Doctoral Thesis

Application of reactive and partly soluble nanomaterials

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Publication Date:
2008

Permanent Link:
https://doi.org/10.3929/ethz-a-005774007

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APPLICATION OF REACTIVE AND PARTLY SOLUBLE NANOMATERIALS

A dissertation submitted to
ETH ZURICH
for the degree of
DOCTOR OF SCIENCES

presented by
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Zürich 2008
Give a man a fish and you feed him for a day.
Teach a man to fish and you feed him for a lifetime.

Chinese proverb
Acknowledgements

I would like to express my gratitude to Prof. Wendelin Stark for giving me the opportunity to perform my PhD thesis in his young research group and for linking science to the “real” world. Prof. Stark contributed much by his belief in my abilities, his foresight and continuous encouragement and the critical discussions inside and outside the laboratory.

Special thanks go to my co-examiner Prof. Erich Windhab for his interest in my work and for his stimulating discussions and suggestions.

I would like to address many thanks to the mechanical and electronic workshop team, especially Urs Krebs and Max Wohlwend. Furthermore, I would like to thank Dr. Frank Krumeich for the high quality TEM images and Michael Schneider and Peter Kälin from the Mikrolabor for element analyses throughout my PhD thesis.

This work would not have been possible without the support of my colleagues and friends Robert Grass, Stefan Loher, Neil Osterwalder, Tobias Brunner, Ludwig Limbach, Evagelos Athanassiou, Oliver Schneider, Norman Lüchinger, Fabian Köhler, Dirk Mohn and Inge Herrmann. I would like to thank them for their continuous support, the critical discussions and memorable times at work as well as outside working hours.

I would like to thank my former chemistry teacher Prof. Dr. Peter Bützer for sparking my interest in science.

I appreciate the support of my friends and am thankful to them for showing me that there is also a different side of life.

I am deeply grateful to my parents and my sister Debbie, for their unrestricted support throughout my whole life and their perpetual encouragements.
# Table of contents

## Acknowledgements

## Table of contents

## Zusammenfassung

## Summary

### 1. Influence of high surface area on the reactivity and solubility

1.1. Introduction

1.2. Why is the nanometer-range interesting?

1.3 Approaches to larger surface area

1.3.1. Gas phase nanoparticle synthesis methods

1.3.1.1. Flame spray synthesis

1.3.1.2. Laser induced gas evaporation method

1.3.1.3. Plasma based nanoparticle production

1.3.2. Liquid-phase synthesis methods of inorganic nanoparticles

1.4. Solubility and reactivity of nanoparticles

1.4.1. How enhanced solubility affects our daily lives

1.4.2. Importance of reactivity in industrial processes

1.4.3. Quantification of solubility and reactivity: Shrinking Core Model

1.5. Nanoparticles for enhancement of commodity products

1.6. References

### 2. Preparation of an ultra fast binding cement from calcium silicate-based mixed oxide nanoparticles

2.1. Introduction

2.2. Experimental

2.2.1. Nanoparticulate powder preparation

2.2.2. Characterization of starting materials and hardening products

2.3. Results and discussion

2.3.1. Characteristics of dry powders

2.3.2. Hardening kinetics and cement characterization

2.4. Conclusion
3. Preparation of submicron and nano-table salt for food applications*  
3.1. Introduction  
3.2. Bottom-up: Large-scale production of sodium chloride nanoparticles  
3.2.1. Introduction  
3.2.2. Experimental  
  3.2.2.1. Particle synthesis  
  3.2.2.2. Particle analysis  
  3.2.2.3. Air stability tests  
  3.2.2.4. Food safety  
3.2.3. Results and discussion  
  3.2.3.1. Absence of toxic compounds from combustion  
  3.2.3.2. External toxicity tests  
3.2.4. Conclusion: bottom-up  
3.3. Top-down: Ball Milling of salt-in-oil-slurries  
3.3.1. Introduction  
3.3.2. Experimental  
  3.3.2.1. Materials synthesis  
  3.3.2.2. Particle analysis  
3.3.3. Results and discussion  
  3.3.3.1. Particle size distribution  
  3.3.3.2. Shelf life  
3.3.4. Conclusion: top-down  
3.4. Conclusion  
3.5. References

4. Evaluation of bismuth-based nanoparticles for sunscreen applications  
4.1. Introduction  
4.2. Materials and Methods  
  4.2.1. Particle synthesis  
  4.2.2. Particle characterization  
  4.2.3. Ultraviolet absorbance measurements  
  4.2.4. Photocatalytic activity measurements  
4.3. Results and Discussion  
4.4. Conclusion  
4.5. References
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. General conclusions and outlook</td>
<td>85</td>
</tr>
<tr>
<td>Appendix A: Supplementary material</td>
<td>89</td>
</tr>
<tr>
<td>A.1. Supplementary information, chapter 2</td>
<td>90</td>
</tr>
<tr>
<td>Curriculum Vitae</td>
<td>91</td>
</tr>
</tbody>
</table>
Zusammenfassung


In der vorgelegten Doktorarbeit wurde der Einfluss der kleinen Partikelgröße von Nanopartikeln und deren resultierende grosse Oberfläche auf die Eigenschaften verschiedener Handelsartikel untersucht. Die Flammenspraypyrolyse und die damit mögliche Nanopartikelvielfalt und mögliche Skalierung der Produktion bildete hierbei die Basis der Untersuchungen. Im Zuge dieser Arbeit wurden drei weit verbreitete und bedeutende Produkte aus verschiedenen Gebieten erforscht, nämlich der Baumaterialien, der Lebensmittelindustrie und der Kosmetik. Die Produkte wurden in Form von Nanopartikeln synthetisiert und mit den bestehenden Werkstoffen vor allem bezüglich Reaktivität und Löslichkeit verglichen.


Kapitel 2 stellt die Bottom-up-Synthese von Kalzium-Silikat-basierten Zement-Nanopartikeln mit definierten Mengen an Aluminium-, Eisen- und Magnesiumoxid über die
Zusammenfassung


Kapitel 5 fasst generelle Schlussfolgerungen der vorgelegten Doktorarbeit sowie zukünftige Forschungsrichtungen auf diesem Gebiet zusammen. Hauptaugenmerk wird dabei auf die Wichtigkeit der Entwicklung nachhaltiger und abbaubarer Nanopartikel gelegt, die langfristige negative Auswirkungen auf die Umwelt minimieren können. Das Kapitel hebt nochmals die Verfügbarkeit einer alternativen – grosstechnisch umsetzbaren – Technologie zur Produktion anorganischer Nanopartikel hervor und unterstreicht die Bedeutung einer weitsichtigen Verwendung neuartiger Nanopartikel für Bedarfsartikel.
Zusammenfassung
Summary

Inorganic nanoparticles have reached annual production volumes of several metric megatons. Most of the worldwide production on an industrial scale can be assigned to carbon black, silica and titania. These compounds are used in a wide range of application areas including the automotive and food industry or pharmaceutics. The large production volume of the nanopowders is opposed to the very limited range of elemental compositions available at an industrial scale. One of the major reasons for the lack of materials disposable containing a wider range of nanoparticles is the limited availability of large-scale production methods besides the compositions mentioned above.

In the here presented thesis the influence of a reduction in size to the nanometer level and the resulting large surface area on the properties of commodity products are investigated. Due to the versatility and scalable production of inorganic nanoparticles, flame spray synthesis formed the basis of these investigations. Within this thesis three widespread and important goods in the field of construction materials, food science and cosmetics were studied. The products were synthesized in nanoparticulate form and compared to existing materials with respect to reactivity and solubility.

Chapter 1 gives a general introduction to nanoscaled materials and discusses the influence of a large surface area on the properties of a material. Different methods enabling the production of inorganic nanoparticles are presented. The relevance and importance of small and reactive materials for large-scale applications is illustrated by the example of Portland cement, a powdery material which – amongst others - has been used for the construction of buildings and bridges since millennia.

Chapter 2 presents the bottom-up synthesis of calcium silicate based cement nanoparticles by flame spray synthesis containing defined amounts of aluminum, iron and magnesium oxide. It was shown that not only the reactivity of this novel construction cement was drastically changed by the decreased particle size, but also modified its hardening behavior. The initial hydration heat generated showed a ten-fold increase if compared to commercial Portland cement. Due to the large surface area of the nanoparticles additional water is needed for cement wetting, to form a cementitious paste, and to complete subsequent hydration reactions. This resulted in an increased porosity and a decreased mechanical
stability of the hydrated cement. The results suggest further optimizations of the cement nanoparticles before being used for load bearing applications. In their current form they might be suitable as early hydration enhancers.

Chapter 3 covers the manufacture of food-grade sodium chloride by flame spray synthesis. This work was conducted in collaboration with a Global-100 company and presents novel top-down and bottom-up approaches to smaller kitchen salt particles. Since this work is confidential only part of the results can be published. The technology developed within this work has been filed as a patent. The results proofed that flame spray synthesis is a viable method to produce large quantities of food-grade kitchen salt nanoparticles. The established hydrophilic properties of small scaled sodium chloride and the resulting particle growth could be inhibited by in situ doping of the sodium chloride with small amounts of tricalcium phosphate or silica. First assessments of contaminates such as solvent residuals, pyrogens or heavy metal levels on the particles have been conducted with a positive outcome. As an alternative to this dry nanoparticle synthesis, submicron sized table salt was produced and stabilized by milling commercial sodium chloride in sunflower oil. By the use of a hydrophobic milling medium the particle size of the salt could be stabilized in the same size range. Both presented methods yielded salts ten to one hundred times smaller than the smallest commercially available salts of 15 micrometer diameter. Furthermore, the composition of these novel salts can be adapted in the same production step.

Chapter 4 presents alternative and more sustainable ultraviolet absorbing pigments. It discusses the potential problems of currently used titania nanoparticles in modern sunscreens. Despite the good ultraviolet absorbance the persistency of these particles could pose a long-term risk to environment and ecosystems. The here presented results show the availability of degradable nanoparticles with similar ultraviolet blocking properties if compared to currently used titania. The presented bismuth compounds show good ultraviolet absorbance, and in the case of bismuth oxide a good solubility (and hence degradability) and a 10-fold decrease in photocatalytic activity if compared to uncoated titania. The results suggest that uncoated bismuth oxide nanoparticles are a viable degradable alternative to currently used persistent titania. For end user applications, the novel ultraviolet irradiation absorbers still need to be optimized, but the results enable a promotion of a proactive development of sustainable sunscreen ingredients.
Chapter 5 draws general conclusions of the presented thesis as well as an outlook on future research directions. Emphasis is put on the development of sustainable and degradable nanoparticles minimizing negative long term impacts on the environment. It is shown that alternative scalable production methods to inorganic nanoparticles are at hand and punctuates the importance of a prospective use of nanoparticles in commodity products.

