecting and/or odorant agents attached to MA copolymers *via* ester bonds was not reported hitherto. Our results in this topic concerning the synthesis, characterization and antimicrobial properties of these conjugates with eugenol (2-methoxy-4-allylphenol) or thymol (2-isopropyl-5-methylphenol) will be summarized in this chapter. For comparison purpose we have also reacted MA copolymers with phenylethyl alcohol (2-phenylethanol) or citronellol (3,7-dimethyl-6-octen-1-ol). The details concerning the synthesis and characterization of these conjugates were given elsewhere [31].

The derivatives of MA copolymers with disinfecting agents bearing OH groups were obtained by esterification in solution at 40-60°C, without catalyst. In these conditions mainly a monoesterification reaction occurs, according to Scheme 5.



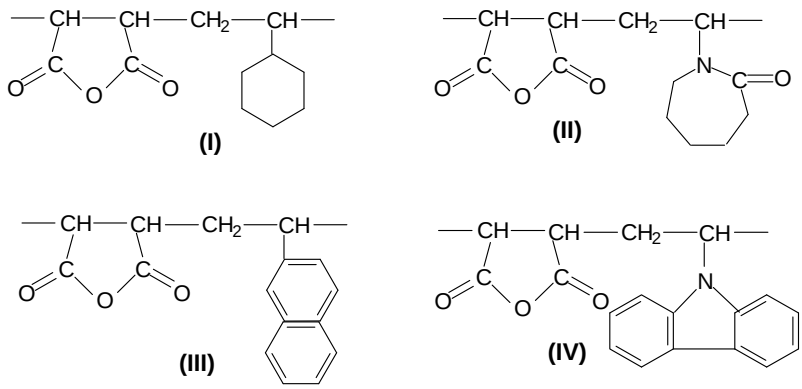
Scheme 5. Chemical reaction between MA copolymers and disinfectant molecules.

The exploratory screening according to the diffusimetric method evidenced that only the conjugate of MA-S copolymer with eugenol was still bioactive. The antimicrobial activity of this conjugate was tested by the evaluation of the phenol coefficient using the species: *Staphylococcus aureus* ATCC 6538 and *Pseudomonas Aeruginosa* ATCC 15442. This conjugate is active only against *S. Aureus*, having values of phenolic coefficient as high as 5.83.

6. COPOLYMERS OF MALEIC ANHYDRIDE WITH BULKY COMONOMERS

The coil-to-globule transition of the “protein-like” copolymers turned out to occur at a higher temperature. In the case of maleic acid (MAc) copolymers the transition globule-coil is induced by the pH increase and was shown to be dependent on the hydrophobic character of the comonomer. This transition could

also influence the interaction of MAc copolymers with other polymers among which the proteins. In order to examine the influence of some bulky hydrophobic comonomers on the solution behavior we have synthesized MA copolymers with vinylcyclohexane (**I**), N-vinylcaprolactam (**II**), 2-vinylnaphthalene (**III**), and N-vinylcarbazole (**IV**) where the hydrophilic units of maleic anhydride alternate with hydrophobic units of comonomer, the chemical structure of which is depicted in Scheme 6.



Scheme 6. The chemical structure of MA copolymers with bulky comonomers.

The copolymers were synthesized by radical copolymerization in organic solvents: benzene or dioxane, with BPO or AIBN as initiators, at 70-90^{o}C. Almost all the reactions occurred in partially homogeneous systems, so that the reaction mixture had to be precipitated with diethyl ether. The composition of the copolymers (Table 2) assessed by conductometric titrations in acetone-water mixture and confirmed by ^{1}H NMR and ^{13}C NMR spectra was approximately 1:1 (moles). The molecular mass was determined by gel permeation chromatography (GPC) in organic solvent, the degree of polymerization being rather low (between 5 and 50) [32].

Table 2. Physico-chemical characteristics of MA copolymers with bulky comonomers

Sample code	Composition, mole MA: mole comonomer	Molecular mass, M_w
(I)	1:0.9	2585
(II)	1:1.3	aggregation
(III)	1:0.9	13382
(IV)	1:1.3	11821

The composition was approximately 1:1 moles in the case of MA-vinylcyclohexane and MA-2-vinylnaphthalene and slightly different from 1:1 in

the case of MA-vinylcaprolactam and MA-N-vinylcarbazole. The explanation could be some hydrolysis of the copolymers during the manipulation or some impurification with comonomers strongly adsorbed on the copolymer. The IR spectra were in agreement with the first hypothesis. The molecular weight of the copolymers is rather low, irrespective of the copolymerization conditions, suggesting that these comonomer pairs are rather reluctant to the copolymerization, additional experiments being in progress by using nonconventional polymerization techniques.

7. CONCLUSION

The results gathered in this review proved the suitability of maleic anhydride copolymers in various nano/bioapplications. Their ability to react with a great variety of low molecular compounds bearing active moieties can be successfully exploited according to the specific goals. The controlled surface modification of different substrates used in tissue engineering or for microarrays is a valuable tool in this respect. Organic-inorganic nanocomposite materials based on maleic copolymers are also worthwhile due to their availability and facility of fabrication. The preparation of nanocystals from inorganic salts or oxides would be another interesting way to use the abilities of maleic anhydride copolymers.

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