PHYSICAL CHARACTERIZATION OF PLASTIC SURFACES IN WEARING AND CLEANABILITY RESEARCH

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ABSTRACT

Plastic surfaces are a group of materials used for many purposes. The present study was focused on methods for investigation of surface topography, wearing and cleanability of polyvinyl chloride (PVC) model surfaces and industrial plastic surfaces.

Contact profilometry, scanning electron microscopy (SEM) and atomic force microscopy (AFM) are powerful methods for studying the topography of plastic surfaces. Although they have their own limitations, they are together an effective tool providing useful information on surface topography, especially when studying laboratory-made PVC model surfaces with known chemical compositions and structures. All examined laboratory-made PVC plastic surfaces examined in this work could be considered as smooth according to both AFM and profilometer measurements because height differences are in the nanoscale on every surface. Industrial plastic surfaces are a complex group of materials because of their chemical and topographical heterogeneity, but they are nevertheless important reference materials when developing cleaning and wearing methods.

According to the results of this study the Soiling and Wearing Drum and the Frick-Taber methods are very useful when simulating three-body wearing of plastic surfaces. Both the investigated wearing methods can be used to compare the wearing of different plastic materials using appropriate evaluation methods of wearing and industrial use.

In this study, physical methods were developed and adapted from other fields of material research to cleanability studies. The thesis focuses on the methodology for investigating the cleanability of plastic surfaces under realistic conditions, where surface topography and the effect of wear cleanability were among the major topics. A colorimetric method proved to be suitable for examining the cleanability of the industrial plastic surfaces. The results were utilized to evaluate the relationship between cleanability and the surface properties of plastic surfaces. The devices and methods used in the work can be utilized both in material research and product development.

Keywords: plastic, microstructure, topography, profilometry, SEM, AFM, wearing, cleaning

FOREWORD

This study was carried out at the Department of Agrotechnology, University of Helsinki. I thank the heads of the Department of Agrotechnology, professor Aarne Pehkonen (-2000) and professor Jukka Ahokas (2001-) for providing me the opportunity to carry out this work. I also thank the ELPI-group leaders and management group for their valuable contribution.

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Helsinki, May 2006

Risto Kuisma

ABBREVIATIONS

Δm	Mass loss
AFM	Atomic Force Microscopy
ASTM	American Society for Testing and Materials
Benzoflex®	Plasticizer, diethylene glycol dibenzoate, triethylene glycol dibenzoate, bis (2-ethylhexyl) adipate, diethylene glycol monobenzoate
CIE	Commission Internationale de l’Eclairage, International Lighting Commission
CIELAB	CIE L*a*b* color space
COM	Confocal Microscope
DIN	German Institute for Standardization
DOP	Plasticizer, dioctyl phthalate
DS	Dansk Standard
ELPI	Elinympäristön pintojen hallinta (Control of surfaces in everyday life) –project
EN	European Standard
ESD	Electrostatic Discharge
Hexamoll® DINCH	Plasticizer, di-isonyl-cyclohexane-1,2-dicarboxylate
ISO	International Organization of Standardization
L*	Lightness L* scale measured as blackness-whiteness
L*a*b*	Color space, the scale is defined by a vertical axis and two intersecting perpendicular axes
PUR	Polyurethane
PVC	Vinyl, poly(vinyl chloride)
R_a	Roughness, arithmetical mean deviation of the profile
R_{ku}	Kurtosis of the profile
R_{sk}	Skewness of the profile
R_q	Root-mean-square deviation of the profile
RH	Relative Humidity
SEM	Scanning Electron Microscope
SFS	Finnish Standard Association

STM	Scanning Tunnelling Microscopy
TEM	Transmission Electron Microscope

LIST OF ORIGINAL PUBLICATIONS

I **Kuisma, R.,** Pesonen-Leinonen, E., Redsven, I., Ylä-Outinen, I., Hautala, M. and Sjöberg, A.-M. 2003. A practical testing procedure for floor coverings: cleanability and resistance to chemical and mechanical wear. Tenside Surfactants Detergents 40 (1), 25-30.

II Redsven, I., **Kuisma, R.,** Laitala, L., Pesonen-Leinonen, E., Mahlberg, R., Kymäläinen, H.-R., Hautala, M. and Sjöberg, A.-M. 2003. Application of a proposed standard for testing soiling and cleanability of resilient floor coverings. Tenside Surfactants Detergents 40 (6), 346-352.

III **Kuisma, R.,** Pesonen-Leinonen, E., Redsven, I., Reunanen, E., Kymäläinen, H.-R., Sjöberg, A-M., and Hautala. M. 2005. Soiling tendency of worn, plastic flooring materials related to their surface topography. Tenside Surfactants Detergents 42 (3), 154-162.

IV **Kuisma, R.,** Redsven, I., Pesonen-Leinonen, E., Sjöberg, A-M. and Hautala, M. 2005. A practical testing procedure for durability studies of resilient floor coverings. Wear 258, 826-834.

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VI Määttä, J., Koponen, H.-K., **Kuisma, R.,** Kymäläinen, H.-R., Pesonen-Leinonen, E., Uusi-Rauva, A., Hurme, K.-R., Sjöberg, A.-M., Suvanto, M., and Pakkanen, T.A. 2006. Development of PVC materials. Effect of plasticizer and surface topography on cleanability of plasticized PVC materials. Submitted

VII Koponen, H.-K., **Kuisma, R.,** Kasanen, J., Kymäläinen, H.-R., Pesonen-Leinonen, E., Hautala, M., Suvanto, M., Pakkanen, T.A., Pakkanen T.T. and Sjöberg, A.-M. 2006. Development of new PVC materials. Characterization and feasibility of diamond coating on model PVC materials. Submitted.

THE AUTHOR’S CONTRIBUTION IN THE ORIGINAL PUBLICATIONS

I Risto Kuisma was the corresponding author and was mainly responsible for experimental design. In addition, he performed wear measurements, analysed the data, interpreted the results and wrote the publication.

II Risto Kuisma was partly responsible for experimental design and analysed part of the data. He commented and revised the whole publication.

III Risto Kuisma was the corresponding author and was mainly responsible for experimental design. In addition, he performed profilometric and scanning electron microscopy measurements, analysed the data, interpreted the results and wrote the publication.

IV Risto Kuisma was the corresponding author and was mainly responsible for experimental design. In addition, he performed measurements, analysed the data, interpreted the results and wrote the publication.

V Risto Kuisma was the corresponding author and was mainly responsible for experimental design. In addition, he performed the measurements, analysed the data, interpreted results and wrote the publication.

VI Risto Kuisma was partly responsible for experimental design and analysed part of the data. He performed profilometric measurements, analysed and reported data. He commented and revised the whole publication.

VII Risto Kuisma was partly responsible for experimental design and analysed part of the data. He performed wear measurements and profilometric measurements and analysed and reported data. He commented and revised the whole publication.

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In this dissertation the Roman numerals I-VII are used to refer to these original publications.

1 INTRODUCTION

In 2002 Tekes (the National Technology Agency of Finland) started the technology programme Clean Surfaces 2002-2006, the primary goal of which was to create comprehensive understanding of the basic phenomena in the chemistry and physics of clean and dirty surfaces. The present study is a part of the ELPI (Control of surfaces in everyday life) project in the Clean Surfaces programme of Tekes. The task of the ELPI –project groups is to acquire knowledge on soiling and cleaning phenomena, firstly by developing methods for soiling, cleaning and soil determination and secondly by modifying surface properties of plastic and ceramic materials to be more soil-resistant.

In Europe, plastic materials are among the most used floor and wall materials in many public buildings (Potting and Blok 1995) and homes. Furthermore, plastics are used in buildings as pipes, window profiles and cable insulations (Menges 1996, Braun 2002). Plastic coated floorings have many kinds of applications. Several factors affect the choice of flooring, such as the duration, slipperiness, load, wearing and care properties.

The plastics industry, especially the flooring industry, has two challenges: continuously to introduce new improved products (often related to new polymers), and to comply with existing test standards. One problem is that the existing standards were developed in the 1960s, whereas products and technologies have evolved to a much higher quality level in terms of wear resistance (Buchheit 2004). Plasticized polyvinyl chloride (PVC) is a soft material with poor wear and soil resistance. For example fat-soluble compounds tend to diffuse into PVC (Wildbrett 2004). Soil resistance of commercial PVC products is influenced by each component of the product formulation, including plasticizers, stabilizers, fillers, extenders, lubricants, antioxidants and dyes. Modification of the topography of plastics for the development of more self-cleaning plastic surfaces is currently the subject of intensive research. The soil resistance and cleaning properties of surfaces can be enhanced by mimicking the surface structures of lotus leaves (Neinhus and Barthlott 1997). Amorphous diamond coating can be used to enhance the wear resistance of laboratory-made PVC model surfaces.

In this study the suitabilities of physical surface characterization methods were investigated in the frame of cleanability. Two wearing methods, the Frick-Taber apparatus and the Soiling and Wearing Drum Tester were applied and evaluated for wearing tests of plastic surfaces. Scanning electron microscopy (SEM), contact profilometry and atomic force microscopy (AFM) were applied for examination of the topography of new and worn industrial plastic surfaces. The cleanability of the surfaces was measured using a colorimeter. The use of a radiochemical method in studying the cleanability of laboratory-made PVC model surfaces will be the focus of the PhD thesis by Jenni Määttä. In the present study, the most relevant information was provided by the study investigating the topography of laboratory-made PVC model plastic surfaces by contact profilometry, AFM and SEM.

2 REVIEW OF THE LITERATURE

2.1 SURFACE TOPOGRAPHY

Surface texture includes roughness (nano- and microroughness), waviness (macroroughness), lay and flaws (ASME B46.1 1995). The symbol R_a is used both for nano- and microroughness and for waviness or macroroughness. Roughness consists of the finer irregularities of the surface texture. Waviness consists of the more widely spaced component of surface texture, which may include very long wavelength components such as form errors. The lay of a surface is the direction of the predominant surface pattern. This is usually determined by the production method used. Flaws, on the other hand, are unintentional irregularities that do not occur in any consistent pattern and include scratches, dents, cracks etc. (Cuthbert and Huynh 1992).

Several techniques have been developed over the years to quantify the topography of surfaces. These can be divided broadly into two categories: contact (profilometry) and non-contact (interferometry) methods (Poon and Bhushan 1995, Gilmour et al. 1999). In recent decades, a variety of new methods have been developed for the evaluation of surface topography properties, including different microscopic methods e.g. atomic force microscopy, phase shifting interferometry, stereo scanning electron microscopy and laser confocal scanning microscopy (Myskhkin et al. 1992, Myskhkin et al. 2003). Various different techniques used to study surface topography are presented in Table 1.

Table 1. Surface topography – a summary of the measurement techniques used for polymeric, ceramic and metal materials.

Device	**Resolution**		**Measurable area**	**Advantages**	**Disadvantages**	**Typical materials**	**References**
	Lateral	**Vertical**					
Stylus profilometry	100 nm	0.5 nm	Typically a few millimetres	No sample preparation, rapid 2D measurements	Stylus can damage the sample. Slow measurement speed (3D)	Metals	Sherrington and Smith 1988, Bhushan 2001, Miyoshi 2002, Chappard et al. 2003, Bhushan 2004
Optical profiler	350 nm to 9000 nm	0.1 nm	0.2 nm to 10^5 nm	No sample preparation, non-contacting	Reflective light	Metals, ceramics, polymeric materials	Bennett 1992, Brundle et al. 1992, Zahidi et al. 1993, Jolic 1994, Whitehouse 1997, Miyoshi 2002
Scanning electron microscopy (SEM)	1 nm to 50 nm (in secondary electron mode)	10 nm to 20 nm	Less than 0.1 mm, up to 10 cm	High magnification imaging (x10-300 000)	Samples must be vacuum compatible. Requires a conducting surface	Metals, polymeric materials, biological materials	Brundle et al. 1992, Bhushan 2001, Miyoshi 2002, Bhushan 2004
Atomic force microscopy (AFM)	0.2 nm to 1 nm	<0.03 nm to 0.05 nm	10^3 nm to 10^5 nm	High resolution pictures	Scans small areas	Metals, polymeric materials, biological materials	Ermakov and Garfunkel 1994, Allen et al. 1997, Chizhik et al. 1998, Lemoine and Mc. Laughlin 1999, Miyoshi 2002, Myshkin et al. 2003, Shulba et al. 2004
Scanning tunnelling microscopy (STM)	0.2 nm	<0.03 nm to 0.05 nm	10^5 nm	High resolution pictures	Requires a coducting surface, scans small areas	Polymeric materials, metals	Song and Vorburger 1991, Stout 2000, Bhushan 2001, Mainsah et al. 2001, Miyoshi 2002
Confocal microscopy (COM)	500 nm to 4000 nm	2 nm to 2000 nm	100 nm to $6x10^5$ nm	Minimal sample preparation	Backround texture often confuses the detectors	Metals, polymeric materials, ceramics, biological materials	Aguilera and Stanley 1999, Miyoshi 2002, Bhushan 2004, Hupa et al. 2005

2.1.1 Profilometry

An important factor in surface science is the evaluation, i.e. measurement and analysis of surface topography. The first modern profiling instrument was the Abbott profilometer (Abbott and Firestone 1933). A transducer converted the vertical mechanical motion of a stylus tracing over the surface features into an electrical signal. This is the same principle used today in modern mechanical contact profiling instruments, but of course they have now been considerably refined. Surface measurement using a stylus instrument is the most widely used surface characterization technique (Bennett 1992, Mathia et al. 1995, Haitjema 1998, Chang et al. 2001). The stylus- based metrology system provides long profile measurements and large surface feature measurements. A diamond stylus with a tip radius of few micrometers moves up and down as it is dragged across a specimen surface. This up-and-down motion effectively replicates the surface topography. Lateral resolution depends on the stylus (Bhushan 2001). The stylus profiler provides two-dimensional and three-dimensional topographical information. The three-dimensional approaches provide more detailed information on the micro aspects of surface topography, and according to Tay et al. (2002) only three-dimensional quantitative measurement can provide a complete description of surface topography.

A typical stylus-based instrument can capture roughness (microroughness), waviness (macroroughness) and form. Figure 1 shows the current metrology measurement spectrum. As the bandwidth of measurement instruments increases, it becomes essential to separate surface profile data into meaningful wavelength regimes before numerical characterization (Raja et al. 2002).