The results presented in this thesis clearly show that flame spray synthesis allows the production of a wide range of highly reactive and soluble nanoparticles with specific properties. The presented examples underline the importance of a responsible use of nanoparticulate compounds for products in our daily life, since the currently used inorganic nanoparticles might pose a long-term risk to environment and ecosystems.
1. Influence of high surface area on the reactivity and solubility
1.1. Introduction

The following chapter highlights the technical importance of small scaled particles. It discusses the influence of higher surface area on the reactivity and solubility of materials and depicts some illustrative examples of widely known commodity products.

1.2. Why is the nanometer-range interesting?

Small scaled materials with particle diameters in the nanometer range have already been used for a long time. The Chinese used carbon black derived from a combustion process for painting applications long time before modern technology allowed its annual megaton production for car tire, other polymer or pigmentary applications. One of the historically most impressive uses of nanoscaled objects for decorative effects is represented by the Lycurgus Cup which dates back to the Roman Times (4th century AD). This extraordinary cup uses dichroic glass, thus changing its color from dull green to bright red when light shines through. The glass contains small amounts of colloidal gold and silver nanoparticles which give it these spectacular optical properties. The phenomenon only occurs if the colloidal metal nanoparticles in the glass have a particle diameter below a certain threshold. In this size range all electrons in the particle resonate in consequence of incident light waves, resulting in strong absorption of a particular wavelength. This gives rise to different colors of the colloidal system.

Above historical example shows most elegantly, how certain properties can change drastically with decreasing particle size. Since Nobel laureate Richard Feynman’s famous lecture “There’s plenty of room at the bottom” in 1959 many scientists and researchers have been investigating different effects caused by the small size of nanoparticulate matter.

A generalization of the reasons for the change in the physical, optical, electronic or chemical properties of a material in the nanometer range can not be made, as diverse phenomena play important roles. Nevertheless, one common denominator can be determined when looking at the peculiarity of nanoscaled material. Traditionally, in a bulk crystal, the properties of the material are independent of the size and are only dependent on the chemical
composition, as most atoms of a material are located in the bulk of a particle and hence exceed the influence of surface atoms on the material’s properties. As the size of the crystal decreases to the nanometer regime, the small size of the particle begins to modify the properties of the crystal. The surface area increases, which results in a larger contribution of the surface energy to the overall energy of the whole system and, thus, results in a reduction of the impact of the bulk atoms on the properties of a material. The significant shift towards surface atoms of nanoparticulate matter is illustrated in Figure 1-1 where the percentage of surface atoms in a particle is plotted against the particle size.

**Figure 1-1.** Percentage of surface atoms in a particle is strongly dependent on the particle size. Particles below 10-20 nm start having a relevant part of their atoms on the surface. This results in surface atoms contributing substantially to the properties of the bulk material.

In general, if particles reach a particle size of below 10 to 20 nanometers a relevant part of the atoms will be located on the surface of the particle, thus determining the properties
of the material. The atoms located on the surface of a solid have fewer adjacent coordinate atoms and therefore these atoms may be chemically more active compared to the bulk atoms. There is a large energy associated with this surface. Gold for instance is well known for its chemical inertness. Haruta and coworkers showed in 1987 and 1989 that even gold becomes a highly active catalyst for CO and H\textsubscript{2} oxidation, if the gold particles are in the nanometer range\textsuperscript{1,2}.

In most of their potential applications, the surface of nanoparticles will undoubtedly play the crucial role in the determination of the nanoparticulate properties, including the stability, solubility, and reactivity which will be discussed in the following paragraphs and chapters.

1.3 Approaches to larger surface area

There have been manifold attempts to create surface area by decreasing the particle size of materials. An engineer would naturally prefer to start with the bulk material and make it smaller, thus breaking up larger particles by the use of physical processes like crushing, milling or grinding. A chemist on the other hand is more familiar with building small scaled materials starting from the atomic scale by traditional wet phase chemistry and stopping the reactions at the right time to inhibit further particle growth. With either of the methods the goal of larger surface area can be reached whilst keeping the chemical composition of the material constant. As a matter of course, depending on the method of choice, the morphology of the product will be different and correspondingly the properties of the nanomaterial.

Generally speaking, there are two approaches towards the synthesis of nanosized materials:

1) \textit{Top-down}: size reduction from bulk materials

2) \textit{Bottom-up}: material synthesis from a atomic level

\textit{Top-down} approaches such as milling have been known and applied within living memory. Modern milling techniques like ball milling are generally straightforward and can yield nanoparticulate materials\textsuperscript{3,4}. Unfortunately, there are a few drawbacks, e.g. the low energy efficiency, the necessity of a liquid medium for nanoscaled material, the susceptibility
to impurities from abrasion and the broader particle size distributions. *Bottom-up* techniques include plasma, laser, liquid phase or flame spray synthesis. These “self-assembly” preparation methods generally result in well controlled nanoparticles which are built on smaller building blocks allowing the synthesis of more complex materials or the fabrication of nanoparticles with a very narrow size distribution.

In the following paragraphs the most common processes yielding inorganic nanoparticles are briefly described.

**1.3.1. Gas phase nanoparticle synthesis methods**

**1.3.1.1. Flame spray synthesis**

In spite of the often cited novelty of nanomaterials, three large scale commodities have been around for half a century. Pigmentary titania (white pigment), aerosol-made silica and carbon black (tire soot) are made by flame processes at several megatons per year\(^5\). Production of these materials started in the 1940s. In principle, it would appear attractive to extend this apparently useful flame processes to other materials\(^1\). Flame-made oxides have been explored for applications in heterogeneous catalysis\(^12\text{-}18\), sensors\(^19\text{,} 20\) lasing materials\(^21\), computer chip manufacturing and numerous other industrial sectors. Earlier this decade, the aerosol community has gained access to most oxide materials, but few other inorganics have been accessible. By studying the chemical problems of preparing complex inorganic materials in flame reactors, the range of accessible products has been successfully extended from oxides to most inorganic salts\(^22\text{,} 23\). As a result, a number of everyday materials have become available in the form of nanoparticles: Nano-gypsum\(^24\), nano-salt\(^22\) and nano-tricalcium phosphate\(^23\text{,} 25\text{-}29\). The latter has been incorporated in a number of biomedical materials\(^26\text{,} 30\text{-}32\) and first *in vivo* tests demonstrated successful application as biomaterials\(^29\). A different, preclinical study has most recently demonstrated the advantageous re-mineralization properties of nano bioactive glass for damaged dentin (tooth repair)\(^33\).

Further adaptations within the flame spray synthesis technology give access to the production of metal nanoparticles\(^19\text{,} 34\). This is achieved by a modification of the flame reactor operating under reducing (oxygen starved) conditions\(^34\). Very recently one step further was taken and the controlled deposition of carbon on the metal surface of nanoparticles also
1.3 Approaches to larger surface area

became accessible\textsuperscript{35}. For example, the suitability of carbon coated copper nanoparticles in water based dispersions or inks of such have been shown to offer a simple production method to highly sensitive humidity sensor coatings\textsuperscript{36}. Summarized, flame spray synthesis allows the scalable fabrication of most accurate mixed oxide compositions, salt, metal and carbon-coated metal or silica-coated metal oxide nanoparticles\textsuperscript{37} based on metal loaded liquid precursors.

1.3.1.2. Laser induced gas evaporation method

Instead of combustion of a liquid precursor giving access to oxidic nanoparticles, Kato showed in 1976 that he was able to produce a range of different ultrafine refractory oxides ($\text{SiO}_2$, $\text{MgO}$, $\text{Al}_2\text{O}_3$, $\text{Fe}_3\text{O}_4$, $\text{Mg}_2\text{SiO}_4$, $\text{CaTiO}_3$ and $\text{MgAl}_2\text{O}_4$) by the use of a $\text{CO}_2$ laser. The laser was used to vaporize starting material in form of powder or sintered or fused blocks. The vaporized material condensed in an environment of inactive gases and resulted in nanoparticles of around 10 nm particle diameter at a production rate of 10 mg/min (0.6 g/hr)\textsuperscript{38}. In 2002 Ullmann et al. studied systematically the influence of the operating parameters during laser ablation on the aerosol generated\textsuperscript{39}. They concluded that laser ablation is a convenient method for laboratory scale nanoparticle generation.

1.3.1.3. Plasma based nanoparticle production

A similar method to laser induced gas evaporation are plasma reactors. In this case plasma delivers the energy necessary to evaporate the starting materials of various types including gases, liquids and solids. At temperatures of around 10,000°C the plasma generates reactive ions and radicals. During the pullout from the plasma region the temperature of the gas drops and nanoparticles are formed\textsuperscript{40}. Plasma based methods have been used to synthesize nanoparticles in form of metal oxides\textsuperscript{41}, metals\textsuperscript{42} or metal nitrides\textsuperscript{43}.

1.3.2. Liquid-phase synthesis methods of inorganic nanoparticles

One of the first modern approaches to nanoparticles was achieved by coprecipitation from aqueous solutions. As numerous processes occur simultaneously influencing the properties of the final product the theory of coprecipitation is not as straightforward and some of the fundamental mechanisms are still not thoroughly understood\textsuperscript{44}. In a first step of a typical coprecipitation reaction the conditions are adjusted to maximize the simultaneous generation
of sparingly soluble particles. The key properties of the final product (above all particle size and morphology) are subsequently determined in secondary processes such as aggregation or Ostwald ripening. In a final step, the as-formed particles are usually thermally decomposed to oxides. Since chemical reactions in a solvent are the base of liquid-phase synthesis, it is crucial to have all reaction conditions influencing the mixing process under control. An advantage of the coprecipitation method is that particle sizes can be well controlled making the fabrication of monodisperse nanoparticles possible. A major disadvantage though is the involvement of vast amounts of solvents and surfactants.

Another nanoparticle synthesis method based on liquid precursors is the processing of materials by the *sol-gel* method. This process dates back to the mid 1800s where scientists found that they were able to synthesize ceramic or glassy material from a viscous gel. Typically, metal alkoxides or metal chlorides are used as starting materials forming the solvated metal precursor (the *sol*). This precursor undergoes hydrolysis and polycondensation reactions to form a gelated colloid (the *gel*). The reactions of this oxide- or alcohol-bridged network continue until the gel transforms into a solid mass under expulsion of the solvent from the pores. Subsequently, the monolith is calcined at temperatures up to 800°C. In the firing step when the temperature rises above 800°C densification and decomposition of the gel occurs under collapse of the gel network. The sol-gel process is ideally suited for the fabrication of synthetic zeolites, where a porous “open” structure is desired for the accommodation of a wide variety of cations.

**1.4. Solubility and reactivity of nanoparticles**

With the availability of a variety of synthesis methods yielding materials with larger surface area, it is possible to adjust and optimize the solubility and reactivity of materials by changing the particle size. The adjustment of solubility and reactivity is most important in a majority of industrial applications, but also affects every-day life.