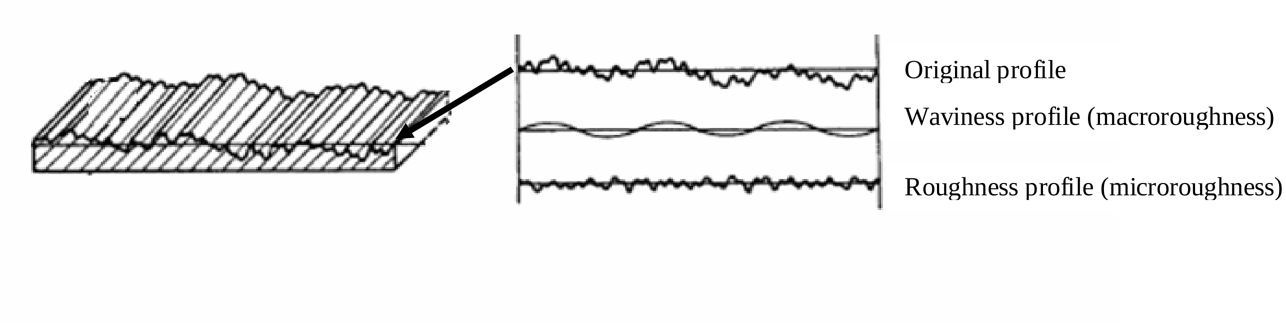


Figure. 1. Roughness and waviness in a surface, modified from Raja et al. (2002).

Profilometric analysis is a routine technique used in material science to quantify the morphology of material surfaces or the irregularities of fracture boundaries. Standard techniques for assessing surface roughness measure directly the peaks and the valleys on the surface (Chappard et al. 2003). Various surface roughness parameters can be generated from a surface profile to represent its geometric characteristics. From the measured profile, roughness parameters can be derived for characterizing the surface (Haitjema 1998). Surface measurements and parameters are standardized in ISO and national standards (ISO 11562, ISO 3274, SFS-ISO 468, SFS-ISO 4287, SFS-ISO 4287/2). In these standards, several measurement conditions are prescribed under which a roughness parameter should be measured. These conditions include filter characteristics, stylus geometry, measuring force, etc. Gadelmawla et al. (2002) presented definitions and mathematical formulae for 59 of the roughness parameters. Two of the most commonly used surface roughness parameters are defined below. R_a is the arithmetical average of surface heights, also known as the centre line average of surface heights (CLA), and can be calculated as

$$R_a = \frac{1}{n} \cdot \sum_{i=1}^{n} |y_i| \qquad (1)$$

R_q is defined as root mean square of surface heights, i.e.

$$R_q = \sqrt{\frac{1}{n} \sum_{i=1}^{n} y_i^2} \qquad (2)$$

The roughness parameters are height quantities of the surface roughness which are related to the unevenness of the profile. Ten-point height of irregularities, mean height of profile irregularities and the longitudinal quantities of the surface roughness are connected to the unevenness of the profile, mean spacing of local peaks of the profile, average wavelength of the profile root-mean square etc. (Conway-Jones and Eastham 1995, Provder and Kunz 1996, Bhushan 2001, Chang et al. 2001). When stylus - material interactions may dramatically affect measurements, non-contact techniques are an alternative (Chappard et al. 2003).

2.1.2 Scanning electron microscopy (SEM)

The Transmission Electron Microscope (TEM) was the first type of Electron Microscope to be developed and is patterned exactly on the Light Transmission Microscope except that a focused beam of electrons is used instead of light to "see through" the specimen. It was developed by Max Knoll and Ernst Ruska in Germany in 1931. The first Scanning Electron Microscope (SEM) debuted in 1942 and the first commercial instruments around 1965 (Ruska 1986). Scanning electron microscopy (SEM) allows a qualitative approach to surface topography and is widely used in industrial and biological studies. The method is a morphological approach to roughness (Chappard et al. 2003). The Scanning Electron Microscope (SEM) produces images by detecting secondary electrons, which are emitted from the surface due to excitation by the primary electron beam. In the SEM, the electron beam is rastered across the sample, with detectors building up an image by mapping the detected signals with the beam position (Brundle et al. 1992, Whitehouse 1997). SEM measurements of the surface topography can be very accurate over the nanometer to millimeter range (Watt 1997). SEM is a popular technique used in the investigation of structures of surfaces and wear particles (Stachowiak and Podsiadlo 2001). However, interpretation of the images is not necessarily straightforward and does not readily yield quantitative data about the height of surface features (Sherrington and Smith 1988).

2.1.3 Atomic force microscopy (AFM)

Atomic force microscopy (AFM) is also known as scanning force microscopy (SFM). The atomic force microscope is a combination of the principles of the scanning tunneling microscope (STM) and stylus profilometer (Binnig et al. 1986). AFM works by bringing a cantilever tip in contact with the surface to be imaged. An ionic repulsive force from the surface applied to the tip bends the cantilever upwards. The amount of bending, measured by a laser spot reflected onto a split photo detector, can be used to calculate the force. By keeping the force constant while scanning the tip across the surface, the vertical movement of the tip follows the surface profile and is recorded as the surface topography by the AFM (Butt et al. 2005). The atomic force microscope is a versatile tool for measuring surface topography. Because of its wide range of applicability, AFM has become an increasingly important tool for the measurement of surface roughness on the nanometer scale (Sedin and Rowlen 2001, Morita et al. 2002, Chen and Huang 2004). Additionally, AFM methods are able to measure surfaces in a number of modes: contact, intermittent-contact and non-contact. The force between tip and sample is low during the AFM measurement and, even in contact mode, reaches only a few nanonewtons (Dai et al. 2004). Unfortunately, one of the main limitations of an AFM is its small scanning range (10-100 µm in most designs). One solution to this problem is to combine AFM with SEM (Ermakov and Garfunkel 1994). The roughness parameters of the AFM measurement are available for example using the Scanning Probe Image Processor (SPIP) image analysis software (Peltonen et al. 2004).

Butt et al. (2005) described force measurements with the atomic force microscope. Atomic force microscopy (AFM) has recently been employed to acquire images of surfaces with nanoscale resolution, as well as direct measurements of interaction forces between approaching surfaces, such as particle-plate (Larson et al. 1995, Considine et al. 2000) and particle-bubble (Fielden et al. 1996) surfaces. Recently, there have been numerous attempts to measure interparticle forces on the molecular scale. Results of several AFM studies have provided information on surface properties such as surface hydrophobicity or hydrophilicity (Ducker et al. 1994) and contact angle (Preuss and Butt 1998).

2.2 WEARING

Wear is defined as damage to a solid surface, generally involving progressive loss of material, due to relative motion between the surface and a contacting substance or substances (ASTM G-40). Wear is a complex process, which involves time-dependent deformation and removal of material at the counter face. A wear process might involve several wear mechanisms, and the synergistic interaction between these mechanisms may make the obtained information difficult to interpret and use (Li et al. 1999). Wear is not a material property; however, it is a system response (Bayer 1994). The wear rate of a material can vary from 10^{-3} to 10^{-10} mm^3 N^{-1} m^{-1} depending on contact conditions, such as the counterpart material, contact pressure, sliding velocity, contact shape, environment and the lubricant. There are many terms to describe wear and they are not always well differentiated. This sometimes makes understanding of wear mechanisms confusing and difficult (Kato and Adachi 2000).

Material loss is often expressed in terms of weight loss per unit distance traveled (Godet et al. 1991). In most studies on wear the quantification of the wear volume is of great importance. However, reliable measurement of wear often presents serious problems to the investigator, mainly due to the fact that the worn off volume is generally very small compared to the size of the worn component (Gåhlin and Jacobson 1998).

2.2.1 Wear mechanisms

Attempts have been made to classify wear as surface damage or as a physical event. In the literature wearing mechanisms have been classified into three, four or five classes. Kimura et al. used three classes: adhesive, abrasive, corrosive wear. Sundquist (1986), Gahr (1988), Kivioja (1997) and Bhushan (2001) had fourth class: fatigue and Kato (2002) a fifth class: flow.

The abrasive wear process is traditionally divided into two groups: two-body and three-body abrasive wear. In two-body abrasion, wear is caused by hard protuberances on one surface which can only slide over the other, and in three-body abrasion particles are trapped between two solid surfaces but are free to roll as well as to slide. The rate of material removal in three-body abrasion is one order of magnitude lower than that for two-body abrasion, because the loose abrasive particles abrade the solid surfaces between which they are situated only about 10 % of the time, whereas they spend about 90 % of the time rolling. Despite the importance of three-body abrasion the vast majority of abrasive wear studies have dealt with two-body abrasion. Two-body and three-body abrasion are usually discussed separately in the literature (Hutchings 2002, Harsha and Tewari 2003). Three-body abrasion is often of considerable practical importance but appears to have received much less attention than the two-body problem (Harsha et al. 2003).

Abrasion occurs by plastic deformation. The wear mechanisms in plastic deformation can be divided into microcutting, microploughing and microfatigue. The abrasive wear depends on a large number of parameters. These include the properties of the worn material, the load and sliding speed of the particular situation and the shape, size distribution, orientation, lateral distribution and material properties of the abrading asperities (Gåhlin 1998).

2.2.2 Determination of wearing

Standard methods imitating real wearing situations are used for examining the surfaces planned for certain applications (Table 2). The tests are often designed to correspond to the worst possible conditions. These standardised research methods are considerably more useful than tests which are performed in the use environment (Blau and Budinski 1999). Examination of the mass loss of materials is one of the most important indicators of wearing (Weinhold 1997). Mere measurement of the thickness of material is not necessarily a reliable way to measure the wear of polymers. Therefore it is important to determine the changes in their mass. The second problem in determination of the wearing of polymers is their tendency to absorb moisture from air, in which case the mass of the specimen may change. Therefore it is important to maintain the comparison part in the same conditions as the test piece (Weinhold 1997, Talja and Järvelä 1998).

Table 2. Standard methods suitable for examination of the wearing of plastic materials.

Standard	**Name of the method**	**The most used or present application**	**Parameters**	**Principle**
DIN 52348 ASTM D 673	Wearing test on flowing sand	Plastic materials	Gloss	Silicon carbide flows through the holes of the turning funnel at an angle of 45 degrees to the sample.
ASTM D 1242	Wearing test on grinding material and grinding tape	Plastic materials	Volume loss	A- Loose abrasive. Grinding material flows from the funnel to the disk. The weight presses the specimen against a disk and grinding material. B- An abrasive band spends the tape turned by the rolls to which the samples have been fixed.
ASTM D 4060 ISO 9352	Taber-test	Plastic materials	Volume loss Mass loss	Two abrasive wheels are applied to test specimen with a specified load.
ASTM D 3363	Pencil test	Films	Hardness test	The pencil is held firmly against the film at an angle of 45 degrees and pushed away from the operator in a 6.5 mm stroke
ASTM D1044	Wearing test Taber-apparatus	Transparent plastics	Transmission of light	Two abrasive wheels are applied to the test specimen with a specified load.
ASTM F 510	Taber-Test	Resilient floor coverings	Volume loss	Principle the same as EN 660-2: The abrasion used by an abrader with a grit feeder.
SFS-EN 425	Castor chair test	Resilient floor coverings	Change of appearance and stability	Movement of a castor chair.
EN 660-1	Stuttgart-test	Resilient floor coverings	Thickness loss	Wear testing apparatus simulates the rotating movements combined with sliding stress which are caused by the shoes of users on floor coverings. The abrasive medium is emery paper.
EN 660-2	Frick-Taber test	Resilient floor coverings	Mass loss	The abrasion used by an abrader with a grit feeder.
ASTM G 65	Dry sand/rubber wheel abrasion test	Hard and soft metals	Volume loss	Abrasion by sand between a specimen and rubber wheel
ASTM G 132	Pin abrasion test method	Wear resistance materials	Volume loss	A pin, which may or may not be rotating about its axis, is pressed against an abrasive surface while relative motion occurs between the pin and the abrasive surface.
ASTM D 968 SFS 3754	Wearing caused by the falling abrasive material	Organic coatings	Calculate the abrasion resistance	Test equipment of ASTM 673 – 93a. The difference is due to the fact that the funnel is not turning but sand flows down due to gravitation, causing wear in the sample.
SFS-EN 1963	Lisson Tretraded machine	Textile floor coverings	Mass loss	Four paddles are mounted on a tetra wheel, covered with removable rubber soles. Once one paddle is in contact with the sample, the centre of the tetrad moves at moves at a constant linear speed.

2.3 PLASTIC SURFACES

Polyvinyl chloride (PVC) is the second most commonly used plastic material in terms of volume. The excellent cost/performance ratio of PVC and the fact that it can be used to achieve a wide variety of tailor-made formulations explain its success in markets as different as building and construction, cables, the automotive industry, electrical appliances, medical devices, packaging and many other sectors (Menges 1996). Great achievements have been made by modifying its structure, behaviour and properties by including miscellaneous additives. Aspects of the mechanical, thermal and electrical properties of PVC composites have been intensively studied. However, knowledge of the effects of fillers on wear resistance of PVC composite materials is limited and wear data are not available. Polymers usually have poor resistance to abrasive sliding attack because of their relatively low levels of hardness and strength, high plasticity and low thermal conductivity (Yang and Hlavacek 1999). The wearing of plastics depends on the temperature of the surface, especially when the temperature reaches its critical value (Barret et al. 1992).

Resistance to degradation often makes PVC the best possible choice for long-life applications such as pipes, window profiles and floor coverings. Materials for floor coverings can be classified into different types such as resilient floorings, carpeting, wood, ceramics and stone (Elvers et al. 1988). Vinyl flooring is manufactured in a variety of styles and compositions and is widely installed in residential and commercial buildings (Foglianisi et al. 1996). Vinyl flooring is primarily composed of a mixture of polyvinyl chloride (PVC), inert filler (usually calcium carbonate, $CaCO_3$), and organic plasticizers such as dioctylphthalate (DOP) (Cox et al. 2001). The main types of PVC floorings are vinyl tiles or sheets and vinyl composition tiles (Levy 2001). Vinyl flooring materials contain the following components: PVC as a binder (24-48 %), plasticizers (6-22 %), stabilizers (< 2 %), fillers (30-70 %), pigments (1-2 %) and others (< 2 %) (Pesonen-Leinonen 2005). Pesonen-Leinonen (2005) described in some detail the components of plastic materials and their effects on cleanability. Plastic floor coverings are classified into three different groups depending on their surface structure: single material or homogenous floorings, layered plastic floorings or multi-material or heterogeneous plastic floorings. Vinyl floor coverings are usually coated with a thin polyurethane (PUR) (<1 %) layer. Such a floor surface is usually so dense when new that polish does not adhere to it. However, the polyurethane layer wears out in use and the vinyl surfaces are exposed, which means that floor polish is needed to keep the vinyl floor covering clean. The polymer chains of PUR are protected against solvents, acids, bases and other chemicals by urethane groups, which are resistant to chemicals, especially to hydrolysis (Melchiors et al. 2000).