**1.4.1. How enhanced solubility affects our daily lives**

From a nutritional point of view, sugar (sucrose, fructose and others) is an important ingredient as it is the main source of fast energy. Besides the nutritional value of these simple
carbohydrates, they are widespread in foodstuffs because of the sweet sensation elicited due to the stimulation of taste receptors. Depending on the size of the sugar particles the solubility can vary enormously. Whereas dissolving regular coffee sugar in hot water takes a few seconds only, the dissolving of the same amount of rock sugar can take minutes. Therefore, milling of the crystallized sugars has been an important processing step yielding better soluble sugars and processing of nutritional sugar has always been laborious.

1.4.2. Importance of reactivity in industrial processes

Next to nutritional sugar changing the reactivity of particles plays a significant role in many industrial processes. A descriptive example of how another commodity product of vast importance relies on breaking particles into smaller ones and thus making them more reactive is Portland cement. With an annual production of over 2.1 billion tons this hydraulic binder is one of the largest volume chemicals globally. Cement production is based on natural raw materials that undergo numerous processing steps adjusting the correct crystal phases and a suitable particle size distribution of the final product. Thereby, milling steps are the basis for the accurate production of the construction material. The adjustment of the correct crystal phases in cement are determined by three main factors: the mineral composition of the raw materials mix, the reactivity of the raw mix and the subsequent firing conditions in the rotary kiln. Since chemical reactions and simultaneous sintering of the particles take place during firing in the kiln, it is crucial to mill the raw materials mix down to the correct particle size ensuring complete reactions and homogeneity of the product. The raw materials are therefore ground in various crushing and milling steps resulting in a fine and homogeneous powder mixture. Based on the precedent milling steps, the as-formed clinker should have fully reacted and consist of the correct crystal phases when exiting the rotary kiln after the firing process. Due to the chemical reactions and the sintering of the particles the clinker consists of large particles of 5 - 25 mm diameter and the resulting limited surface availability of the material makes clinker virtually unreactive with regards to the final application despite the adjustment of the clinker phases. The only process lying in between unreactive clinker balls and highly reactive cement powder is another time- and energy-intense grinding step. As a result, modern cement production sites usually possess a variety of high-pressure grinding rolls and ball mills.
1.4.3. Quantification of solubility and reactivity: Shrinking Core Model

The phenomena occurring during a chemical reaction between a solid and a fluid can well be described with mathematical models used in heterogeneous catalysis. For solubility and reactivity considerations of solids in a fluid, possible occurring mechanisms and rate limiting steps can be well estimated and compared to the shrinking core model. It is widely used to model fluid-solid reactions of chemical processes and is applicable to an initially non-porous particle, which reacts with a reagent leaving a reacted layer around the unreacted core. A general form of such a reaction can be described as follows:

\[ A \text{ (fluid)} + b \cdot B \text{(solid)} \rightarrow \text{fluid and solid products} \]

According to this model the rate-limiting step can be one of the following three:

- Liquid film diffusion control: diffusion through the liquid film surrounding the solid particle
- Shell layer diffusion control: diffusion through the ash/inert solid layer
- Chemical reaction diffusion control: chemical reaction at the surface of the unreacted core

By applying the shrinking core model the limitation of a chemical reaction can be assigned to either the chemical reaction or the mass transfer. Since Yagi and Kunii published the fundamentals of their shrinking core model in 1961, numerous studies followed and concluded that the model can be applied for the majority of reacting fluid-solid systems.
1.4. Solubility and reactivity of nanoparticles

Figure 1-2. The rate-limiting step in a fluid-solid reaction can be assigned to one of three different cases according to the shrinking core model\textsuperscript{16}: limitation of (a) diffusion through a liquid film, (b) diffusion through a shell layer or (c) chemical reaction. These three shrinking core models can ideally be illustrated as shown in (d), where the radius of the particle core $r_c$ (where $R$ is the initial particle radius) is a function of the dimensionless reaction time $t/\tau$ (where $t$ is the time, $\tau$ is the total reaction time).

1.5. Nanoparticles for the enhancement of commodity products

The following chapters will discuss how the small size of nanoparticles can influence the properties of three major commodity products. The products examined are from three totally different areas: construction materials, food and cosmetics.
1.6. References


1. Influence of high surface area on the reactivity and solubility


2. Preparation of an ultra fast binding cement from calcium silicate-based mixed oxide nanoparticles

Abstract:

Building construction takes time, in parts because the binding process of cement is based on the slow re-crystallization and precipitation of calcium silicate species. Since the material’s reactivity is surface area limited, a reduction in particle size of Portland cements has been used to result in faster binding formulations. The present work investigates a new and direct, one-step preparation of calcium silicate-based nanoparticles of a typical Portland cement composition by flame spray synthesis. Isothermal calorimetry revealed that the hardening of this new nano cement corroborated a more than ten fold increase of initial reactivity with different reaction kinetics if compared to conventionally prepared cements. At present, the unfavorably high porosity of nano-cements, however, underlines the need for additional improvements of chemical composition and formulation to make these highly reactive materials applicable to modern construction work or biomedical applications, where load-bearing strength is of importance.

Published in part as:

2.1. Introduction

Cements literally provide the backbone for construction of modern infrastructure and industrial as well as domestic buildings. Consequently such reactive materials have been in the focus of materials engineering for decades and the availability of advanced cements for modern architecture or construction at climatically challenging sites is a direct result of such materials development. Beyond chemical and physical stability, the hardening time of cement materials strongly influences both area and cost of application. Portland cement is manufactured at over 2.1 billion tons annually making it one of the largest volume chemicals globally. In a complex and energy-intensive process a homogenized mixture of raw materials (mainly limestone and quartz) is heated up to a sintering temperature of about 1450°C. During the heating process melting of around 25-30 wt% of the material occurs. The resulting liquid draws the remaining solid particles together by surface tension, and acts as a solvent for the final chemical reaction in which aluminum-, iron- and magnesium-doped polymorphs of calcium silicates are formed. This so-called clinker is subsequently milled to its final particle size. During application, the reactive material slowly transforms into a hydrated, basic calcium silicate and silica (C₃S + (x + y)H → CₓSHₜ + zCH, with C = CaO, S = SiO₂, H = H₂O, x + z = 3 but x, y and z not necessarily integers). Since this heterogeneous reaction proceeds at a solid-liquid interface and entails the partial dissolution of the constituents prior to re-crystallization, a reduction of particle size to the micrometer region has been used to successfully improve the reactivity of such cements. The use of nanoparticulate cements therefore appears most attractive for ultra-rapidly binding cement formulations.

Since traditional Portland cement consists of high temperature modifications (mainly substituted impure forms of tricalcium silicate C₃S, dicalcium silicate C₂S, tricalcium aluminate C₃A and ferrite C₄AF with A = Al₂O₃ and F = Fe₂O₃), classical water-based precipitation or sol-gel chemistry can not be applied to the production of the desired cement nanoparticles. As a consequence, the need for high preparation temperature and small particles size limits the range of possible preparation methods to gas-phase aerosol manufacturing or milling. We therefore developed a continuous, one-step flame-spray based route to cement nanoparticles. The here presented preparation route was derived from the
broadly used flame aerosol process as applied in the production of several megatons of carbon black, titania and silica, annually\textsuperscript{15,16}. This process similarity facilitates scale-up and transfer to industrial scale manufacturing and enables the implementation of such highly reactive nanoparticles on an application scale.

The reactivity of the resulting calcium silicate-based nanoparticles was compared to conventional cement formulations in terms of hardening time, heat release profile and product properties.

\section{2.2. Experimental}

\subsection{2.2.1. Nanoparticulate powder preparation}

The one-step preparation of complex nanoparticles by flame spray synthesis requires the use of a combustible precursor that can be fed into a flame spray reactor. Based on previous detailed investigations on simple compounds (e.g. ceria-zirconia), a suitable liquid precursor containing calcium, aluminum, iron and magnesium carboxylates\textsuperscript{17-19} and hexamethyldisiloxane (HMDSO) with a metal loading corresponding to a typical Portland cement composition (see Table 2-1) was prepared.

\begin{table}
\centering
\caption{Portland cement composition used for the preparation of the precursor\textsuperscript{19}.}
\begin{tabular}{ccccc}
\hline
 & CaO & SiO$_2$ & Al$_2$O$_3$ & Fe$_2$O$_3$ & MgO \\
\hline
 & 68 wt\% & 22 wt\% & 5.8 wt\% & 2.6 wt\% & 1.5 wt\% \\
\hline
\end{tabular}
\end{table}

More specifically, calcium 2-ethylhexanoate was prepared as described by Brunner et al.\textsuperscript{20}. Aluminum 2-ethylhexanoate was obtained from basic aluminum 2-ethylhexanoate (ABCR), acetic anhydride (Fluka, puriss) and 2-ethylhexanoic acid (Soctech SA, Romania, techn.)\textsuperscript{21}. Magnesium oxide (Fluka, purum) was dissolved in 2-ethylhexanoate at 140°C for 4 hours. Iron naphthenate (Strem, purum) and HMDSO (Fluka, purum) were used as-received. Corresponding amounts of metal precursors were mixed and diluted with tetrahydrofuran to a final metal loading of 0.5 M, filtered and subsequently fed into a flame spray reactor. The
precursor was dispersed by an oxygen jet and combusted using an oxygen/methane supporting flame for ignition. The setup was placed in a glove-box filled with air that was recirculated by a vacuum pump (Seco SV1040CV, Busch) at about 20 m$^3$ h$^{-1}$. As commercial reference material Normo 4 Portland cement (Holcim, Switzerland) was used.

### 2.2.2. Characterization of starting materials and hardening products

The specific surface area (SSA) of the as-synthesized nanopowders was measured on a Tristar 3000 (Micromeritics) instrument by nitrogen adsorption at 77 K using the Brunauer-Emmett-Teller (BET) method. The average BET-equivalent particle diameter $d_{\text{BET}}$ was calculated using $d_{\text{BET}} = 6/(\text{SSA} \cdot \rho)$, where $\rho$ denotes the density (kg m$^{-3}$), assuming monodisperse, spherical particles. The hydrodynamic particle size distribution was collected by X-ray disk centrifugation (XDC) on a BI-XDC (Brookhaven Instruments) using dry ethyl alcohol (Fluka, puriss) for dispersion. The phase compositions were analyzed by X-ray powder diffraction (XRD, Stoe STADI-P2, Ge monochromator, CuK$\alpha_1$, PSD detector). Transmission electron microscopy (TEM) images were recorded on a CM30 ST (Philips, LaB$_6$ cathode, operated at 300 kV, point resolution ~4Å). Particles were deposited onto a carbon foil supported grid. Scanning electron microscopy (SEM) analysis was performed on a LEO 1530 Gemini after sputtering the samples with ~4 nm of platinum. Isothermal calorimetry (TAM Air, Thermometric AB, Sweden) analysis was performed at 25°C by the addition of deionized water at a water/cement (w/c) ratio of 1.5. The plastic limit of the cements was determined by adding deionized water dropwise to 0.2 g of powder in a 1.5 ml tube until a single pasty block of material was formed upon continuous mixing. Cement pastes were cured in PTFE molds for 7 or 14 days under 100% relative humidity yielding cylinders of 10 mm diameter. The bulk density of hardened cement samples was calculated following the procedure described in ASTM C20. The hardness of the dry blocks was determined by a Vickers micro-hardness test (Wolpert MTX-\(\alpha\)) following a procedure described elsewhere$^{23, 24}$. Nitrogen adsorption was further performed measuring 86 points using the Barrett-Joyner-Halalendar (BJH) method to evaluate the adsorbed volumes and the pore size distributions of hardened samples.
2. Preparation of an ultra fast binding cement from calcium silicate-based mixed oxide nanoparticles

2.3. Results and discussion

2.3.1. Characteristics of dry powders

Dispersion and combustion of the metal containing precursor yielded slightly sintered nanoparticles of 20 to 50 nm primary particle size (see Figure 2-1).