In addition to PVC, the family of resilient flooring materials includes rubber floorings, linoleum, and asphalt tiles. Linoleum consists of a very hard layer of linoleum compound on a backing cloth of jute. The linoleum compound is a mixture of linseed oil (27 %), colophonium (8 %), limestone (10 %), ground wood (10 %), ground cork (10 %) and pigment (5 %) (Potting and Blok 1995). The linoleum usually has a PVC coating, increasing the impact resistance stiffness and toughness of the final product.

Development of new plastic surfaces is a major challenge for the floor material industry. Polyvinyl chloride has recently experienced competition from other plastics such as polyolefin-based materials (Rahman and Brazel 2004). Polyolefin has a hydrophobic surface that causes poor adhesion between the flooring and different protective films (Krüßmann et al. 2001). The stain resistance of PVC surfaces would increase if stain solubilization by plasticizers could be prevented (Colletti et al. 1998). One approach to making floor coverings more stain resistant is to apply a clear, less plasticized PVC topcoat to a plasticized vinyl floor base. Alternatively, urethanes, acrylic blends, acrylic-vinyl blends or polyesters might be applied as a coating. UV curing of trifunctional urethane acrylate monomers with a carboxylic acid group has been shown to improve the stain resistance of the PVC plastic surfaces (Ohtaka et al. 1993). Modification of plastics for the development of more self-cleaning surface materials is currently on the subject of intensive in research. Nano- and microscale surface patterns are common in nature, giving rise to certain functional properties. A combination of nano- and microscale structures has been reported to influence the soil resistance of the surface. The self-cleaning effect of Lotus plant leaves is due to the special surface structure of the leaves (Lotus effect) (Neinhuis and Barthlott 1997, Gould 2003). The main characteristic of these superhydrophobic surfaces is their roughness on the micro- and nanometer scale (Fürstner et al. 2005).

2.4 SOILING AND CLEANING OF SURFACES

A large number of laboratory methods have been developed for examining the cleanability of plastic surfaces, but their results are not fully comparable (Stoye 1993). The chemical composition of soils is very wide, and numerous substances may therefore be involved in the soiling of indoor plastic surfaces. Pesonen-Leinonen (2003 and 2005) collected the compositions of different model and standard soils which were used in studies of the cleanability of surface materials.

The cleanability of hard and resilient surfaces has been studied for example by Karlsson (1999), Suontamo (2004) and Pesonen-Leinonen (2005) in their dissertation theses. Karlsson (1999) studied the cleanability of metal surfaces used in the food industry. In the study by Suontamo (2004) a testing method and a cleaning simulator of the washing efficiency of the cleaners of hard surfaces was developed for ceramic plates. Pesonen-Leinonen (2005) presented different methods for evaluation of the cleanability of PVC plastic materials. Different soiling and cleaning apparatuses are used in laboratory studies, e.g. Gardner (ASTM D 4488), Erichsen (EN ISO 11998), Lisson (Burrows 1999), Kappasoil (ISO 11378-1), Elcometer Abrasion Scrubbing and Washability Tester (Krüßmann et al. 2001), cleaning simulator (Suontamo 2004) and soiling drum (SFS EN 1269, ISO 10361, EN ISO 11378-2, EN 14565, Pesonen-Leinonen et al. 2005). These soiling and cleaning apparatuses have been developed to simulate and control the soiling and cleaning of surfaces. In the standard EN 14565 the soiling drum is used for the soiling of resilient floor coverings. Comparison of the methods was presented by Pesonen-Leinonen (2005).

Numerous methods are available for determination of surface cleanability, ranging from subjective visual techniques to molecular and elemental scale techniques (Chawla 2001). An example of a quantitative technique to detect soil accumulation is e.g. the radiochemical method. This method was previously used for resilient flooring materials (Ohlson and Wäänänen 1971, Jokelainen and Uusi-Rauva 1976). Pesonen-Leinonen et al. (2006) presented a radiochemical method for determination of soil adhesion to plastic surfaces using a radioactive tracer. Another method is FTIR (Fourier Transform Infrared) technique. Ritschkoff et al. (2004) used the FTIR technique to detect the anti-soiling properties of coated surfaces.

Cleanability is commonly determined as the colour change of the soiled or cleaned surface by colorimetry (Krüssmann and Garvens 1997, Burrows 1999, Pesonen-Leinonen 2003, Pesonen-Leinonen 2005). Most of the current means for quantifying visual perception of colours have been introduced by the International Committee of Illumination (CIE). In the standard EN 14565, a grey scale is used for evaluation of the soiling and cleaning. However, the colorimetric method provides quantitative results and is considered to be more objective (Burrows 1999), precise and accurate than the grey scale evaluation. The basic colour of the floor covering has only a slight effect on the measuring values and it correlates well with visual assessment of the flooring (Krüssmann and Garvens 1997).

3 AIMS OF THE RESEARCH

The purpose of the present study was to implement physical characterization methods in studies of laboratory-made PVC model surfaces and industrial plastic surfaces. The main focus was on examining the suitability of determination methods of topography for wearing and cleanability studies of plastic materials.

The specific aims were:

1. To examine the suitability of contact profilometry, scanning electron microscopy and atomic force microscopy in topography studies of laboratory-made PVC model surfaces and industrial plastic surfaces (III-VII).

2. To examine and develop research methods for the wearing of plastic surfaces by implementing the Soiling and Wearing Drum Tester (EN 14565) and the Frick-Taber method (EN 660-2) (I, IV, VII).

3. To examine the relationships between surface topography, wearing and soiling or cleanability of the industrial plastic surfaces by colorimetry (III, V).

4 MATERIALS AND METHODS

4.1 Study design

Surface topography of laboratory-made PVC model surfaces and industrial plastic surfaces was studied using contact profilometry, scanning electron microscopy and atomic force microscopy. The cleanability of industrial plastic surfaces was examined using colorimetric measurements. Wearing was studied using the Frick-Taber-test and the Soiling and Wearing Drum Tester. In the original publications a radiochemical method (VI) and other methods were also used to describe the cleanability of industrial plastic surfaces. However, in this thesis only the colorimetric measurement is focused on and is presented in Figure 2.

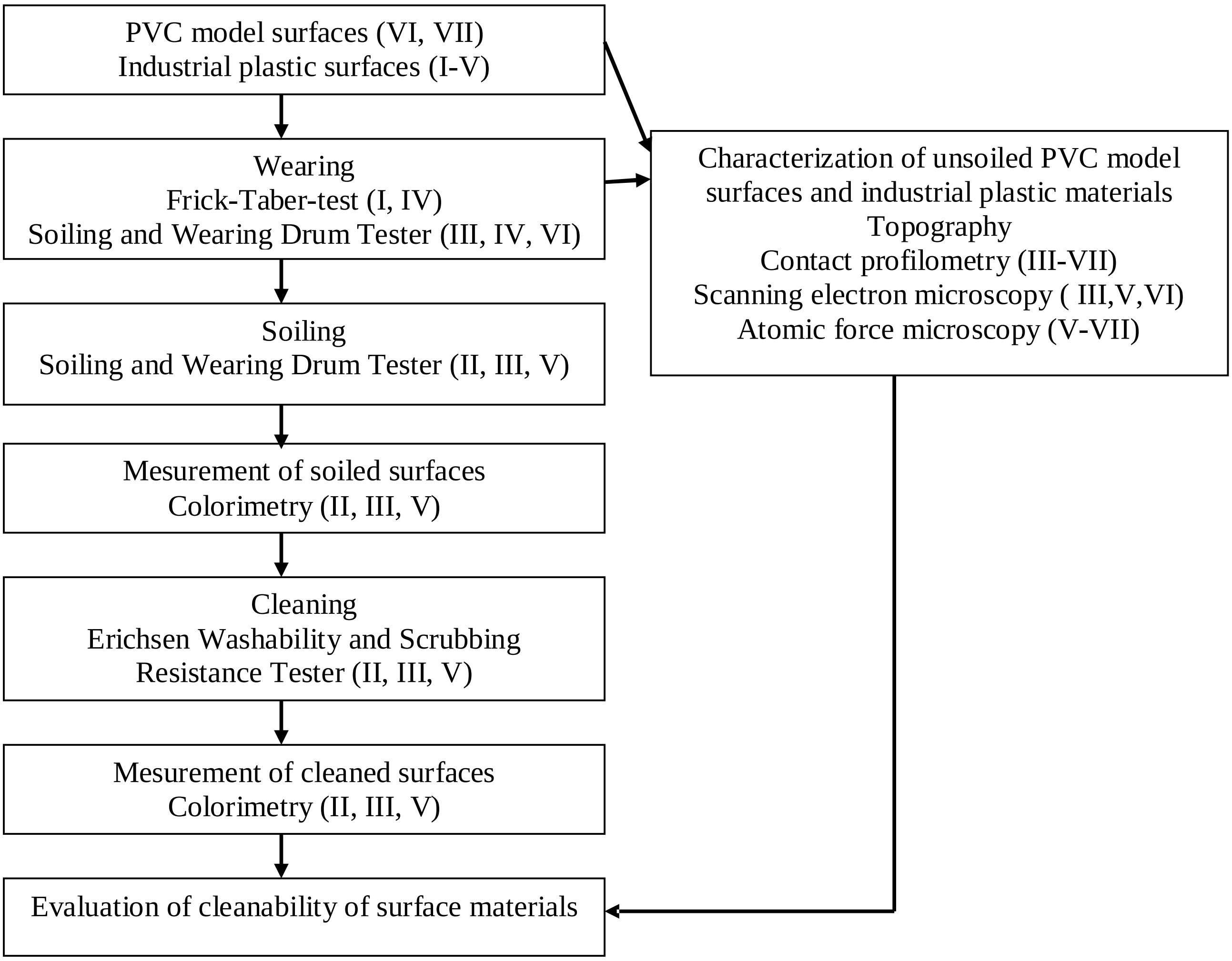


Figure 2. The experimental design of the study.

4.2 Materials

Twenty two different laboratory-made PVC model surfaces and twenty one different industrial plastic surfaces were investigated. The PVC model surfaces were made by the Department of Chemistry at the University of Joensuu and the industrial plastic surfaces were obtained from companies. Detailed preparation of laboratory-made PVC model surfaces is described in Publications VI and VII. For the PVC model surfaces different microstructures were prepared with sizes of 25 µm and 40 µm. The microstructures were regular, with repeating patterns. PVC model surfaces were examined both uncoated and amorphous diamond coated by DIARC-Technology Inc. Descriptions of the laboratory made PVC model surfaces are presented in Table 3 and of the industrial plastic surfaces in Table 4.

Table 3. Compositions of the uncoated and diamond-coated PVC model surfaces made by the Department of Chemistry at the University of Joensuu and DIARC-Technology

Publication	**Code**	**Composition of materials**						**Profile**
		Plastic polymer		**Plasticizer**		**Stabilizer**		
		Chemical substance	**Content (% w/w)**	**Chemical substance**	**Content (% w/w)**	**Chemical substance**	**Content (% w/w)**	
VI, VII	DOP20	S 98 PVC (Dynea)	77	DOP, dioctyl phthalate (Borealis)	20	Therm-Check® 7500L: Calcium/Zinc Complex mixture (Ferro)	3	Smooth 25 µm 40 µm
VI, VII	DOP30	S 98 PVC (Dynea)	67	DOP, dioctyl phthalate (Borealis)	30	Therm-Check® 7500L: Calcium/Zinc Complex mixture (Ferro)	3	Smooth 25 µm 40 µm
VI, VII	Hexa20	S 98 PVC (Dynea)	77	Hexamoll DINCH, di-isononyl-cyclohexane-1,2-dicarboxylate (BASF)	20	Therm-Check® 7500L: Calcium/Zinc Complex mixture (Ferro)	3	Smooth 25 µm 40 µm
VI, VII	Hexa30	S 98 PVC (Dynea)	67	Hexamoll DINCH, di-isononyl-cyclohexane-1,2-dicarboxylate (BASF)	30	Therm-Check® 7500L: Calcium/Zinc Complex mixture (Ferro)	3	Smooth 25 µm 40 µm
VI	Benzo20[#]	S 98 PVC (Dynea)	77	Diethylene glycol dibenzoate, triethylene glycol dibenzoate, bis (2-ethylhexyl) adipate, diethylene glycol monobenzoate (Velsicol)	20	Therm-Check® 7500L: Calcium/Zinc Complex mixture (Ferro)	3	Smooth 25 µm 40 µm
VI	Benzo30[#]	S 98 PVC (Dynea)	67	Diethylene glycol dibenzoate, triethylene glycol dibenzoate, bis (2-ethylhexyl) adipate, diethylene glycol monobenzoate (Velsicol)	30	Therm-Check® 7500L: Calcium/Zinc Complex mixture (Ferro)	3	Smooth 25 µm 40 µm
VII	Benzo20[##]	S 98 PVC (Dynea)	77	Diethylene glycol dibenzoate, triethylene glycol dibenzoate, bis (2-ethylhexyl) adipate, diethylene glycol monobenzoate (Velsicol)	20	Therm-Check® 7500L: Calcium/Zinc Complex mixture (Ferro)	3	25 µm 40 µm
VII	Benzo30[##]	S 98 PVC (Dynea)	67	Diethylene glycol dibenzoate, triethylene glycol dibenzoate, bis (2-ethylhexyl) adipate, diethylene glycol monobenzoate (Velsicol)	30	Therm-Check® 7500L: Calcium/Zinc Complex mixture (Ferro)	3	25 µm 40 µm

Inc. (VI, VII). Two or three surface profiles of each PVC model surfaces were examined.

[#] Benzoflex 2160

[##] Benzoflex 2088

Table 4. Compositions of the plastic surfaces obtained from the industrial companies.

Publication	**Codes**	**Flooring type**	**Composition**	**Surface treatment / outmost top layer**
I	S1	Vinyl sheet	Binder: Polyvinyl chloride, PVC[#] Plasticizers, stabilizers, fillers, pigments	Polyurethane (PUR) coating [#]
I	S2	Vinyl sheet	Binder: Polyvinyl chloride, PVC[#] Plasticizers, stabilizers, fillers, pigments	Polyurethane (PUR) coating [#]
I	S3	Vinyl sheet	Binder: Polyvinyl chloride, PVC[#] Plasticizers, stabilizers, fillers, pigments	Polyurethane (PUR) coating [#]
I	S4	Vinyl sheet	Binder: Polyvinyl chloride, PVC[#] Plasticizers, stabilizers, fillers, pigments	Polyurethane (PUR) coating [#]
II, IV	QV, FT11	Vinyl composition tile	Binder: Polyvinyl chloride, PVC[#] Plasticizers, stabilizers, fillers, pigments	Polyurethane (PUR) coating *
II, IV	STP, FT8	Plastic composition tile	Binder: Thermoplastic polymer Fillers, pigments	Polyurethane (PUR) coating [#]
II, IV	PVC, FT3	Vinyl sheet	Binder: Polyvinyl chloride, PVC[#] Plasticizers, stabilizers, fillers, pigments	Polished
II, IV	LIN, FT9	Linoleum sheet	wood flour, oxidized linseed oil, gums or other ingredients, coloring matter	Acrylate coated[#]
II	LIN-A	Linoleum sheet	wood flour, oxidized linseed oil, gums or other ingredients, coloring matter	Abraded with brown pad and alkaline detergent
II	LIN-AP	Linoleum sheet	wood flour, oxidized linseed oil, gums or other ingredients, coloring matter	Sealed with maintenance agent
III, IV,V	S11, FT7	Vinyl composition tile	Binder: Polyvinyl chloride, PVC, 24 wt% Plasticizers, stabilizers, fillers, pigments, others	Polyurethane (PUR) surface treatment < 1 wt%
III, IV,V	S12, FT15	Vinyl sheet	Binder: Polyvinyl chloride, PVC, 27 wt% Plasticizers, stabilizers, fillers, pigments	None (bulk material)
III, IV,V	S12c, FT14	Vinyl sheet	Binder: Polyvinyl chloride, PVC, 27 wt% Plasticizers, stabilizers, fillers, pigments	Polymeric floor finish containing styrene acrylate copolymers
III, IV,V	S13, FT10	Vinyl sheet	Binder: Polyvinyl chloride, PVC [#] Plasticizers, stabilizers, fillers, pigments	Polyurethane (PUR) coating [#]
III, IV,V	S14, FT1	Plastic composition tile	Binder: Thermoplastic polymer, 20%, Fillers, pigments	Ionomer impregnated
III, IV,V	S15, FT6	Vinyl sheet	Binder: Polyvinyl chloride, PVC, 47wt% Plasticizers, stabilizers, fillers pigments	Polyurethane (PUR) coating <1 wt%
III, IV,V	S16, FT12	Vinyl tile, static dissipative	Binder: Polyvinyl chloride, PVC [#] Plasticizers, stabilizers, fillers pigments	None (bulk material)
III, IV,V	S17, FT4	Vinyl sheet	Binder: Polyvinyl chloride, PVC, 44 wt% Plasticizers, stabilizers, fillers pigments	Polyurethane (PUR) surface treatment < 2 wt%
III, IV,V	S18, FT5	Vinyl sheet	Binder: Polyvinyl chloride, PVC, 45 wt% Plasticizers, stabilizers, fillers pigments	Polyurethane (PUR) coating <1 wt%
III, IV,V	S19, FT2	Vinyl sheet	Binder: Polyvinyl chloride, PVC, 43 wt% Plasticizers, stabilizers, fillers, pigments	Polyurethane (PUR) coating <2 wt% (with carborundum and quartz crystals)
III, IV,V	S20, FT13	Vinyl sheet	Binder: Polyvinyl chloride, PVC[#] Plasticizers, stabilizers, fillers, pigments	Polyurethane (PUR) surface treatment < 1 wt%

In some cases different codes refer to the same materials. For example QV (II) and FT11 (IV) are both the same vinyl composition tile.

[#] no detailed information available

4.3 Topography

Topography of the samples was studied using contact stylus profilometry Kla-Tencor P-15 (III-VII), scanning electron microscopy JEOL JSM-840 (III, V, VI) and atomic force microscopy Thermo Microscopes EXPLORER 4400-11 (V-VII). Scanning electron microscopy photomicrographs were taken with magnifications of 100x, 500x and 1500x. The magnification of 100x was used for final observation of new laboratory-made PVC model surfaces (VI) and magnification of 1500x for final observation of new and worn industrial plastic surfaces (III). In publication V, photomicrographs were taken at 500x magnification. Two- (III-VII) and three-dimensional (III-VII) roughness profiles of surfaces were measured using a contact profilometer. The length of the two-dimensional scan was 10 000 µm (III-VII) and of the three-dimensional scan 500 µm x 500 µm (VI, VII) and 200 µm x 200 µm (III, V). In publication V, the measuring area of the atomic force microscopy was 100 µm x 100 µm. Detailed descriptions of the methods are presented in the publications III-V. The same methods (contact profilometry and scanning electron microscopy) were used for the PVC model surfaces (VI, VII) as in the publications III-V.

4.4 Wearing

In this study two wearing methods were applied and evaluated for the wearing tests of plastic surfaces. A Frick-Taber apparatus (I and IV) and a Soiling and Wearing Drum Tester (III, IV and VII) were constructed. The wearing methods and the definition methods of wearing are presented in Table 5. Change of the mass of industrial plastic surfaces was measured by weighing the plastic surfaces with analysis scales (Mettler AE 260) before wearing and in the Frick-Taber test always after 1000 revolutions (I and IV). In the Soiling and Wearing Drum Tester method, cumulative mass losses were determined as a function of time after every 2 h time period of wearing (IV).

Table 5. Wearing methods and definition of wearing.

Publication	Wearing method	Abrasive material /amount	Rotating speed	Wear time/ revolutions	Definition of wearing
I	Frick-Taber-test (EN-660) Taber abraser model 505	Corundum (grain size 45-75 µm) 21±3 g/min	The rotating speed of the holder table was 60±2 r/min	5000 r	Weighing of the sample Analysis scales: Mettler AE 260
III, VII	Applied drum method (EN 14565) Soiling and wearing drum +hexapod	Quarz silica (grain size 200 µm)	The rotation speed of the plastic drum was 50±2 r/min	40 min	Definition of the topography Contact profilometry: Kla-Tencor P15 Microscopy Scanning electron microscopy: JEOL JSM-840
IV	Frick-Taber-test (EN-660) Taber abraser model 505 Applied drum method (EN 14565) Soiling and wearing drum	Corundum (grain size 45-75 µm) 21±3 g/min Quarz silica (grain size 200 µm) 21±3 g/100 g	The rotating speed of the holder table was 60±2 r/min The rotation speed of the plastic drum was 50±2 r/min	5000 r 8 h	Weighing of the sample Analysis scales: Mettler AE 260 Weighing of the sample Analysis scales: Mettler AE 260 Definition of the topography Contact profilometry: Kla-Tencor P15

4.5 Soiling and cleaning methods

The radiochemical soiling and cleaning procedure is presented in the Publication VI. Two model soils were labelled with the gamma-ray emitter ^{51}Cr. Two other model soils were labelled with the beta-ray emitter ^{14}C.

Other types of model soils were used as soiling agents. The soils represented the typical soils which are found in public premises. They were multi-component model soils simulating practical soils on indoor surfaces. The inorganic particle soil (II, III and V) and organic oil soil (III and V) represented soils that are difficult to remove and which were both black. In II and III the inorganic particle soil was used in accordance with the standard EN 14565. Inorganic particle soil simulates soil typical on floorings in buildings, and oil soil is typical as a chemical model. The compositions of the model soils are presented in Table 6.

Table 6. Compositions of the model soils.

Publication	**Type of model soil**	**Composition**
II, III, V	Inorganic particle soil (EN 14565)	Quarz silica 88.30% (SP Minerals Oy) Kaolin 9.35% (Bang & Bonsomer Oy) Yellow ferrous paraffin oxide 0.02% (Bayer Ag) Black ferrous paraffin oxide 0.60% (Degussa Ag) Paraffin oil 1.55 % (Merck Eurolab)
III,V	Organic oil soil	Paraffin oil 73% (Merck Eurolab) Carbon black E 153 27% (Overseal Foods Ltd)

Industrial plastic surfaces were soiled with standardized methods in laboratory conditions (II, III and V). Soiling was performed by two different techniques: 1) soil was applied using the Soiling Drum Tester including a hexapod (II, III, V) or 2) soil was deposited with a pipette, spread with the Erichsen Washability and Scrubbing Resistance Tester and allowed to dry (III, V). The soils were allowed to consolidate for 24 ± 2 hours before the cleaning. The temperature in the soiling and cleaning was 23 °C ± 2 °C and the relative humidity 32 % ± 5 % (II, III, V). In the publications II, III and V the number of replicate tests was five.

Cleaning methods and their parameters are presented in Table 7. In the publications (II, III and V) the industrial plastic surfaces were cleaned with the Erichsen Washability and Scrub Resistance Tester. Detailed descriptions of soiling and cleaning methods and cleaning solutions are presented in the publications II, III and V.

Table 7. Cleaning methods using the Erichsen Washability and Scrub Resistance Tester (II, III, V).

Publication	**II**	**III, V**
Method	Damp wiping and wet wiping	Wet wiping
Pressure applied to the surface	7 g/cm^2 (700 Pa)	14 g/cm^2 (1.4 kPa)
Wiping times	6	6
Material of mop cloths	Micro fibre mop (100 % polyester fibres) and yarn mop (50 % polyester and 50 % viscose)	Micro fibre mop (100 % polyester fibres)
Moisture regain of the mop cloth ¤	100 % and 200 %	150 %
Amount of the different cleaning agents	3[#]	4[#]

¤ Moisture regain of the mop cloth means the moisture content of the mop cloth expressed as a percentage of the weight of the dry mop.

[#] One of the cleaning agents was pure water

4.6 Determination of cleanability

A quantitative radiochemical measuring procedure (VI) was used for investigating soil adhesion on polyvinyl chloride (PVC) materials containing different plasticizers quality (DOP, Hexamoll® DINCH and Benzoflex® 2160) and amount (20 % and 30 %) and also different microstructures (smooth, 20 µm and 40 µm).

The colorimetric method was used to detect black-coloured soils on light-coloured plastic surface materials (II, III, V). On that basis, the use of L*-differences was valid for the examined surfaces. The cleanabilities of industrial plastic surfaces were measured with a colorimeter Minolta Chroma meter CR-210, equipped with Standard Illuminant D65. The parameter L*, lightness, of the colour system CIE L*a*b* was used (Minolta 1998). The colorimeter was calibrated each time it was used. The colour of the surfaces was measured before and after soiling and after cleaning. The measuring points are presented in Table 1 of publication II. Detailed descriptions of the colorimetric method are presented in the publications II, III and V. Averaged L* values of the five measurement points of each replicate were used to calculate the changes in soil amount as colour differences of the industrial plastic surfaces. The soiling and cleaning results were calculated from the means of the ΔL* values of a sample:

Total amount of soil $\Delta L^*_{\mathrm{TOTAL}} = L^*_{\mathrm{unsoiled}} – L^*_{\mathrm{soiled}}$

Amount of soil removed $\Delta L^*_{\mathrm{REMOVED}} = L^*_{\mathrm{cleaned}} – L^*_{\mathrm{soiled}}$

Soil residue on the surface $\Delta L^*_{\mathrm{RESIDUE}} = L^*_{\mathrm{unsoiled}} – L^*_{\mathrm{cleaned}}$

Cleaning index$= \Delta L^*_{\mathrm{REMOVED}} / \Delta L^*_{\mathrm{TOTAL}}$

4.7 Statistical analyses

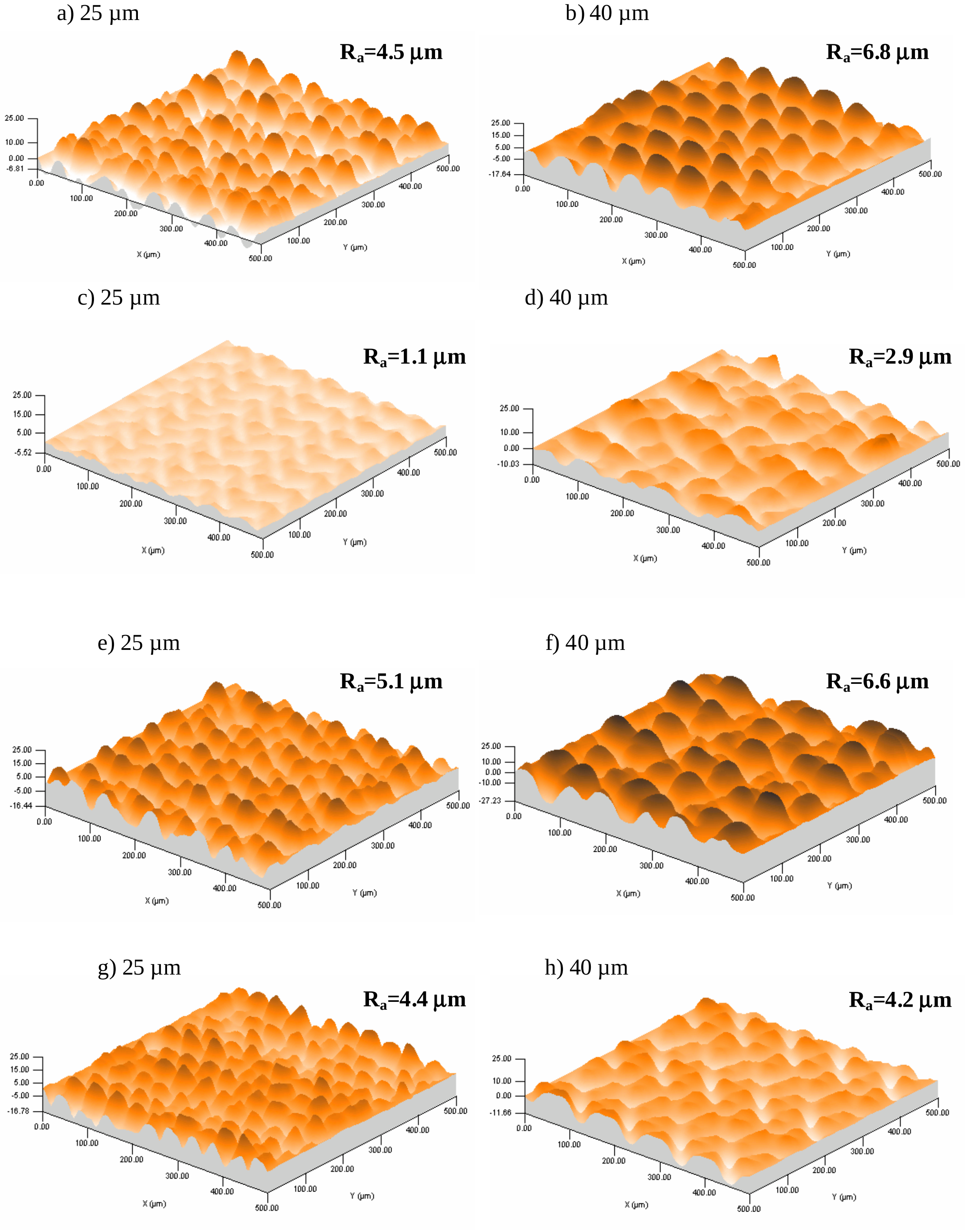
Statistical analyses were based on the mean values of the measurements. The two- and one way analysis of variance (I), univariate analysis of variance and Tukey’s tests (II) were used to test the differences between the cleaning efficiencies of the industrial plastic surfaces. Correlation analysis was used to examine correlations between cleanability and roughness of industrial plastic surfaces (III, V) and between the results of the Frick-Taber method, the Soiling and Wearing Drum Tester and roughness parameters (IV). Statistical analyses were performed using the SPSS version 12.0 (SPSS Inc., Chicago IL, USA). Correlation analysis was performed to examine correlations between cleanability and roughness of laboratory-made PVC model plastic surfaces (VI).