![Image](a) Flame spray reactor during production of mixed metal oxide nanoparticles of a Portland cement composition; (b) Transmission electron micrograph (TEM) of as-prepared particles revealed partially sintered nanoparticles with a morphology similar to flame-made silica.

The flame-made nanoparticles were up to three orders of magnitude smaller than the conventionally prepared counter parts. The difference in agglomerate size can clearly be observed in the particle size distributions measured by XDC (see Figure 2-2). The presence of small agglomerates in the flame-made material was confirmed by the discrepancy between the surface-equivalent primary particle size $d_{\text{BET}}$ derived from nitrogen adsorption (20 nm, see Table 2-2) and the mean hydrodynamic (agglomerate) size of 39 nm (see Figure 2-2) and stays in agreement with earlier investigations on simple compounds.\(^{17}\)
Figure 2-2. (a) Representative hydrodynamic (agglomerate) particle size distributions measured by X-ray disk centrifugation (XDC) of flame-made cement; (b) and a commercial reference material (inset: Scanning electron micrograph (SEM) of as-received commercial Portland cement).
Conventionally manufactured Portland cement consists of irregularly shaped, micron-sized particles of a broad particle size distribution ranging from a few to over 60 μm (Figure 2-2b). The primary particle size of as-prepared nano cement particles was measured after different thermal treatments up to a temperature of 1450°C which represents the typical temperature for clinker formation in modern cement production. These harsh conditions resulted in complete sintering of the nano cement and loss of the high specific surface area (Table 2-2).

<table>
<thead>
<tr>
<th>Commercial cement</th>
<th>Cement nanoparticles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>as prep.</td>
</tr>
<tr>
<td>1.7 μm</td>
<td>20 nm</td>
</tr>
</tbody>
</table>

*Measured by nitrogen adsorption according to the BET method.

Tricalcium silicate is thermodynamically unstable below 1250°C, but can be preserved in a metastable state at room temperature by fast cooling. During production of nanoparticles by flame spray synthesis temperatures rise well above 1500°C. Intimate mixing on a molecular level and ultra-fast cooling rates with a calculated dwell time of only around 10 ms are reached and make crystallization of the particles impossible.
2.3. Results and discussion

Figure 2-3. X-ray diffraction (XRD) pattern of commercial Portland cement and as-prepared flame cement subjected to additional thermal treatments at 700°C, 1000°C and 1450°C for 1h. While the as-prepared nanoparticles showed few, very weak reflections, additional phases were formed at intermediate sintering temperatures (700 to 1000°C) and vanished again at 1450°C.

The crystalline structures (XRD patterns) of commercial Portland cement and flame cement particles are summarized in Figure 2-3. Commercial Portland cement appears rather amorphous (bottom trace)\textsuperscript{26, 27} with few, weak reflections, while the as-prepared nanoparticulate material displayed some weak, additional features that gradually transformed into a similarly amorphous XRD pattern upon thermal treatment.
2.3.2. Hardening kinetics and cement characterization

Since the cement hydration is a highly exothermic reaction, the cement reactivity can be accurately followed by calorimetry as described by Bogue\textsuperscript{28}. The heat release profile directly correlates to the amount of material reacted over time and allows the comparison of different samples in terms of overall activity (total energy released) and temporal evolution (differential energy release). Figure 2-4 compares the nanoparticulate and the conventional Portland cement material during the first 10 days upon addition of water. The nano cement showed a rapid heat release within minutes after contact with water peaking at around 7 minutes. In contrast, conventional Portland cement showed a first, short intense heat release (about 7 mW g\textsuperscript{-1} versus about 100 mW g\textsuperscript{-1} for the nanoparticulate material) and a second broad peak after around 10 hours as has been described in the literature\textsuperscript{9}. The total energy released after 10 days of hardening was comparable (around 370 J g\textsuperscript{-1}, Figure 2-2b) and supports the presence of a similar chemical starting composition in both materials.

For the preparation of cement pastes the plastic limit for both cements was determined. A plastic limit with a water to cement (w/c) ratio of 1.25 and 0.2, for the flame-made and the commercial cement was found, respectively. The need for higher w/c ratios for the nanoparticulate material can be explained with the increased available surface area and corroborates earlier findings by Brunner et al.\textsuperscript{20}. Curing of the cements for 7 or 14 days in PTFE molds under 100\% relative humidity resulted in compacted blocks. While the commercial Portland cement showed a dark-grey color, the nanoparticles-based cement block was light-colored with a brownish touch (Figure 2-5a and b). Both materials were investigated for residual porosity, density and micro-hardness. The reaction profile of the nano cement (Figure 2-4) clearly shows that the reaction was finished after these two time points. Commercial Portland cement attained a bulk density of 2.2 g cm\textsuperscript{-3} after hardening which stays in full agreement with literature values\textsuperscript{29}. The nanoparticulate cement block showed a much lower density of about 0.9 g cm\textsuperscript{-3} (Table 2-3). This pronounced difference in pore content was also reflected in differential pore volume measurements by nitrogen desorption. The relatively dense, commercial Portland cement showed little porosity and a compact structure with large grains (Figure 2-5d) while the hardened flame-derived material displayed an open, flake and needle rich morphology (Figure 2-5c, for a full pore size distribution see Figure A-1-1).
2.3. Results and discussion

**Figure 2-4.** Heat release profile as measured by isothermal calorimetry for flame-made (dashed) and commercial cement (solid). The differential heat release (a) showed only one peak confirming the elevated activity of the nano material within minutes after contact with water. The reaction of commercial Portland cement was much slower in the first hours after the addition of water. The total heat release profile (b) suggests that both materials consisted of virtually the same chemical composition since both materials released a similar amount of heat after 10 days, i.e. same enthalpy of reaction. Please note the break in the time-axis.
Table 2-3. Calculated bulk densities and measured micro hardness of hardened cements.

<table>
<thead>
<tr>
<th></th>
<th>Nano cement</th>
<th>Commercial</th>
<th>Literature&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density / g cm&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>0.92 +/- 0.07</td>
<td>2.15 +/- 0.02</td>
<td>1.9-2.7&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Vickers hardness / HV</td>
<td>9.3 +/- 2.6</td>
<td>50.0 +/- 9.0</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>a</sup> Values dependent on composition and water/cement ratio.

The Vickers hardness (HV) of hardened samples revealed significant differences between the flame-made cement and the commercial cement (Table 2-3) which can mainly be attributed to the porous structure of the flame-derived cement samples (Figure 2-5c). This high porosity can be linked to a substantially higher w/c ratio needed to wet the additional available surface area of the nano cement. The relationship of decreased mechanical properties with increased porosity in cements has been discussed previously<sup>30, 31</sup> and stays in agreement with the rule of mixing predicting a much lower Vickers hardness for porous cements<sup>32</sup>. This low Vickers hardness found for the nano material suggests further adaptations on the chemical composition and the formulation before such materials may be used for load-bearing applications.
2.3. Results and discussion

Figure 2-5. Pictures of hardened cement blocks and corresponding scanning electron micrographs of nanoparticle (a and c) and commercial Portland cement based fracture surfaces (b and d). Both materials showed a similar macroscopic appearance while the microstructure revealed pronounced differences in porosity.

2.4. Conclusion

In summary, the present work shows the one-step preparation of nanoparticulate cement with a conventional Portland cement composition. The small size of the particles changed the hydration behavior of the cement completely and suggests different reaction kinetics while maintaining similar reaction thermodynamics. The reduction in particle size resulted in a drastically increased early reactivity of the cement. Additional improvements in composition, formulation and compaction of the nanoparticles prior to application will be required in order to enhance the currently unfavorable mechanical properties on nano cements.

The here reported early reactivity of the nano cement might open up entirely new fields of applications for Portland type cements, where short hardening times are crucial (e.g. medical applications in orthopedic surgery). Earlier biocompatibility studies already confirmed the non-toxicity of Portland cement in human tissue. In its present form, the nanoparticle derived,
porous cement could be used in renovation or insulation applications where compressive strength is less critical or might enhance the hardening behavior of conventional cements if deployed as admixture. Further improvements in terms of hardness, however, will be necessary before such materials can be used in load-bearing applications.

2.5. Acknowledgements

We would like to thank Dr. F. Krumeich for providing TEM images and Prof. L. Gauckler for SEM measurement time. Financial support by the Gebert Rüf Foundation, grant number GRS-048/04, and ETH Zurich is kindly acknowledged.
2.6. References


2. Preparation of an ultra fast binding cement from calcium silicate-based mixed oxide nanoparticles


3. Preparation of submicron and nano-table salt for food applications

* This work has been pursued in collaboration with a Global-100 company and currently undergoes application testing for food production. Since this work is confidential only parts of the results can be published. The technology developed in the course of this collaboration has been filed as a patent on February 2nd 2008 under the application number PCT/CH 2008/000042.
3.1. Introduction

Already in 1954 Dahl and Love found evidence for the relationship between sodium intake and human essential hypertension\textsuperscript{1}. Hypertension is a major risk factor in the development of cardiovascular diseases (CVD). The major source of sodium in the diet is from salt (sodium chloride, NaCl). Appel and coworkers showed a graded linear relation between salt intake and blood pressure\textsuperscript{2}. However, it must be stated that sodium intake is only one of many factors that contribute to the possible development of CVD.

Since the first data about the relation between salt intake and CVD were published the addition of salt to foodstuffs has become a major issue, particularly in the processed food sector. The average daily intake of salt in the Western societies has been estimated to be between 6 and 10 grams whereas several national public health organs recommend an upper level of no higher than 6 g of salt per day.

Most of the daily salt intake can be linked to the consumption of high-in-salt foods like bread, meat products, soups, cheese or cold meat. The main sources of sodium from foods and the contribution of each to the salt intake are listed in Table 3-1. Cereals & cereal products including bread, breakfast cereals, biscuits, cakes and pastries provide nearly 40% of the average intake and meat and meat products contribute approximately 21% to the average intake.

There are a number of approaches to lower the sodium content in every day food products without changing the eating behavior of the consumer:

The use of salt substitutes like potassium chloride is one of the most common strategies to lower sodium intake. However, a significant increase in bitterness and loss of saltiness has been observed for high potassium chloride concentrations.
Table 3-1. Amount of sodium and percentage contributions contributing to average intake of sodium/person/day

<table>
<thead>
<tr>
<th>Food</th>
<th>Sodium [g]</th>
<th>Salt [g]</th>
<th>Contribution [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereals &amp; cereal products</td>
<td>0.98</td>
<td>2.50</td>
<td>37.7</td>
</tr>
<tr>
<td>(e.g. bread, breakfast cereals, biscuits, cakes, pastries)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meat &amp; meat products</td>
<td>0.54</td>
<td>1.38</td>
<td>20.8</td>
</tr>
<tr>
<td>Other foods</td>
<td>0.33</td>
<td>0.84</td>
<td>12.7</td>
</tr>
<tr>
<td>(e.g. soups, pickles, sauces)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dairy products</td>
<td>0.27</td>
<td>0.69</td>
<td>10.4</td>
</tr>
<tr>
<td>Processed vegetables</td>
<td>0.22</td>
<td>0.56</td>
<td>8.5</td>
</tr>
<tr>
<td>(including chips &amp; snacks)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fats &amp; Oils</td>
<td>0.12</td>
<td>0.31</td>
<td>4.6</td>
</tr>
<tr>
<td>Fruits &amp; vegetables</td>
<td>0.03</td>
<td>0.08</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Bitter blockers prevent taste nerve simulation and are often used to mask bitterness in such potassium chloride rich salts.

Flavor enhancing agents like yeast extracts, lactates, monosodium glutamate and nucleotides amongst others are commercially available and are also targeted on lowering the sodium intake.

Taste enhancers work by activating receptors in the mouth and throat, which helps compensate for the salt reduction.

Unfortunately, food additives like the ones mentioned above are often not favored by the consumer. Especially the Chinese restaurant syndrome which was related to the addition of monosodium glutamate (MSG) in Chinese restaurants, sensitized consumers and subsequently was responsible for a cautious application of such food additives.
The alternative to lowering the sodium content in food products without (partly) replacing sodium chloride by other food additives is to leave the chemical composition of the salts constant whilst optimizing the physical aspects of salts. It has been supposed that lowering the particles size of nutritional salts would lead to enhanced saltiness. This hypothesis is based on the fact that the smaller the salt grains the faster the dissolution rate of the salts in saliva. It has been speculated that this faster dissolution rate inherently would lead to a more efficient transfer of the ions to the taste buds and hence a saltier perception of the food product.

There are several ways to reach smaller salt particle sizes. In this work two different approaches were applied: the bottom-up approach via Flame Spray Synthesis should result in sodium chloride particles with a particle size of below 100 nm, whereas the top-down approach by modern ball milling in a liquid medium should yield particle sizes in the micron to submicron range.

3.2. **Bottom-up: Large-scale production of sodium chloride nanoparticles**

3.2.1. **Introduction**

In the present study we produced pilot-scale quantities of suitable salt samples for the application as food additives. The goal of the study was to investigate the potential of sodium chloride nanoparticles to act as a highly efficient vehicle for delivering saltiness to foods. To ensure prevention of potential cross-contamination with toxic material we used a fully enclosed pilot-scale reactor system engineered for the production of biomaterials. Relevant toxicity experiments were carried out by external accredited laboratories.

3.2.2. **Experimental**

3.2.2.1. **Particle synthesis**

Sodium hydroxide (Ph. Eur., Fluka) was dissolved in 2-ethylhexanoic acid (puriss., Fluka) to form sodium 2-ethylhexanoate and mixed in stoichiometric ratios with chlorobenzene (puriss.,
3. Preparation of submicron and nano-table salt for food applications

Fluka). This mixture was diluted with 50 vol% tetrahydrofuran (puriss., Riedel-de Haën) to adjust the viscosity of the precursor. The final solution was fed into four identical flame spray reactors where it was combusted using an oxygen/methane flame to ignite the liquid sprays. Calibrated mass flow controllers (Brooks) were used to monitor gas flows. The air was pre-cleaned using high efficiency particulate filters (HEPA) leaving less than 0.1 % of dust particles larger than 100 nanometers behind. The off-gas containing the as-formed particles were transferred to the filter tower and collected on four polytetrafluorethylene (PTFE) baghouse filters (TULONA R, Technische Textilien Lörrach, 120 mm diameter, 1640 mm length). The as-prepared nanoparticles were collected on the filters by the aid of a compact drive (VEM motors Thurm GmbH) and fell to the particle catchment tank by pressurized air impulses through the filters.

3.2.2.2. Particle analysis

The specific surface area (SSA) of the as-synthesized nanoparticles was measured on a Tristar 3000 (Micromeritics) instrument by nitrogen adsorption at 77 K and the mean particle diameter was calculated using the Brunauer-Emmett-Teller (BET) method assuming monodisperse particles. The phase compositions were analyzed by X-ray diffraction (Stoe STADI-P2, Ge monochromator, CuKα1, PSD detector).

3.2.2.3. Air stability tests

The air stability of as-prepared sodium chloride powders was tested and compared to in situ doped sodium chloride nanoparticles (5 wt% calcium phosphate or silica). As calcium and phosphate sources, calcium oxide (99.9%, Aldrich) and tributyl phosphate (puriss., 99%, Fluka) were dissolved in 2-ethylhexanoic acid (purum., 98%, Fluka) and added to the precursor solution. Silica was introduced by the addition of corresponding amounts of Hexamethyldisiloxane (purum, Fluka).

3.2.2.4. Food safety

Prior to sensory analyses the flame-derived salt product was tested for food safety. Element analysis (C, H, and N) was conducted via thermal decomposition/combustion of a sample up to 1000°C and consecutive determinations of the decomposition/combustion gases via
infrared detectors (C/CO$_2$ and H/H$_2$O) were completed. The amount of organic remainders on the particles was further analyzed by infrared (IR) spectroscopy of a thoroughly mortared 20 wt% as-prepared sodium chloride and dry potassium bromide (KBr) mixture. Ultraviolet-visible spectroscopy (UV/VIS) was used to support results from IR spectroscopy. Differential Thermal Analysis (DTA) was applied to determine the melting point of as-prepared samples. To appraise the heavy metals content the as-prepared samples were analyzed by an accredited external laboratory (BMG Engineering). The same laboratory was used to analyze the potential presence of 16 of the most prominent (and potentially toxic) polyaromatic hydrocarbons (PAH). The Soxtherm-extraction method with toluene and subsequent GC-MS analysis was used. The flame-derived NaCl samples were tested for the presence of bacterial endotoxins and fungal beta glucans by another external accredited laboratory (Interlabor Belp) using the gel-clot LAL (Limulus amoebocyte lysate) test.

### 3.2.3. Results and discussion

As measured by nitrogen adsorption, the produced powders consist of nanoparticles with a specific surface area (SSA) of 47 m$^2$/g which corresponds to a calculated particle diameter of $d_{\text{BET}} = 59$ nm after the method of Brunauer-Emmett-Teller (BET). This particle size is in agreement with the expected particle size of flame synthesized nanoparticles under chosen conditions. Under the scanning electron microscope Grass et al. observed large sodium chloride nanoparticles in the range of up to 1 µm and hypothesized that the presence of large particles results from grain growth due to moisture uptake as observed by Sata$^8$. If this hypothesis was valid, it should be possible to minimize this observed grain growth by the addition of small amounts of other minerals since these minerals would disrupt the occurring diffusion processes and minimize particle growth (see schematics in Figure 3-1).
Figure 3-1. If sodium chloride nanoparticles (white) are exposed to humidity, the particles are prone to particle growth due to occurring diffusion processes aiming for surface energy minimization (upper part). Silica or calcium phosphate nanoparticles (grey, lower part) homogeneously mixed should disrupt such occurring diffusion processes and reduce extensive particle growth.

We therefore added small amounts of silicon or calcium and phosphate sources to the sodium chloride precursor. In other words, we in situ doped our sodium chloride nanoparticles with calcium phosphate and silica, respectively. Post production, we exposed the powder samples to ambient humidity (~ 60% relative humidity) for 6 days. The results confirmed our hypothesis. While the particle size of the calcium phosphate and silica doped samples stayed between 46 and 58 nm, the pure sodium chloride sample underwent extensive grain growth and reached a calculated particle size of over 2500 nm (see Figures 3-2 and 3-3).
Figure 3-2. The air stability after 6 days (checkered) of NaCl nanoparticles could drastically be improved by the in situ doping with 5 wt% tricalcium phosphate (TCP) or silica.

In the scanning electron micrographs in Figure 3-3 (same magnitude) the difference in particle size of the three NaCl samples is evident. Whilst the pure sodium chloride sample (bottom micrograph) shows cubic particles in the micrometer range, both tricalcium phosphate (TCP) and silica doped samples stay clearly in the nanometer range. Some particles in the micrometer range show partly grown microparticles.
Figure 3-3. The improved air stability after 6 days of NaCl nanoparticles by the in situ doping with 5 wt% tricalcium phosphate (TCP, top left) or silica (top right) is evident. The bottom micrograph shows NaCl crystals having grown up to the 20-fold of their initial size. Note the same magnitude on all electron micrographs.

3.2.3.1. Absence of toxic compounds from combustion

The ability of flame spray synthesis to produce salt nanoparticles with high phase purity is well-established\textsuperscript{7, 9}. A question mark has remained regarding the possible presence of toxic
substances due to incomplete combustion of the precursor. To answer this question and to quantify the organic remainders on the nanoparticles two analyses methods were applied.

The carbon ratio of as-synthesized nanoparticles is directly relative to the organics content in the sample and can most likely be linked to precursor remainders due to incomplete combustion of the precursor. Such an incomplete combustion of the precursor results inherently in a higher carbon content, which implies a higher risk of the presence of organics.