5 RESULTS

5.1 *Surface topography of new and worn plastic materials*

5.1.1 Profilometry

In this study new laboratory-made PVC model surfaces containing of different types and amounts of plasticizers were examined (Table 3). The materials had different surface microstructures (Figures 3-4). It was observed that both the quality and the amount of the plasticizers, as well as the surface structure had an effect on the roughness profile (Figures 3 of Publications VI and VII).



a) 25 µm

b) 40 µm

c) 25 µm

d) 40 µm

e) 25 µm

f) 40 µm

g) 25 µm

h) 40 µm

Figure 3. Three-dimensional contact profilometric images of new laboratory-made PVC model surfaces with different surface microstructures 25 µm or 40 µm. Plasticizers: DOP20 (a, b), DOP30 (c, d), Hexa20 (e, f), Hexa30 (g, h). The preparation, codes and details of the laboratory-made PVC model surfaces are presented in Table 3.

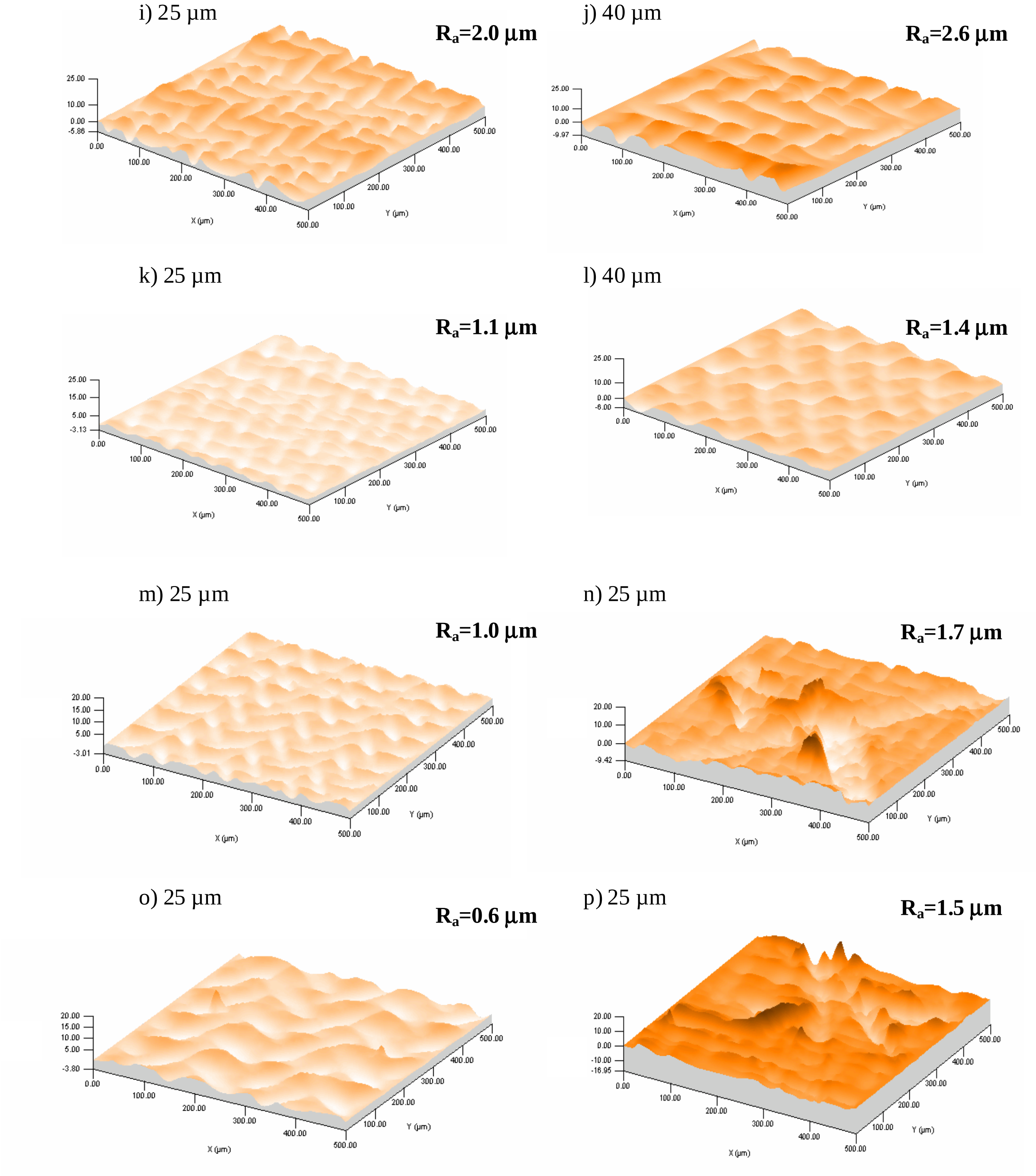


Figure 4. Three-dimensional contact profilometric images of new laboratory-made PVC model surfaces with different surface microstructures 25 µm or 40 µm, Plasticizers: Benzo20$^{\#\#}$ (i, j), Benzo30$^{\#\#}$ (k, l), new (m) and worn (n) diamond coated Benzo20$^{\#\#}$ and new (o) and worn (p) diamond-coated Benzo30$^{\#\#}$. The Soiling and Wearing Drum Tester was used for wearing. The preparation, codes and details of the laboratory-made PVC model surfaces are presented in Table 3.

$^{\#\#}$ Benzoflex 2088

The three-dimensional contact profilometry images showed that microscale structures of PVC model surfaces were regular and repeatable. The roughness (R_a) values mainly increased in the case of the biggest microstructure (40 µm) and decreased in the case of 30 % plasticizer.

Different roughness values (R_a, R_q, R_{ku}, R_{sk}) of new, diamond-coated and worn PVC model materials are shown in Table 8. The mean values of the roughness of the new laboratory-made PVC model surfaces (R_a) varied between 0.02 µm and 6.8 µm. The PVC model surfaces become smoother when surfaces were coated with diamond. The Ra value of the diamond-coated PVC model surfaces varied between 1.0 µm and 2.5 µm and of the worn PVC model surfaces between 1.2 µm and 3.8 µm.

Kurtosis (R_{ku}) is a measure of the spikiness of the statistical distribution. A Gaussian distribution has a kurtosis equal to 3, and a kurtosis smaller than 3 corresponds to a statistical distribution that is flatter than the normal distribution. The opposite goes for distributions with a kurtosis higher than 3. Kurtosis values (R_{ku}) of the uncoated PVC model surfaces varied between 2.3 and 3.5. The R_{ku} value of the diamond-coated PVC model surfaces varied between 1.7 and 3.4 and of the worn PVC model surfaces between 2.7 and 15.9.

The skewness parameter (R_{sk}) provides information about the symmetry of the amplitude function. Symmetrical distributions have skewness equal to 0, which means that they have evenly distributed peaks and valleys of specific heights. Profiles with larger valleys than peaks present a negative skewness, whereas a surface with higher peaks than valleys would be characterized by positive skewness. The skewness (R_{sk}) values of uncoated PVC model surfaces varied between -0.8 and 0.2. The R_{sk} value of the diamond-coated PVC model surfaces varied between -0.5 and 1.1 and of the worn PVC model surfaces between -0.8 and 1.9.

Table 8. The roughness values of uncoated, diamond-coated and worn laboratory-made PVC model surfaces. The codes of the PVC model surfaces are given in Table 3.

	Codes	**Profile (µm)**	**R_a (µm)**	**R_q (µm)**	**R_{ku}**	**R_{sk}**
New uncoated laboratory-made PVC model surfaces	DOP20	Smooth	0.03±0.01	0.05±0.01	3.5±0.02	-0.8±0.6
		25	4.5±0.2	5.6±0.2	2.4±0.02	0.03±0.05
		40	6.8±0.4	8.4±0.5	2.3±0.02	0.03±0.1
	DOP30	Smooth	0.04±0.01	0.1±0.01	2.3±0.2	0.1±0.1
		25	1.1±0.02	1.3±0.03	2.5±0.02	-0.4±0.1
		40	2.9±0.1	3.6±0.1	3.1±0.3	0.1±0.1
	Hexa 20	Smooth	0.1±0.01	0.1±0.01	2.4±0.1	-0.1±0.02
		25	5.1±0.2	6.2±0.2	2.4±0.03	-0.1±0.03
		40	6.6±0.4	8.2±0.5	2.5±0.04	-0.1±0.02
	Hexa 30	Smooth	0.04±0.01	0.05±0.02	2.5±0.1	0.2±0.02
		25	4.4±0.2	5.4±0.2	2.5±0.02	0.0±0.2
		40	4.2±0.4	5.2±0.4	2.8±0.1	-0.3± 0.02
	Benzo20[#]	Smooth	0.1±0.01	0.1±0.01	2.6±0.4	0.2±0.02
		25	5.0±0.04	6.2±0.1	2.5±0.1	-0.1±0.2
		40	5.1±0.1	6.3±0.1	2.6±0.1	0.1±0.1
	Benzo30[#]	Smooth	0.02±0.01	0.1±0.03	2.2±0.1	0.1±0.02
		25	1.5 ±0.1	1.3±0.1	2.5±0.02	-0.1±0.02
		40	1.6±0.1	1.8±0.1	2.6±0.1	0.2±0.2
New diamond-coated laboratory-made PVC model surfaces	DOP20	25	1.4±0.1	1.7±0.1	2.6±0.02	0.1±0.1
		40	3.8±0.2	4.7±0.2	2.4±0.1	0.1±0.1
	DOP30	25	1.2±0.1	1.2±0.1	3.4±0.2	-0.2±0.1
		40	1.8±0.1	2.3±0.2	3.4±0.2	-0.5±0.1
	Hexa 20	25	2.5±0.1	2.6±0.3	2.4±0.1	-0.2±0.03
		40	2.5±0.2	3.1±0.2	2.5±0.1	0.03±0.1
	Hexa 30	25	2.4±0.1	3.0±0.1	2.5±0.02	0.03±0.1
		40	2.5± 0.1	3.1± 0.1	1.7± 0.6	1.1± 0.6
	Benzo20[##]	25	1.0 ±0.03	1.2±0.04	2.4±0.02	0.4±0.1
		40	1.3±0.01	1.6±0.01	2.6±0.04	0.3±0.04
	Benzo30[##]	25	0.6±0.02	0.7±0.02	2.5±0.02	0.2±0.05
		40	1.0±0.1	1.2±0.1	2.5±0.02	0.03±0.1
Worn diamond-coated laboratory-made PVC model surfaces (wear by Soiling and Wearing drum Tester, hexapod and sand)	DOP20	25	1.9±0.1	2.4±0.1	4.2±0.3	0.3±0.1
		40	2.4±0.1	3.1±0.2	3.4±0.3	0.4±0.1
	DOP30	25	1.4±0.2	1.8±0.3	3.9±0.1	-0.1±0.1
		40	2.6±0.4	3.7±0.6	7.5±1.9	0.3±0.7
	Hexa 20	25	2.6±0.2	3.4±0.3	3.8±0.1	-0.1±0.4
		40	3.1±0.2	4.2±0.4	4.3±0.5	0.3±0.3
	Hexa 30	25	4.1±0.8	6.0±1.3	5.1±0.8	0.1±0.4
		40	3.3±0.3	4.1±0.3	2.7±0.1	0.03± 0.1
	Benzo20[##]	25	1.7±0.2	2.0±0.4	3.6±0.3	-0.3±0.05
		40	2.4±0.3	3.3±0.4	4.5±0.2	-0.8±0.1
	Benzo30[##]	25	1.5±0.3	2.2±0.4	6.9±1.2	-0.6±0.4
		40	1.9±0.3	3.9±1.1	15.9±4.0	1.9±1.0

[#] Benzoflex 2160

[##] Benzoflex 2088

Contact profilometry was used to assess changes of topography in the industrial plastic surfaces before and after wearing. As can be seen in Table 9, the mean values of the macro roughness (waviness) of the new plastic surfaces (R_a) varied between 1.6 µm and 11.4 µm and of the worn plastic surfaces between 1.7 µm and 11.0 µm. The micro roughness (R_a) values of the new industrial plastic surfaces varied between 1.0 µm and 3.6 µm and of the worn industrial plastic surfaces between 1.2 µm and 3.1 µm. The root mean square deviation of the roughness profile (R_q) of the new industrial plastic surfaces varied between 1.3 µm and 4.6 µm and of the worn industrial plastic surfaces between 1.6 µm and 4.4 µm. The kurtosis (R_{ku}) of the new industrial plastic surfaces varied between 2.3 and 6.9 and of the worn industrial plastic surfaces between 2.3 and 9.3. The skewness (R_{sk}) of the new industrial plastic surfaces varied between -1.4 and 1.3 and of the worn industrial plastic surfaces between -1.9 and 1.1 (Table 9). A summary of changes between new and worn industrial plastic surfaces measured using contact profilometry and scanning electron microscopy is presented in Table 9.

The macroroughness parameter (R_a) of the new thermoplastic composition tile (S14) was the highest and that of the new static dissipative PVC industrial plastic surfaces (S16) the lowest before wearing. Values of macroroughness (R_a) decreased markedly in the PUR-coated PVC industrial plastic surfaces (S18 and S20), for which changes of R_a-values after wear were 1.6 µm and 2.9 µm, respectively. For the other materials the effect of wear on roughness was small or negligible. Examples of two- and three-dimensional profilometric measurements are presented in Figures 5-6 of publication III to illustrate different types of changes in the surfaces after wearing. It can be seen from Figures 5 and 6 (III) that new static dissipative PVC industrial plastic surfaces (S16) and new PVC sheet (S19) became rougher after wearing with the hexapod and sand. The difference between laboratory-made PVC model surfaces and industrial plastic surfaces was that industrial plastic surfaces did not have a clear microstructure. In addition, damages were less severe on the industrial plastic surfaces than on the diamond-coated laboratory-made PVC model surfaces.

Table 9. A qualitative summary of the effects of wearing on the industrial plastic surfaces evaluated by measurements of topography and wearing (III, IV). The codes of industrial plastic surfaces are given in Table 3. R_a = arithmetic average of surface heights, R_q = root mean square deviation of the roughness profile, R_{ku} =kurtosis, R_{sk} = skewness

Codes	**Topography**											**Wearing**[#]		
	Contact profilometry										**SEM**	**Worn in the drum (mass loss)**	**Worn in the drum with sand (mass loss)**	**Frick-Taber (mass loss)**
	new R_a¤ (μm)	**worn R_a¤ (μm)**	**new R_a (μm)**	**worn R_a (μm)**	**new R_q (μm)**	**worn R_q (μm)**	**new R_{ku}**	**worn R_{ku}**	**new R_{sk}-**	**worn R_{sk}**				
FT4, S17	7.3±1.5	8.4±0.4	1.2±0.2	1.3±0.2	1.6±0.2	1.6±0.2	4.2±0.7	3.6±0.7	0.5±0.6	-0.5±0.7	hollows deepened	**4**	**3**	6
FT5, S18	11.3±1.6	9.6±1.3	2.6±0.2	1.4±0.1	3.0±0.2	1.8±0.2	2.6±0.6	3.4±0.6	1.3±0.1	1.1±0.1	scratches	10	*12*	7
FT6, S15	4.3±1.2	4.6±1.1	2.1±0.2	2.4±0.4	2.7±0.2	3.9±0.8	3.4±0.4	9.3±2.6	0.5±0.3	0.5±0.3	scratches	*11*	8	8
FT10, S13	4.1±0.6	4.1±0.3	2.0±0.2	1.9±0.1	2.6±0.1	2.2±0.1	3.3±0.3	2.5±0.4	0.4±0.8	0.6±0.5	scratches	9	9	13
FT13, S20	6.5±0.8	3.6±0.3	2.8±0.3	2.0±0.2	3.7±0.3	2.9±0.2	4.4±0.3	4.5±0.5	1.0±0.5	0.5±0.4	scratches	*13*	*14*	*17*
FT1, S14	11.4±0.5	11.0±1.9	3.6±0.3	2.9±0.2	4.6±0.3	4.4±0.1	4.3±0.6	4.5±0.2	-1.4±0.1	0.4±0.6	scratches	*12*	7	**2**
STP, FT8	6.5±0.3	3.8±2.5	2.3±0.1	1.3±0.4	2.6±0.4	1.8±0.2	3.0±0.3	2.5±0.1	0.4±0.3	0.6±0.1	scratches	**5**	**2**	11
QV, FT11	8.3±0.1	8.7±0.1	3.0±0.2	3.1±0.3	3.6±0.6	3.3±0.4	2.4±0.3	2.5±0.5	1.0±0.2	0.1±0.3	hollows	7	**5**	14
FT7, S11	1.8±0.3	2.2±0.4	1.0±0.0	2.0±0.5	1.3±0.0	2.4±0.5	3.4±0.3	2.3±0.2	0.1±0.5	-1.1±0.2	became rougher	6	**1**	9
FT2, S19	8.2±1.5	9.1±1.6	1.9±0.5	2.4±0.7	2.3±0.5	3.3±1.0	2.6±0.3	4.2±0.8	0.1±0.4	-1.9±0.1	hollows deepened	**3**	6	**4**
PVC, FT3	1.9±0.1	2.3±0.3	1.0±0.1	1.4±0.3	1.8±0.3	1.9±0.1	2.3±0.3	3.0±0.2	1.3±0.3	0.5±0.2	scratches	*15*	*13*	**5**
FT12, S16	1.6±0.4	1.7±0.1	1.1±0.2	1.2±+0.1	1.4±0.2	1.6±0.1	3.6±0.1	5.0±0.4	-0.4±0.3	-0.2±0.3	hollows deepened	**1**	*11*	*16*
FT14, S12C	2.2±0.5	2.6±0.6	2.3±0.1	2.7±0.2	3.0±0.2	3.2±0.4	2.9±0.2	3.8±0.4	-0.1±0.6	0.22±0.4	became rougher	8	**4**	*18*
FT15, S12	2.7±0.6	3.8±0.9	1.9±0.2	3.0±0.1	2.9±0.3	4.0±0.1	6.9±0.5	3.5±0.3	-1.1±0.6	0.2±0.1	hollows	**2**	10	*19*
LIN, FT9	10.0±0.6	10.4±0.5	3.0±0.4	2.9±0.6	3.5±0.1	3.6±0.3	2.3±0.2	2.6±0.2	0.3±0.1	0.2±0.1	scratches	*14*	*15*	12
S1	-	-	-	-	-	-	-	-	-	-	-	-	-	10
S2	-	-	-	-	-	-	-	-	-	-	-	-	-	*15*
S3	-	-	-	-	-	-	-	-	-	-	-	-	-	**3**
S4	-	-	-	-	-	-	-	-	-	-	-	-	-	**1**

.- Not included in the study

¤ Macroroughness (waviness)

[#] The best wear resistance is rated as 1 and the poorest as 15 or 19. The five best results are marked as **bold** and the five poorest results are marked as *italic*.

5.1.2 Scanning electron microscopy (SEM)

The regular microstructure of the laboratory-made PVC model surfaces was clearly seen in the SEM micrographs (Figures 5-6). These micrographs show that PVC model surfaces which contained 20 % plasticizer had a sharper surface microstructure than the materials with 30 % plasticizer. The feasibility of topography measurements on plastic surfaces was examined using scanning electron microscopy. The SEM figures were informative in evaluating the effect of wear on the plastic surface. In order to illustrate this, typical scanning electron microscopy (SEM) photomicrographs from new and worn industrial plastic surfaces were presented in Figures 8-9 of publication III. According to the SEM results, different changes were observed between new and worn industrial plastic surfaces. As can be seen in Table 7, during wear the surfaces became smoother or rougher, or scratches appeared in them. The PUR coating protected the surfaces better from scratching than the uncoated plastic surfaces.

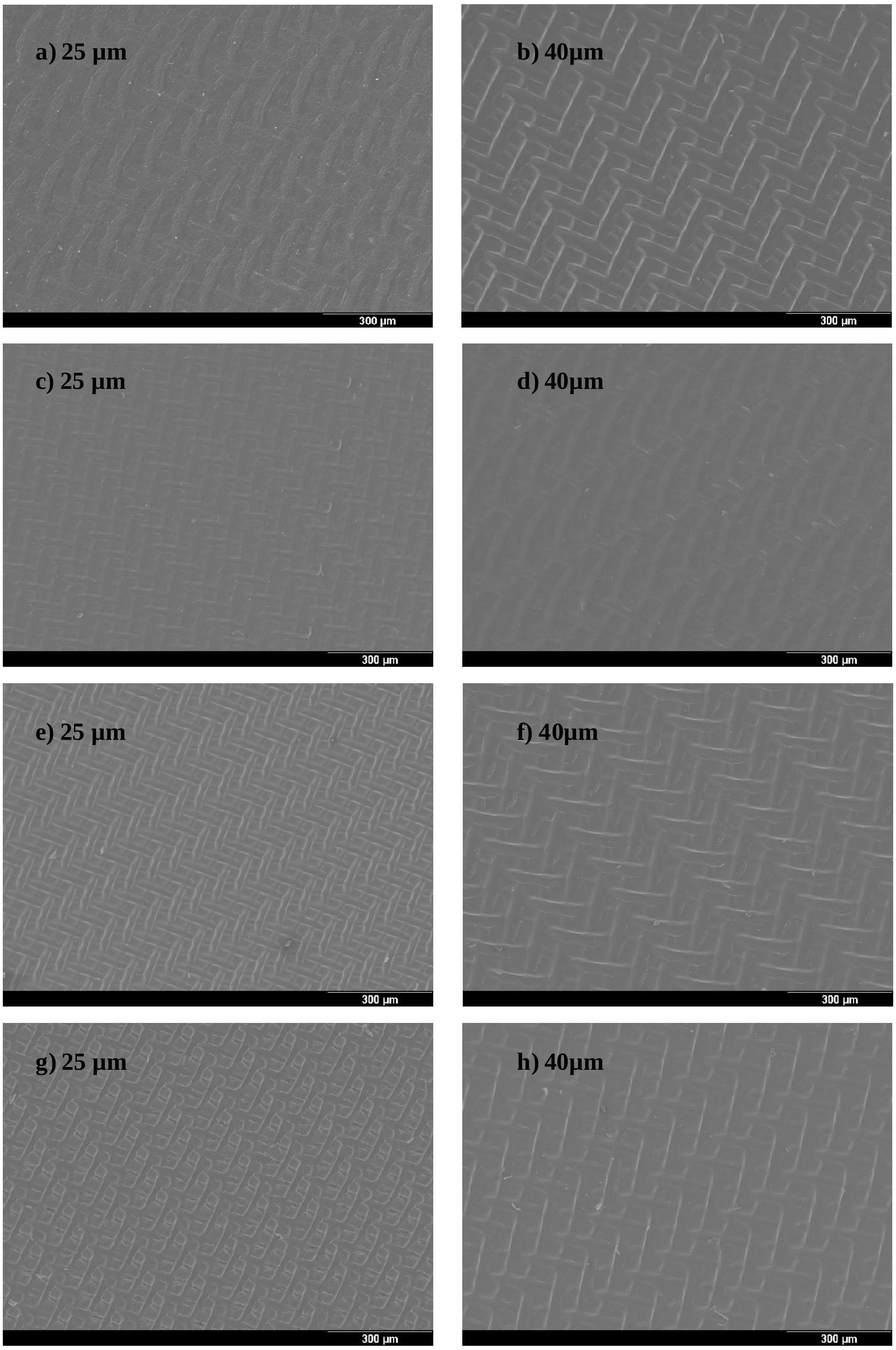


Figure 5. SEM micrographs of new laboratory-made PVC model surfaces with different surface microstructures of 25 µm or 40 µm. Plasticizers: DOP20 (a, b), DOP30 (c, d), Hexa20 (e, f) and Hexa30 (g, h), magnification x500. The preparation, codes and details of the PVC model surfaces are presented in Table 3.

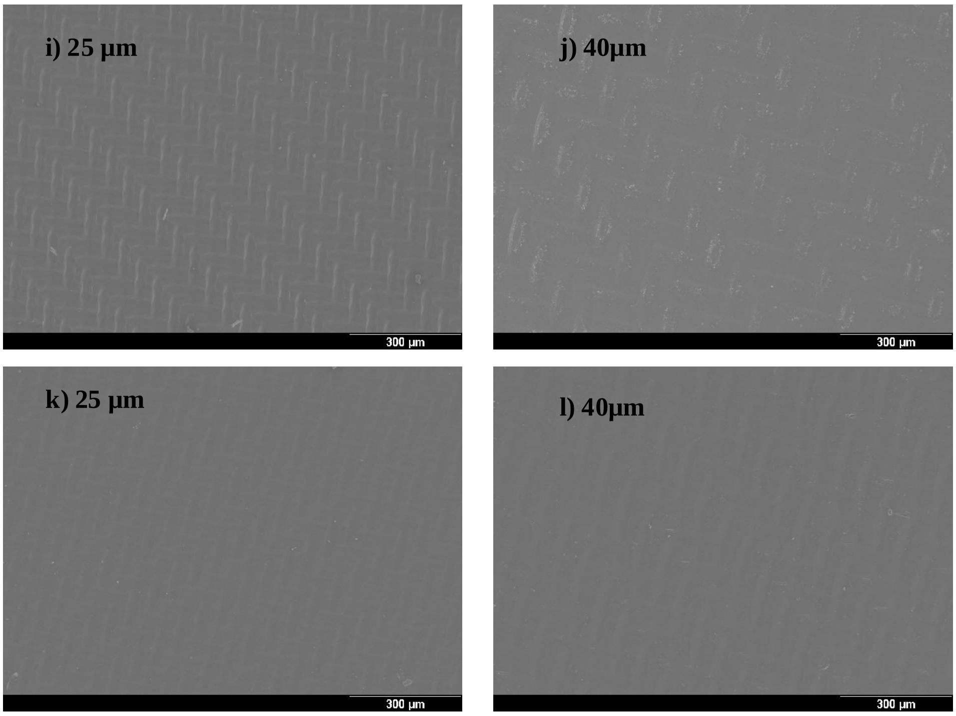
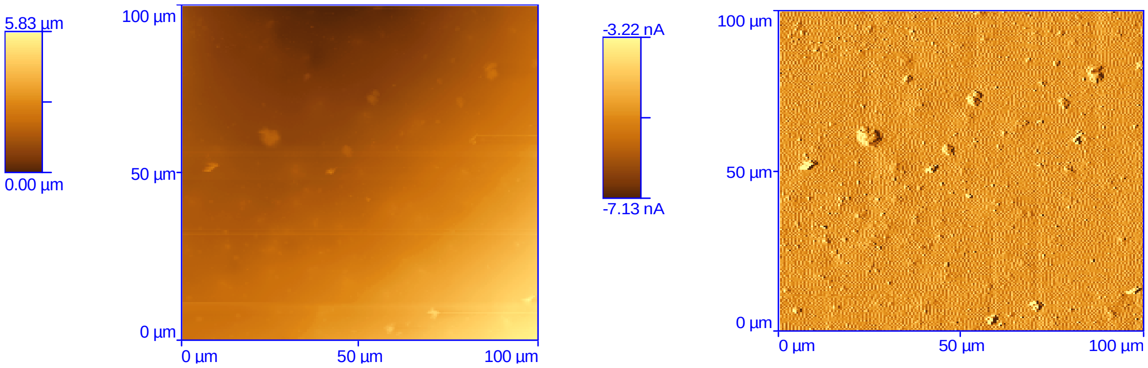