In the course of this study three pilot-scale production runs of pure sodium chloride nanoparticles were executed (samples A, B and C). During the production process of samples A and C, no flame instabilities or unexpected process flow changes were observed and the subsequent analysis showed carbon contents of around 0.1 wt% carbon were detected in the as-prepared powder (see Figure 3-4). By contrast, as the synthesis of sample B was ongoing, one of the four burners showed unusual unsteadiness and therefore was suspected of improper combustion of the precursor. As soon as these instabilities in the flame were noted the respective burner was switched off to prevent contamination of the entire batch. After completion of the synthesis and subsequent collection of the as-synthesized particles sample B also underwent carbon analysis. The graph in Figure 3-4 clearly shows an increase of the carbon content by a factor of eight and confirms the suitability of carbon analysis as a quality control measurement to prevent the presence of potentially dangerous organics.
To confirm that the organic remainders in the flame-derived samples could be assigned to the incomplete combustion of the precursor, Infrared (IR) spectroscopy was applied. The three sodium chloride samples A, B and C (20 wt% in KBr) were compared to 2-ethylhexanoic acid (0.75 wt% in KBr). The bottom line in Figure 3-5 shows that the most prominent signals from the carboxylic acid are between 2900 and 3000 cm\(^{-1}\) and can be related to symmetrical stretching of the C-H bonds.
3.2. Bottom-up: Large-scale production of sodium chloride nanoparticles

Figure 3-5. Infrared spectrograph of proper and neat samples (A and C) compared to an impure sample (B) with organics remainders.

All prominent stretching peaks of 2-ethylhexanoic acid between 2900 and 3000 cm$^{-1}$ are present in all three samples. It can therefore be concluded that even proper runs from a process point of view yield nanoparticles with slight organics impurities which can be related to an incomplete combustion of the precursor solution.

3.2.3.2. External toxicity tests

Above discussed analyses methods enable a quality control of the product from a process point of view. To ensure product safety and demonstrate the safety from a nutritional point of view, additional tests were commissioned to external accredited labs.

Dioxins are known teratogens, mutagens, and suspected human carcinogens. Dioxin enters the general population almost exclusively from ingestion of food, specifically through
the consumption of fish, meat, and dairy products since dioxins are fat-soluble and readily climb the food chain. According to the U.S. Environmental Protection Agency, the average total exposure of toxic equivalents (TEQ) of a human being in North America is $64 \text{ pg/day}$\textsuperscript{10}. Figure 3-6 shows an elevated WHO-TEQ of 137 pg/kg for the impure sample B. Considering a maximal salt intake of around 10 g salt per day a maximum dioxin ingestion of around 1.4 pg WHO-TEQ per day per person due to salt intake would result. This is equivalent to around 2% of the average daily human exposure to dioxins. It can therefore be concluded that the consumption of flame-derived sodium chloride is not considered critical to health with regards to dioxin uptake if the flame instabilities during production are under control.

![Figure 3-6](image)

**Figure 3-6.** Measured WHO-TEQ (World Health Organization Toxic Equivalents) for dioxins for as-prepared samples

A clear sign of the presence of toxic material inside the body is the development of a fever due to pyrogens (e.g. endotoxins) exposure. The most sensitive test available to screen medical devices and raw materials for the presence of harmful levels of endotoxins is the
Limulus Ameobocyte Lysate Gel-Clot Assay (LAL). According to USP the endotoxin limit for 0.9 % NaCl is 0.5 I.U./mg (International Units per milligram). The endotoxin concentration of all three samples was < 0.05 I.U./mg. It can therefore be stated that flame-derived sodium chloride nanoparticles can be considered safe regarding the provocation of endotoxins.

### 3.2.4. Conclusion: bottom-up

With the currently used pilot-scale flame synthesis setup we successfully produced hundred-gram quantities of edible sodium chloride nanoparticles. The particles are very susceptible to the absorption of humidity and consequent particle growth up to the micrometer-level. By *in situ* addition of minerals like calcium phosphate or silica it was possible to produce salt particles with good air stability.

Element analysis in combination with IR spectroscopy are simple methods to check the quality of the combustion from a process point of view. With these two analyses methods it is possible to detect and assign even small quantities of organic remainders which could potentially be harmful to health of a consumer.

As expected the measured dioxin proportion on flame-derived nanoparticles is insignificant. The LAL gel-clot assay did not show any quantities of pyrogens present in the as-prepared powder samples.

In summary, we successfully synthesized food-grade nanoparticulate sodium chloride, but no enhanced saltiness was found in sensory analyses.

### 3.3. Top-down: Ball Milling of salt-in-oil-slurries

#### 3.3.1. Introduction

The introduction of smaller sized salts in dry food products for enhanced saltiness entails several problems. Due to an enhanced surface area of smaller salt particles their hydrophilic properties emerge. The particles take up ambient humidity which provokes grain growth. To counteract this grain growth, flow and anti-caking agents like silica are added to commercial
products, hence keeping the particles small and apart from each other. The smallest commercially available food salts have a particle size of around 15 µm. Due to processing, application and/or stabilization problems no smaller salts are currently on the market.

Depending on the material to be milled, modern ball mills can easily mill down to the submicron level. Sodium chloride is a brittle material and therefore suitable for milling and achieving particles sizes in the submicron-level should be possible. By the use of a suitable water-free liquid milling medium it should be possible not only to mill the salts down to the submicron level, but also to stabilize the salts in the same process step to enhance storage capacity.

3.3.2. Experimental

3.3.2.1. Materials synthesis

Different amounts (225 g, 450 g, 675 g, and 900 g) of food grade table salt (Fine 50 Pure Dried Vacuum Salt, British Salt) were dried for 6 hours at 300°C. Subsequently, 1500 g of high oleic sunflower oil (HOSO, Cargill) was added to each of the samples. Subsequently, the samples were strongly mixed with a mixing turbine (Ytron-Y, Ytron) and milled using a laboratory agitator bead mill (Dyno-mill multi lab, Willy A. Bachofen AG, 0.6 L standard Inox steel/PA6 grinding vessel, agitator discs or ECM-accelerators, 0.5 mm diameter Yttria Stabilized Zirconia (YSZ) grinding balls, filling degree 70%). The milling was run continuously using silicon tubes (inner diameter 8 mm, Siwa Silikon Schlauch, Unicohaberkorn) and a flexible-tube pump (R17 DT71D4/TF, SEW Eurodrive). During milling the mill feed was continuously agitated. The milling was conducted at a maximal flow rate of 60 L/h and a maximal agitator disc speed of 12 m/s. Thereby, the pressure at the inlet of the grinding vessel never exceeded a maximal pressure of 1 bar and the temperature at the grinding vessel outlet was below 100°C at all time. The approximate salt particle size in the milled slurry was measured by a Grindometer (Hegman Modell 232, Erichsen). The grinding time of the samples was between 20 and 60 min depending on the salt concentration.
3.3.2.2. Particle analysis

After grinding the samples were diluted with HOSO to a final concentration of 1.5 wt% and dispersed using an ultrasonic horn (200W, cycle 0.5, 1 min, Hielscher GmbH UP-400S) for particle size distribution analyses. To determine particle size distributions, a X-ray disk centrifugation system (BI-XDC, Brookhaven Instruments) was used\textsuperscript{12}.

3.3.3. Results and discussion

3.3.3.1. Particle size distribution

Within minutes after the milling start the formation of a hand cream-type lotion could be observed. With longer milling time and higher salt concentrations the viscosity of the suspension increased and reached even tooth paste-type viscosities. Since the mill was loaded with 500g of HOSO, the final concentrations of the samples were 10 wt % (sample A), 18 wt % (sample B), 25 wt% (sample C) and 31 wt% (sample D) NaCl in HOSO. The particle size distribution was measured using X-Ray Disc Centrifuge (XDC) at a NaCl in HOSO concentration of 1.5 wt% (see Figure 3-7).
Figure 3-7. Typical particle size distributions as measured by BI-XDC in a 1.5 wt% sodium chloride in High Oleic sunflower oil suspension. The highest concentration shows a particle size distribution shifted to larger particles with a wider particle size distribution (sample D), whereas the sample with the lowest NaCl loading (sample A) represents the smallest particle size distribution.

The geometric mean of the four samples is 0.48 micrometer (sample A), 0.53 micrometer (sample B), 0.52 micrometer (sample C) and 0.60 micrometer (sample D), respectively. The particle size distributions were fitted with a log normal function which can be described with (mu1=-0.737, sigma1=0.091), (mu2=-0.642, sigma2=0.079), (mu3=-0.648, sigma3=0.102) and (mu4=-0.504, sigma4=0.140), respectively.
3.3.3.2. Shelf life

To determine the shelf life of as-prepared slurries, the four samples were stored in closed Schott flasks. The particle size distribution was measured by BI-XDC again after a storage time of 30 days.

![Graph showing particle size distribution](image)

**Figure 3-8.** Particle size distribution of samples A, B, C and D as measured by BI-XDC as a 1.5 wt% sodium chloride in High Oleic sunflower oil suspension as produced (filled) and resuspended after 30 days (checkered).

The measured particle size distributions still have a log normal shape. As can be seen in Figure 3-8, the median shift of the samples was between 12 and 63% of the original particle size. The particle size distributions were fitted with a log normal function can be described with \( \mu_1=-0.375, \sigma_1=0.129 \), \( \mu_2=-0.530, \sigma_2=0.108 \), \( \mu_3=-0.391, \sigma_3=0.124 \) and \( \mu_4=-0.016, \sigma_4=0.217 \), respectively. Considering the storage time of 30 days, these results show drastically enhanced size stability by storage as a suspension in
oil. It can be assumed that this enhanced stability is created by a protecting oil layer on the surface of the milled salts. Thus, storage under oil improves stability of the sodium chloride micron-sized particles.

### 3.3.4. Conclusion: top-down

Modern ball mills are well suited for the milling of salt particles in a viscous medium like sunflower oil. The particle of the cream-like product can reach sizes well below 1 micrometer. By the use of a water-free milling medium, slurries with a long shelf life with regards to particle size can be produced in one step. Although sedimentation of the salt particles occurs, the particles can even be resuspended without strong dispersion techniques.

### 3.4. Conclusion

With both top-down and bottom-up approaches it is possible to cover the whole range of sodium chloride particle sizes. Flame Spray Synthesis is able to produce food-grade sodium chloride samples with a particle size of between 30-100 nanometers, whilst with ball milling it is possible to crush salt particles down to a few hundred nanometer range. By the *in situ* addition of minerals like calcium phosphate or silica the particle growth of the nanoparticles can be inhibited. In the latter technique a liquid medium like sunflower oil is required, which can be advantageous regarding shelf life due to a protecting oil layer around the milled particles.
3.5. References


4. Evaluation of bismuth-based nanoparticles for sunscreen applications

Abstract:

Sunscreens have become part of our culture. Our long-time contact to ultraviolet absorbers, however, has resulted in controversial discussions about the associated risks for humans and the environment. The introduction of nano-pigments (titania) should have diminished the critical discussions, but instead, other concerns about these physical absorbers have been raised. Although classified as biocompatible, some early results show that the persistence of titania nanoparticles might have negative long-term effects on the ecosystems. In this work, degradable, inorganic pigments with similar ultraviolet absorbance if compared to titania are presented. In contrast to uncoated titania, some of the prepared bismuth compounds exhibit enhanced degradability and low photocatalytic activity. These novel nanopigments could substitute current used titania.
4.1. Introduction

Extensive unprotected exposure to ultraviolet radiation is a major reason for the development of skin cancer\textsuperscript{1,2}. The use of sunscreens to protect our skin against the damaging action of intense solar irradiation has become part of daily live particularly in the tropics. The protective effect through regular use of sunscreens is without controversy\textsuperscript{3,4} albeit often re-discussed in public. Such discussions have been particularly fueled through an increasing number of studies concerning the safety of sunscreen ingredients. Water streams containing elevated levels of these compounds affect the gender ratio of fish, snails and micro-organisms in contaminated rivers, lakes and even seaside water. Some studies revealed a systematic absorption of sunscreen substances\textsuperscript{5} while others have shown that a series of frequently used organic UV filters possess estrogenic activity in vitro and in vivo\textsuperscript{6-9}. Very recent results prove the liability of organic sunscreen agents for the bleaching of corals\textsuperscript{10}. These concerns have provoked development and application of inorganic UV filters to partially replace or minimize the use of organic filters with potential estrogenic activity.