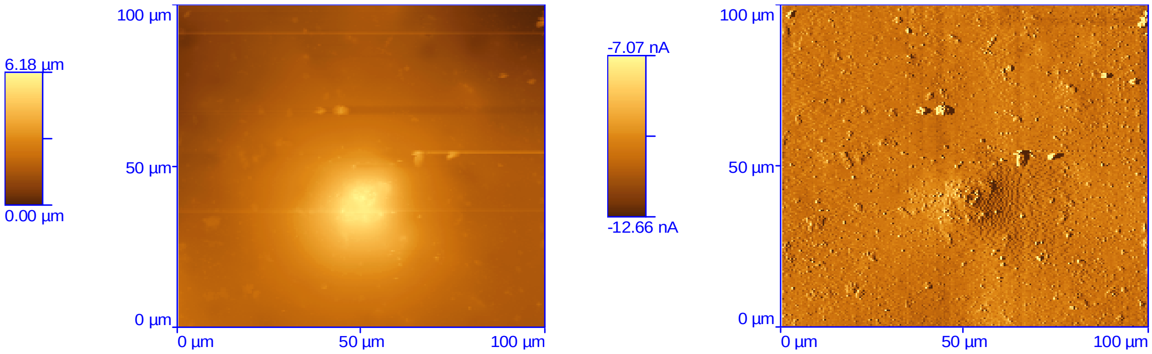
Figure 6. SEM micrographs of new laboratory-made PVC model surfaces with different surface microstructures of 25 µm or 40 µm. Plasticizers: Benzo20[##] (i, j) and Benzo30[##] (k, l) , magnification x500. The preparation, codes and details of the PVC model surfaces are presented in Table 3.
[##] Benzoflex 2088

5.1.3 Atomic force microscopy (AFM)

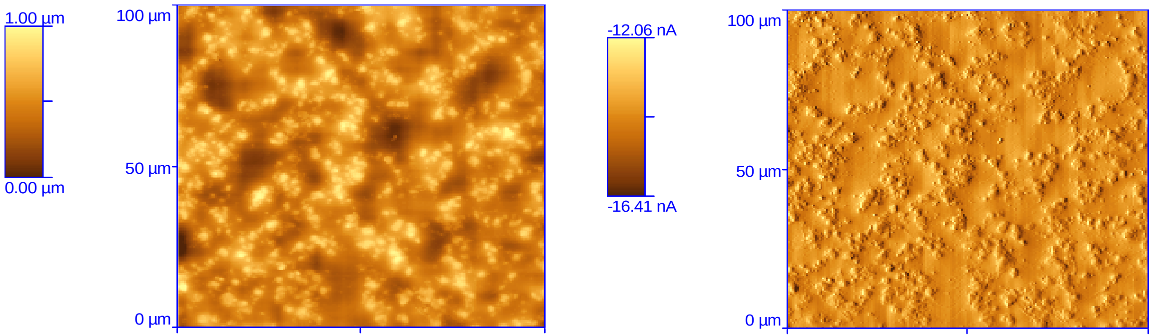
The feasibility of topography measurement on laboratory-made smooth PVC model surfaces and industrial plastic surfaces was examined using atomic force microscopy. The AFM photomicrographs were measured in non-contact mode. The topography pictures provide a general idea about the surface but in the internal sensor pictures the details of the form of the surface are shown. Although the AFM-topography pictures look rather inaccurate compared to the internal sensor pictures, the advantage of the topography pictures is that in them a numerical height profile (height of the highest peak on the sample) is shown. AFM photomicrographs obtained from new industrial plastic surfaces using the non-contact mode are presented in Figure 2 of Publication V. The examples of topographies of uncoated Benzo and DOP surfaces are shown in Figure 1 of Publication VII and diamond–coated Benzo surfaces are shown in Figure 1 of Publication VII. For the laboratory-made PVC model surfaces the AFM method could not be applied because the height of the profiles of the materials exceeded 8 μm, which is the measuring limit for the equipment. The differences between internal sensor and non-contact mode pictures can be seen in Figure 7, illustrating the new and worn industrial plastic surfaces. Wearing with hexapod and sand caused scratches on the thermoplastic composite tile (Fig. 7d).



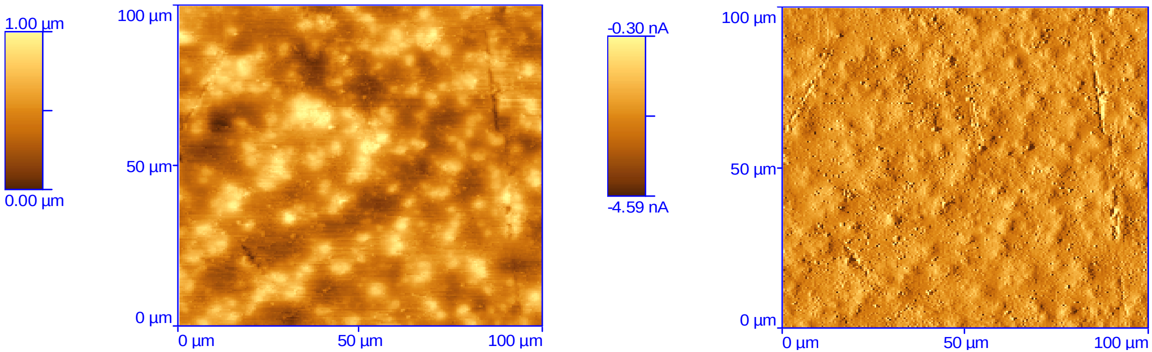
a) PUR-coated composite tile (S11), new



b) PUR-coated composite tile (S11), worn



c) Thermoplastic composite tile (S14), new



d) Thermoplastic composite tile (S14), worn

Figure 7. AFM micrographs of some industrial plastic materials. The topography pictures are on the left and internal sensor pictures on the right. The codes and details of industrial plastic surfaces are presented in Table 4. AFM micrographs were taken by Inka Saarikoski (Department of Chemistry at the University of Joensuu).

5.2 Wearing of plastic surfaces

Wearing caused the breakage of the microstructure on the diamond-coated PVC surfaces All diamond-coated model surfaces became rougher after wearing except the DOP20 surface with 40 µm structure (Figure 3 of Publication VII) due to the formation of cracks and scratches during wearing. However it is possible that the roughness (R_a) value does not perfectly describe the effect of wear. In proportion to that, the R_a values of the worn PVC model surfaces were higher than that of the new surfaces. The R_a values of the worn surfaces were between 1.4 µm and 4.1 µm (Figure 3 of Publication VII).

Soiling and Wearing Drum Tester (EN 14565) and the Frick-Taber method (EN 660-2) were used to assess changes in the amount of mass loss on industrial plastic surfaces after wearing. When comparing the results of the Frick-Taber test with the results of the Soiling and Wearing Drum Test, it was observed that there was no correlation between the results of these two methods (Figure 5, publication IV). This is due to the fact that the two methods represent different kinds of wear mechanisms. As shown in Figure 8, the Frick Taber method is a much more aggressive wearing method than the Soiling and Wearing Drum Tester. Most of the industrial plastic surfaces (I, IV) were PUR-coated. After 1000 cycles of the Frick Taber method all of the PUR coating had disappeared, but after the drum wearing the PUR coating of the surfaces still remained. The PUR coating did not protect the industrial plastic surfaces against heavy wearing. No correlations were observed between the roughness parameters R_a, R_q, R_{ku}, R_{sk} and mass losses. The ionomer integrated thermoplastic composite tile (FT1) had almost the same wear resistance as the PUR-coated plastic surface (S4).

The Soiling and Wearing Drum Tester (EN 14565) and the Frick-Taber method (EN 660-2) had good repeatability, the standard deviations of mass loss values being <41 mg/mm^2. Sand generally increases the wear, but the correlation graph showed that the industrial plastic surfaces wore with the hexapod in a similar way independently of whether sand was included or not (Figure 4 of publication IV). When using the Soiling and Wearing Drum Test (IV) with hexapod and quartz sand, the best resistance was obtained for the

PUR-coated PVC composite tile FT7 (Δm=39 mg/m^2) and the poorest wear resistance was observed for acrylate-coated linoleum FT9 (Δm=301 mg/m^2).

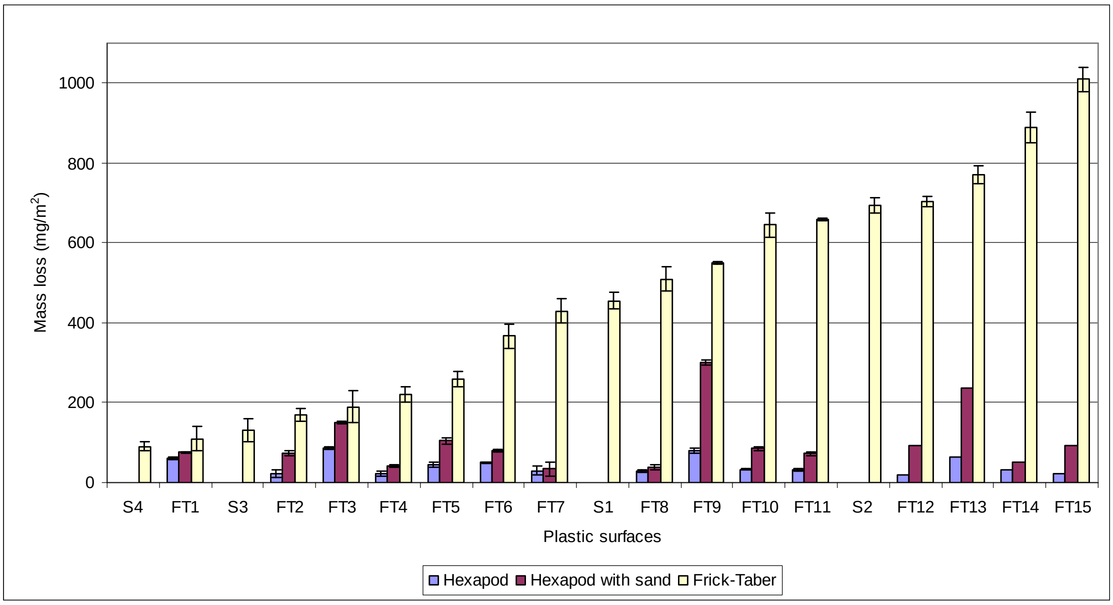


Figure 8. Cumulative mass losses for some of the industrial plastic surfaces using the Soiling and Wearing Drum test (IV) and the Frick-Taber test (I, IV). Columns are means and bars standard deviations of five replicates. The codes and details of industrial plastic surfaces are presented in Table 4.

5.3 Cleanability

Cleanability studies have been carried out for laboratory-made PVC model surfaces with a radiochemical method (VI). Additionally in the present investigation the cleanability studies were carried out for the new and worn industrial plastic surfaces using a colorimetric method for assessing the cleanability result.

5.3.1 Cleanability determined using colorimetry

Colorimetry was used to assess changes in the amount of soil on the industrial plastic surfaces after soiling and cleaning. The differences in the cleaning indices between the worn and new industrial plastic surfaces are presented in Figure 9 in the following and in Figure 4 of Publication III. In general, more particle soil was removed from new than from worn industrial plastic surfaces, and soil residues were in most cases lower on the new than on worn surfaces (exceptions were polished PVC sheet S12c and the static dissipative plastic surface S16). Most industrial plastic surfaces were soiled with oil soil more heavily when new than when worn (exceptions were PUR-coated PVC composite tile S11 and thermoplastic composite tile S14), but the differences in the cleaning indices were negative, i.e. new industrial plastic surfaces were cleaned better than worn industrial plastic surfaces. When the new industrial materials were examined, the acrylate-coated linoleum was the most soiled of the plastic surfaces and was clearly more difficult to clean than the other plastic surfaces (Figure 2 of Publication II). The difference between all the materials was significant ($p<0.05$).

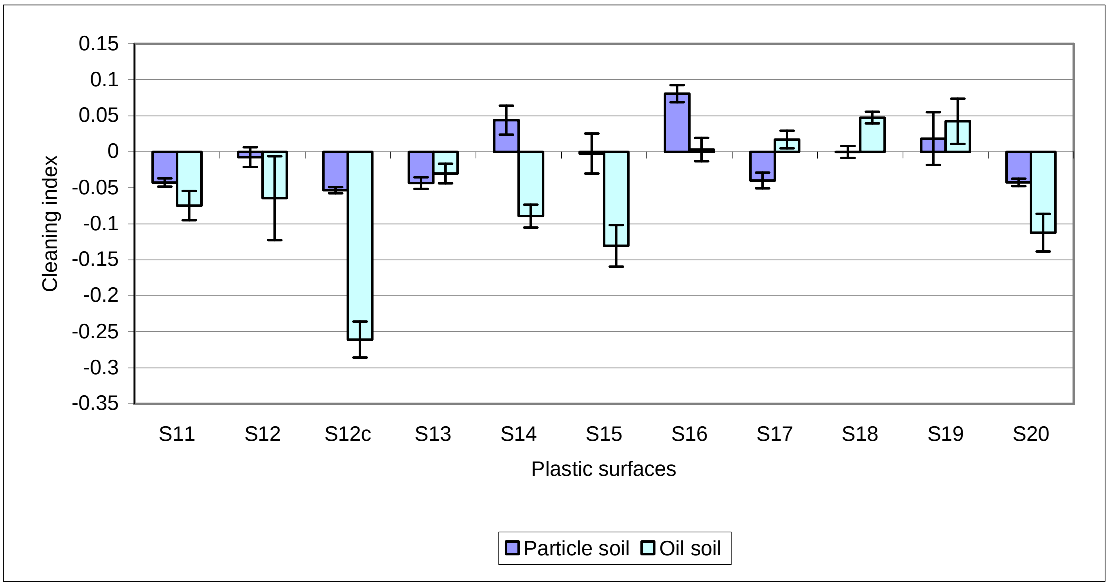


Figure 9. Differences between cleaning indices for some worn and new industrial plastic surfaces when the surfaces were particle- and oil soiled. The error bars are standard errors. The descriptions of industrial plastic surfaces are presented in Table 4.