The introduction of inorganic pigments like zinc oxide or titania should have brought relief to these concerns, but consumer response was dissatisfactory due to a visible whiteness of originally applied pigments in the late nineties. A reduction in particle size to the nanometer range circumvented visible light scattering while maintaining the excellent UV blocking properties of these semiconducting oxides. As one of the first large scale applications of engineered nanoparticles in consumer products with direct body contact, criticism on the use of such nano-materials in cosmetics have initiated several large research programs on the health risks of nanoparticles when topically applied. Early studies have shown controversial results on the uptake of nanoparticles through the human skin\textsuperscript{11-13}. A conclusive proof of a non-damaging action (safe use), however, is difficult per se as the absence of a negative effect can not be directly demonstrated due to a lack of suitable control groups.

Furthermore, the large production volumes of cosmetics directly entail the question whether the release of persistent inorganic nanoparticles into the environment may be harmful to our ecosystems. While both human health concerns and ecotoxicological investigations are
under way requiring several years to completion, the only timely alternative to a wait-and-see attitude is a proactive search for alternative sunscreen pigments circumventing above risks.

A possible way to circumvent the foreseeable endless debate about the risks associated with an epidemiological use of titania nanoparticles in sunscreens may be found in a more detailed analysis: While the persistence of titania has been a key factor enabling its commercial use on a megaton scale, exactly the same persistence has given rise to concerns about its fate within the human body. While the uptake of nanoparticles through the human skin is still subject of checkered discussions, early studies on the possible impact of nanoparticles on the ecological scale are unsettling in view of a reported increase in Daphnia magna mortality following exposure to titania nanoparticles\textsuperscript{14}. This is particularly unsettling, since titania itself has been regarded as biocompatible\textsuperscript{15-17}. Up to the present, most major chemical incidents with global impact (polychlorinated biphenyls, chlorofluorocarbons, asbestos etc.) have been caused by persistent compounds without any measurable acute toxicity\textsuperscript{18-22}. Taking into account that the use of sunscreens is typically limited to a few hours it can be stated that this form of application does not inherently require a persistent compound. Therefore, most of the potential long-term risks related to the use of persistent nanoparticles in health care products could be avoided by the use of degradable compounds.

How to find a suitable degradable, yet non toxic, inorganic compound with reliable UV blocking properties? In terms of material class, only semiconductors have sufficiently large quantum yields for efficient UV photon absorption – yet, the traditional semiconductors are either persistent (silicon based materials), toxic (selenides, phosphines, tellurides), or water sensitive (nitrides). As most heavy metals from the transition elements can rapidly be excluded from a pre-selection (e.g. Cr, Mn, Co, Ni, Cu etc.), most potential candidates are main-group elements. Here, particularly one element stands out for its century-long history of medical use. Applied since the late medieval times, bismuth containing preparations were used to fight fungal skin infections and syphilis. Since the 19\textsuperscript{th} century, bismuth compounds have increasingly been used for stomach infections and today constitute one of the major treatments for stomach ulcer caused by Helicobacter pylori\textsuperscript{23}. Since the early 20\textsuperscript{th} century bismuth has been introduced to cosmetics, e.g. bismuth oxychloride as white-silvery pigment. In view of the traditional use of bismuth compounds for medical and cosmetic applications, the here presented study was focused on evaluating suitable bismuth derivatives to fulfill the
need for a more sustainable and degradable UV absorbing ingredient for sunscreens. Advantages and risks associated with these new nanomaterials are discussed.

4.2. Materials and Methods

4.2.1. Particle synthesis

A series of bismuth compounds with established safe track record in dermatological formulations was selected. Despite the optimal scattering power of a material being highest when its particle size is equal to about half the wavelength of the light (~ 100-200 nm)\textsuperscript{24}, the candidates were prepared in the form of nanoparticles to circumvent the undesired whitening effect of a sunscreen formulation. Along with titania nanoparticles for reference purposes, three bismuth compounds (BiOCl, Bi\textsubscript{2}O\textsubscript{3} and BiPO\textsubscript{4}) were produced from combustion of precursor solutions in a flame spray reactor\textsuperscript{25-27}. Bismuth oxide was prepared by flame spray pyrolysis using bismuth(III) 2-ethylhexanoate in mineral spirit (28 wt% Bi, Strem). Bismuth phosphate and bismuth oxychloride were prepared by addition of the corresponding ratios of tributyl phosphate (puriss., 99%, Fluka) as phosphate source or chlorobenzene (98%, Fluka) as chlorine source to bismuth 2-ethylhexanoate. The precursor solutions were diluted with xylene (96%, Riedel-de-Haen). The mixture was fed through a capillary (diameter 0.4 mm) into a methane (1.13 L min\textsuperscript{-1}, tech., Pan Gas, Dagmersellen, Switzerland)/oxygen (2.4 L min\textsuperscript{-1}, tech., Pan Gas) flame, using a gear-ring pump (HNP Mikrosysteme, Parchim, Germany) at a rate of 5 mL min\textsuperscript{-1}. Oxygen (5 L min\textsuperscript{-1}, Pan Gas, tech.) was used to disperse the liquid leaving the capillary. Calibrated mass flow controllers (Brooks Instrument) were used to control all gas flows. The as-formed nanoparticles were collected on glass fiber filters (GF/A, 25.7 cm diameter, Whatman), placed on a cylinder mounted above the flame, by the aid of a vacuum pump (Seco SV 1040 C, Busch).

4.2.2. Particle characterization

The specific surface area (SSA) of the as-synthesized nanoparticles was measured on a Tristar 3000 (Micromeritics) instrument by nitrogen adsorption at 77 K and the mean particle diameter was calculated using the Brunauer-Emmett-Teller (BET) method assuming
monodisperse particles. X-ray powder diffraction (XRD) patterns were collected on a Stoe STADI-P2 (Ge monochromator, CuKα1, PSD detector) at ambient condition. TEM images were recorded on a CM30 ST (Philips, LaB6 cathode, operated at 300 kV, point resolution ~4Å). Particles were deposited onto a carbon foil supported grid. Solubility measurements of aqueous solutions of as-prepared 0.5 wt% bismuth compounds were performed at pH 5.5 (Bis-tris, molecular biology grade, AppliChem) and pH 7.4 (Trizma® base, BioChemika Ultra, Fluka). The powder samples were dissolved at a weighted sample concentration of 0.5 wt% under constant stirring in high purity deionized water (>18.2 MΩ·cm). After 48 hours the samples were centrifuged at 10,000 g for 30 min (RC5C Plus, Sorvall). Subsequently, the bismuth concentration of the supernatant was measured by ICP-OES on an Iris AP (Thermo Jarrell Ash).

4.2.3. Ultraviolet absorbance measurements

The preparation of a standard sunscreen base followed a procedure by the U.S. EPA.10 wt% of nanoparticles were mixed into this standard sunscreen base by magnetic stirring during 5 min. The obtained sunscreens were subsequently homogeneously distributed onto transpore™ surgical tape (3M) at a concentration of 2 mg/cm². Ultraviolet absorbance measurements of these sunscreens between 290 and 400 nm were carried out on a UV-1650PC spectrometer (Shimazdu) in transmission mode. The sun protection factor (SPF) was predicted from the transmission measurements according to equation 4-1:

\[
SPF = \frac{\sum_{290}^{400} E(\lambda) \varepsilon(\lambda)}{\sum_{290}^{400} \frac{E(\lambda) \varepsilon(\lambda)}{PF(\lambda)}}
\]  

(4-1)

Where \( E(\lambda) \) is the spectral irradiation of terrestrial sunlight under defined conditions and \( \varepsilon(\lambda) \) is the relative effectiveness of UV radiation at wavelength \( \lambda \) nm in producing delayed erythema in human skin. Numerical values for \( E(\lambda) \) and \( \varepsilon(\lambda) \) were taken from the work from Diffey and Robson.29
4.2.4. Photocatalytic activity measurements

A 50 ml beaker (Schott) was used as the photo reactor vessel. 10 ml of 0.1 wt% aqueous nanoparticle suspensions were mixed with 20 ml of a $7.5 \times 10^{-5}$ M Eosin B solution (Standard Fluka, Fluka) and magnetically stirred in the dark for 15 min to reach the adsorption equilibrium of Eosin B with the catalyst, and then exposed to light from an ultraviolet lamp (Philips Hg TUV PL-L 55W/ HF). Commercial TiO$_2$ (P25, Degussa) was adopted as the reference to compare the photocatalytic activity under the same experimental conditions. Ultraviolet absorbance spectra were recorded on a UV-1650PC spectrometer (Shimazdu) in transmission mode at different intervals to monitor the reaction. The reaction constant $k$ was calculated based on the data points at 517 nm by using the dye concentration at different intervals.

4.3. Results and Discussion

Flame spray synthesis of appropriate organic precursor solutions yielded nanoparticles with a mean particle diameter of 10 - 30 nm (see Figure 4-1). The laboratory scale setup yielded an approximate nanoparticles production rate of 10 g h$^{-1}$.

Under the electron microscope the partial agglomeration of the as-prepared nanopowders could be observed. Nitrogen adsorption measurements confirmed BET particle diameters of 31 nm for TiO$_2$, 11 nm (BiOCl), 16 nm (Bi$_2$O$_3$) and 23 nm (BiPO$_4$).
Figure 4-1. Production steps during the preparation of bismuth based sunscreens: a) Synthesis of bismuth compounds in a flame spray reactor, b) BiOCl nanoparticles produced at a production rate of 10 g h⁻¹, c) Transmission electron micrographs revealing agglomerated 10-30 nm particles, d) Final sunscreen formulations containing 10 wt% of TiO₂, BiOCl, Bi₂O₃ and BiPO₄ degradable nanoparticles, respectively (left to right).
Figure 4-2. X-Ray Diffraction spectra of the three as prepared bismuth compounds compared to literature values\textsuperscript{30-32}.
As-prepared bismuth compounds were analyzed by X-ray diffraction (XRD). The recorded XRD spectra of the respective compounds are in good agreement with available literature values (see Figure 4-2).

To confirm our hypothesis and demonstrate UV blocking properties qualifying for sunscreen applications, the UV absorbance of the particles was tested as a 10 wt% suspension in a standard sunscreen formulation according to the U.S. EPA (United States Environmental Protection Agency)\(^{28}\). The incorporation of the as-prepared white (TiO\(_2\) and BiPO\(_4\)), pale yellow (BiOCl) and yellow (Bi\(_2\)O\(_3\)) powders into the standard sunscreen base yielded sunscreens with similar colors if compared to the base powders (see Figure 4-1). We applied the different compositions onto transpore\textsuperscript{TM} surgical tape and tested for UVA/UVB absorbance as proposed by Diffey and Robson\(^{29}\). BiOCl and Bi\(_2\)O\(_3\) exhibited a similar absorption spectrum if compared to the flame-derived titania (mainly rutile) in a standard sunscreen (Figure 4-3) suggesting a UV protection potential in a similar range like titania based sunscreens.

**Figure 4-3.** UV absorbance of 10 wt% nanoparticles in a standard sunscreen base indicates a similar UV absorption potential as compared to nanosized titania. The dotted line represents the standard sunscreen base without nanoparticles loading.
Based on these recorded UV absorption spectra the sun protection factor (SPF) of the novel sunscreens was determined (see Figure 4-4). Despite their smaller particle sizes the sunscreens containing BiOCl and Bi$_2$O$_3$ exhibit an SPF in the vicinity of the titania reference. The influence of the particle size on the UV absorbance is established$^{24}$. The particle size for optimal UV protection should hence be around 100-200 nanometers. In case of flame spray synthesis, the chosen conditions and resulting production rate of the combustion process as well as the concentration of the liquid precursor used have a major influence on the particle size of as-prepared powders$^{33}$. It can therefore be assumed that the particle size of both BiOCl and Bi$_2$O$_3$ can be further optimized for ideal UV blocking properties.

![Graph showing calculated sun protection factors (SPF) for TiO$_2$, BiOCl, Bi$_2$O$_3$, and BiPO$_4$.]

**Figure 4-4.** Calculated sun protection factors (SPF) based on the recorded absorbance spectra of 10 wt% nanoparticles in a standard sunscreen base (n=3)

The role of inorganic nanoparticles in sunscreens is to protect the human skin from the harmful UV irradiation. The downside of the use of ingredients such as titania is the possible uptake of these compounds by the human organism or else the release of such inorganic
4. Evaluation of bismuth-based nanoparticles for sunscreen applications

materials to the environment. The potentially negative effects of a release of large amounts of sunscreen ingredients have been investigated for ecological systems in marine areas\textsuperscript{9, 10, 34, 35}. Naturally, most of the sunscreens ingredients are either washed off from the skin during showering or released by waste water from washing machines. In modern areas, such liquid waste is usually directly transferred to waste water treatment plants. Wiesner and coworkers assumed that even most mobile nanoparticles are likely to be removed in filters during water treatment due to aggregation processes\textsuperscript{36}. Unfortunately, Limbach et al. showed in their model wastewater treatment plant that a significant fraction of engineered oxide nanoparticles escaped the wastewater plant’s clearing system. They found up to 6 wt\% of their model compound cerium oxide in the exit stream of the model plant\textsuperscript{37}. These findings signify that if nanoparticles should not be taken up by the human body a relevant part might pass through waste water treatment plants and end up in the ecosystems. This is particularly unsettling as potentially negative effects of “safe” and vastly produced nanomaterials like titania or silica have been found\textsuperscript{14, 36}. To what extent these commonly used nanoparticles could be harmful to the environment is still an unanswered question and will be a topic of controversial discussions. Yet it is clear that once these totally persistent materials are released into the ecosystems they will persist and not easily be removed by any means.

In areas with high UV radiation exposure, sunscreens are typically applied several times a day. This means that sunscreens need a protection time of several hours only. It can therefore be stated that it is unnecessary to use persistent material like titania for UV protection. Ideally, such inorganic UV filters would guarantee a UV protection during the application and then degrade to nonhazardous compounds. Therefore, the persistency of the as-prepared compounds was determined in solubility measurements. The solubility of the three as-prepared bismuth compounds was recorded at pH 5.5 and pH 7.4 in buffered water (see Figure 4-5). The solubility of Bi\textsubscript{2}O\textsubscript{3} is especially elevated at pH 5.5 if compared to BiOCl and BiPO\textsubscript{4}. The measured bismuth concentration of 427 ppm corresponds to a dissolved amount of 9.5 wt\% bismuth oxide after 48 hours. In addition to the good UV absorbance bismuth oxide is also degradable.
4.3. Results and Discussion

Figure 4-5. Solubility of bismuth compounds after 48 h. The different pigment compounds were dissolved in buffered water at a concentration of 0.5 wt% under constant stirring. The solubility of all as-prepared particles was elevated at pH 5.5 which represents a typical pH value in lysosomes of mammalian cells.

One of the major concerns about the use of titanium dioxide for sunscreen applications is its possible photocatalytic activity on living tissues. To reduce potential adverse effects, titanium dioxide used in cosmetic preparations is often coated\textsuperscript{38}. Hence, the introduction of new inorganic UV filters requires the knowledge about its potential photocatalytic activity. Therefore, the photocatalytic activity of as-prepared bismuth compounds and titania was recorded following a procedure described by Hu et al\textsuperscript{39}. For this purpose the degradation state of a dye (Eosin B) was recorded by UV-Vis and the reaction constant of the first order reaction calculated (Figure 4-6).
Figure 4-6. Reaction constants of the investigated nanoparticles derived from flame spray synthesis compared to a commercial reference. The reaction constant of bismuth oxychloride is around 4 times higher than the one from uncoated titania. By contrast, bismuth oxide and phosphate show a very low photocatalytic activity.

UV absorbance measurements of investigated nanoparticles indicated the potential suitability of BiOCl and Bi$_2$O$_3$ as uncoated inorganic UV filters in sunscreens. Unfortunately uncoated BiOCl also showed to be a highly efficient photocatalyst and is therefore not suited for dermatological application in the uncoated form. BiPO$_4$ does not meet any of the requirements needed for the replacement of titania in sunscreen applications.

4.4. Conclusion

The continuing depletion of the UV absorbing ozone layer in the Earth’s atmosphere and the increasing awareness of health risks due to the exposure of unprotected skin to UV radiation are opposed to the human wish of perfectly sun-tanned skin. The demand for sunscreens will
4.4. Conclusion

therefore further increase in the future. To eliminate a potential hazard posed to health and environment by the persistency of non-acute-toxic particles the development of sustainable sunscreens is important. The here presented results show the high potential of bismuth oxide to be applied in cosmetic applications as inorganic UV filters for modern sunscreens. Bismuth oxide shows a good UV absorbance (SPF: 7.5) and low catalytic activity (~ 1/10 of commercial uncoated TiO$_2$). In combination with its enhanced solubility (around 10 wt% dissolved after 48 h), bismuth oxide seems to be an interesting alternative for sunscreen applications. It needs to be shown though that the yellow color of the particles doesn’t have a negative optical effect when applied on the skin which would inherently affect consumer acceptance. Certainly, recommended bismuth oxide nanoparticles still need to be optimized for the use in sunscreens. However, this work makes it apparent that potential candidates for alternative sunscreen ingredients are readily available.
4.5. References


5. General conclusions and outlook
Influencing the reactivity and solubility of materials by the modification or invention of production processes has been successfully applied for a long time. With modern technologies it is possible to synthesize a wide range of different compounds (oxides, salts, metals, composites) in manifold compositions with a particle size down to the nanometer range. When decreasing the particle size to the nanometer level surface atoms start playing a significant role determining the overall properties of a material. This can result in drastically changed properties.

The availability of large-scale production methods allowed the annual megaton production of inorganic nanoparticles for commodity products like carbon black, pigmentary titania or silica. Besides being produced on an industrial scale for commodity applications, these three examples have another common denominator, namely their persistency. The property of being immune to chemical, biological and physical processes and thus remaining unmodified during a long period of time allowed the annual megaton production of these compounds. Unfortunately, exactly the same property causes more and more concerns. The inhalation of nanoparticles has gained attention due to the possible negative effects resulting from the interaction of the human organism with nanoparticulate matter. An increasing amount of these concerns will be expanded to the potential negative effects of such persistent nanoparticles on any living matter. Investigations in such a direction are very complex and time consuming; as such studies have to be conducted in a reasonable biological system and over an extended time period to address long-term effects. History has shown multiple times that non-toxic, but persistent materials have caused severe health problems (e.g. silicosis) with even fatal consequences decades after the actual exposure (e.g. asbestos).

With the availability of improved synthesis processes the amount of nanoparticles applied in commodity products will certainly increase. The lack of clear regulations on the labeling of such products will support this development. It is clear that the launch of a larger variety of products containing nanoparticles will augment the release of nanosized material into the environment. But as the detailed effects of the disposal of highly mobile and persistent material into our ecosystems are unclear a responsible handling of such compounds is most important.

Opportunities of nanoparticulate matter are clearly at hand. Recent advances in the production of inorganic nanoparticles do not only allow the synthesis of a very broad variety
of compositions; they also permit the production and introduction of more sustainable products, e.g. by developing new products to be non-toxic and degradable. Advanced technologies like flame spray synthesis now enable the replacement of currently used persistent by degradable compounds without losing the desired properties. Obviously, such developments are elaborate and the resulting products not only need to be compatible with market needs, but also competitive with regard to price. Nevertheless, the possible longterm impacts resulting from the industrial introduction of highly mobile and persistent materials needs to be taken into consideration.
A.1. Supplementary information, chapter 2

A.1.1. Pore size distribution

Figure A-1-1. Pore size distributions of hardened cement blocks derived from flame-made cement nanoparticles (dashed) and commercial Portland cement (solid) calculated from the nitrogen desorption isotherm using the method of Barrett-Joyner-Halender (BJH). The pronounced difference in density (Table 2-2) stays in full agreement with the significantly higher porosity of the nanoparticle derived material.
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Refereed journal articles
Featured article in Nanotechnology and featured on nanotechweb.org

Patents

Conference proceedings
S.C. Halim, T.J. Brunner, and W.J. Stark, Flame spray synthesis of nanoparticles for


**Invited talks**


**Courses and laboratories**

Chemistry (1 ECTS), teaching assistant, D-MAVT, ETHZ 151-0010-00 U, 2007

Frontiers in nanotechnology, teaching assistant, D-CHAB/D-MATL, ETHZ 327-1103-00 V, 2007

General Chemistry I (6 ECTS), laboratory course, D-CHAB, ETHZ 529-1001-00L, 2005

**Student supervision**

Lukas Gerber
“Alternative salt application techniques for snack products”, 04 – 06/2008

Andreas Eichenberger

**Varia**

Reviewer for the Journal of the American Ceramic Society