The cleaning indices of the industrial plastic surfaces soiled with organic oil soil and inorganic particle soil had no clear correlation with the R_a values (III) but had weak correlations with the roughness parameters R_a, R_q, R_{ku} and R_{sk} (IV). The cleanability results are comparable only when they are obtained from the same study system, but the study systems of publications II, III and V had several differences.

6 DISCUSSION

6.1 Materials

Two different types of plastic surface materials were studied: laboratory-made PVC model surfaces with known chemical composition and surface structure, and industrial materials for which only general information was available. In order to examine the validity of the research methods for physical characterization and cleanability of industrial plastic surfaces, it is very important to have laboratory-made PVC model surfaces with know properties. Detailed information of the chemical composition of the PVC model surfaces was obtained from the Department of Chemistry at University of Joensuu. The resulting structure on the polymer has nano- and microscale bumps imitating the Lotus structure found in plants. A combination of nano- and microscale structures has been reported to increase the soil resistance of the surface (Neinhuis and Barthlott 1997, Gould 2003).

The examined industrial surfaces also represent new materials: manufacturers of plastic surfaces made available their new products under development for these studies. Evaluation of the results of wearing and cleanability is problematic without detailed information on the chemical composition of the plastic surfaces used. However, when developing methods for practical purposes it was important to have industrial plastic surfaces as test materials.

6.2 Determination of surface topography

6.2.1 Profilometry

The most widely used and reliable surface measuring instruments currently available are mechanical profilometers such as stylus instruments. Unfortunately these instruments have many disadvantages. For example they are unable to perform non-scratching measurement of the profile of soft materials and thin films (Jolic et al. 1994). Contact profilometry has generally been used for examining hard surfaces such as diamond, titanium, steel and gold (Sayles 2001, Chappard et al. 2003, Bagno et al. 2004). There is no published literature in which the device would have been used for the examining of resilient floor coverings. The stylus of the contact profilometry may damage and modify a soft coating during the measurement. However, in the present study repeated measurement in two-dimensional and three dimensional figures gave the same results and in the statistical analysis changes were not detected (III-VII). This suggests that no damage was caused by the stylus.

Contact profilometric measurements are concerned with height distributions, mean spacings between peaks and the slopes of the peaks as a function of stylus radius. Some important points pertain to the dependence of surface location on the instrument used to measure it; in particular the stylus radius can affect the apparent measurement of surface depths. Furthermore, it is important to define the scale of roughness (Vandenberg and Osborne 1992). Gadelmawla et al. (2002) illustrated the definitions and the mathematical formulae for 59 of the roughness parameters but most generally used roughness parameters in different studies are arithmetical averages of surface heights (R_a), root mean square roughness (R_q) and ten-point height (R_z) (Provder and Kunz 1996, Kim and Smith 2000, Liko and Bohnen 2002). In this study it was chosen to use roughness parameters R_a, R_q, kurtosis (R_{ku}) and skewness (R_{sk}).

6.2.2 Scanning electron microscopy (SEM)

In this study, changes in the microstructure of the laboratory-made PVC model plastic surfaces were presented in Figures 5 and 6. The microstructures of the PVC model plastic surfaces were regular and the surface structure became even when the plasticizer was added to the materials. The SEM figures of publications III-IV were informative in evaluating the effect of wear on the industrial plastic surfaces: different changes (i.e. scratches, roughness, deepened hollows) caused by wear were seen on surfaces in the SEM figures (III), although there were not necessarily any changes in roughness. According to the SEM figures, wear caused changes in the surfaces. However, the changes were specific to the different materials. Because differences between materials were variable, we cannot derive a general rule of relationship between wear and soiling or cleanability. The general premise that a rough surface will yield poor cleanability was not confirmed here for all plastic materials.

The most accurate profilometer probes allow measurement of summit heights of several Ångstroms when optical instruments have the same ultimate vertical resolutions. The development of techniques using probes smaller than the radius of the probing needle or the wavelength of light makes it possible to extend the spectrum of surfaces studied. The electron beam in the scanning electron microscope (SEM) is an example of such a probe. By interpreting the emission intensity of the secondary electrons the topographic pattern can be restored, and the SEM technique can be used to gauge topography with a comparable resolution both vertically and laterally (Myshkin et al. 2003). SEM offers significantly better resolution and depth of field than its optical counterparts. As a consequence, the SEM figures are much more useful in the study of surface topography than pictures from conventional optical light microscopes (Sherrington and Smith 1988).

The profilometric and SEM techniques are complementary. The SEM technique yields high resolution pictures of the microtopography of surfaces but does not readily provide quantitative information. The stylus instrument has coarser resolution than the scanning microscope but provides precise numerical information about the topography (Thomas 1986).

6.2.3 Atomic force microscopy (AFM)

Atomic force microscopy (AFM) can image the surface topography of conducting and non-conducting surfaces with sub-nanometer resolution (Ermakov and Garfunkel 1994). When stylus-material interactions may dramatically a effect measurements, non-contact techniques are an alternative (Chappard et al. 2003). The non-contact mode is especially suitable for soft and deposited materials because it does not damage or change the topography of samples. The examples shown in Figure 7 and in Figure 2 of Publication V clearly indicate the nature of the industrial plastic surfaces as a group. The AFM measurements revealed that the surface of the injection molded plasticized PVC was very smooth and there was no significant differences in topography caused by plasticizer (Figure 1 of Publication VI). The AFM and STM systems have the higher resolution than other topography measurement techniques but are limited in measuring range (Mainsah et al. 2001, Verran et al. 2003).

Probing of the surface mechanical properties with nanometer-scale lateral and vertical resolution became a reality as a result of the introduction of nanomechanical probing based on atomic force microscopy principles (Domke and Radmacher 1998, Chen and Vlassak 2001). Shulba et al. (2004) analyzed how the approach developed for microindentation of non-uniform elastic solids can be adapted to analyze the AFM probing of ultrathin (1-100 nm thick) polymer films on a solid substrate, as well as polymer films with a multilayered structure. AFM allows imaging of plastic surfaces under ambient conditions and without the need for any additional sample preparation, such as gold coating, which is required for electron microscopy. This makes it an ideal technique for investigating the effect of surface roughness on cleaning on a much higher scale than has been previously possible using profilometry techniques.

6.3 Methods for examining wear resistance of surfaces

The wear rates of polymers depended critically on the polymer type. Wearing of the laboratory-made PVC model plastic surfaces caused deep scratches and hollows in the surfaces and the microstructure was almost totally destroyed (VII). Diamond coatings were added onto PVC surfaces in order to improve their wear resistance. The poor wear resistance of diamond coated PVC surfaces was a consequence of the softness of plasticized PVC surfaces. The breakage of the PVC surface under the coating caused also the breakage of the thin diamond coating. That can be prevented if thicker diamond coatings can be applied onto PVC and thus the whole surface can be made harder. However, these PVC model plastic surfaces could not resist wearing because they were prototypes. Wear-resistant properties will later be developed in these materials.

When comparing the results of the Frick-Taber test with those of the of Soiling and Wearing Drum test for industrial plastic surfaces it was observed that there was no correlation between the two methods. This is due to the fact that the methods represent different wearing mechanisms. Buchheit (2004) mentioned in his thesis that the Frick-Taber test is too aggressive to simulate real wear of plastic surfaces, and showed that in the case of coated products the entire coating in the removed at early stages of the test. He also measured the thickness of a PUR coating. After 1000 cycles the PUR coating had entirely disappeared and the thickness of the worn coating was around 10 µm. After 5000 cycles, the abrasion level (50 µm lost) was much greater than the thickness of the coating.

By using the soiling and wearing drum method, the effects of shoes or shoes and sand in the wearing out of plastic surfaces can be simulated. However, the short-term mechanical effect obtained using the soiling and wearing drum is possibly stronger than that caused by walking over a long time.

Furthermore, it is not known whether the arching of the drum and the fastening of plastic surfaces to the walls of the drum had an effect on the results. The extent of wearing out of surfaces depends on the size, form and hardness of the abrasive particles and on the touch frequency of the surface to the abrasive particles (Harsha et al. 2003). In the Soiling and Wearing Drum the same quartz sand which was used as a main component (88.3 %) in inorganic particle soil (EN 14565) was used for wearing tests. This sand is rather fine and wearing is not as rapid as it would be if using some more coarse-grained sand. In the literature it is mentioned that different rollers and granulates have been developed to replace the hexapod (Krüssman and Garvens 1997, Burrows 1999, ISO 11378-2). On the other hand, in the standard EN 14565 such alternatives are not used and hexapod walking mimics the real situation better than the rollers and granulates. Previously Budinski (1997) investigated the abrasion resistance of 21 types of plastics and reported that polyurethane had better abrasion resistance than the other materials. Hard reinforced and filled engineering plastics also had relatively poor abrasion resistance to silica sand. Wearing of polymers has been shown to depend on general surface roughness, but only poor correlation exists between hardness and wearing of polymers (Beck and Truss 1998).

In summary, differences of roughness parameters between various laboratory-made PVC model plastic surfaces resulted from diamond coating and wearing. In order to fulfil the requirements of commercial plastics, the wearing resistance properties of these materials must be developed. The Frick-Taber and Soiling and Wearing Drum methods are very useful when simulating three-body wearing.

6.4 *Evaluation of physical surface topography, wearing and cleanability*

6.4.1 Plastic surfaces

The radiochemical method provides more detailed information on cleanability than colorimetry. Pesonen-Leinonen et al. (2006) first studied the cleanability of smooth plastic surfaces containing plasticizers. The soilability associated with plasticizers depends on the structure properties such as chain length, volatility, concentration, extraction resistance and solubility of the plasticizer (Colletti et al. 1998). The radiochemical method proved to be suitable for assessing soil accumulation on plastic materials during successive soiling and cleaning cycles (Pesonen-Leinonen et al. 2006). In this study (VI) the laboratory-made PVC model surfaces (Table 3) were examined with the radiochemical method. Different model soils were labelled with ^{51}Cr and ^{14}C. It was found that both the quality and the amount of the plasticizers and the surface structure had an effect on the cleanability of PVC model surfaces. In this study the cleanability of the materials containing 20 % plasticizer was better than that of the materials with 30 % plasticizer. The microstructure of the PVC model surfaces had an effect on cleanability of materials measured by the radiochemical method (VI). Roughness parameters R_a, R_q, R_{sk} and R_{ku} had no general impact on cleanability (all true values of the correlation efficients $r < 0.532$) (Figure 10).

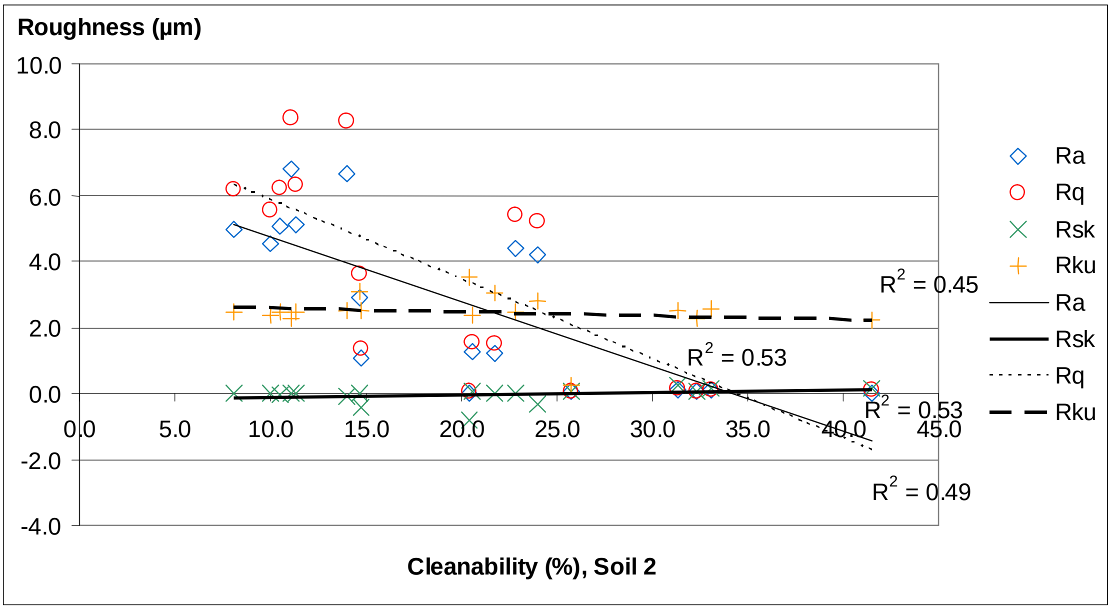


Figure 10. Correlation between the roughness parameters and cleanability, calculated from means of the results. The codes and details of the surfaces are presented in Tables 1 and 2 of Publication VI.

Colorimetry provides a rapid, non-destructive, and semi-quantitative measure of the colour of surfaces, confirming the conclusions of Pitts et al. (1998) and Pesonen-Leinonen (2005). The laboratory-made PVC model surfaces were not investigated by the colorimetric method. Industrial surfaces that were examined in studies II, III and V were light-coloured, new or worn plastic surfaces. Colorimetry offers an easy to use and reproducible method to evaluate the cleanability of light-coloured plastic surfaces, as dark-coloured soil is used. The soil residue has been considered to be the most valuable of the parameters calculated from the L*-value because it shows whether the plastic surfaces can be cleaned easily and economically. The soiling value is also important because it provides an indication of the need for cleaning of the flooring (Krüssmann and Garvens 1997).

Some industrial plastic surfaces became smoother and others became rougher, but all industrial plastic surfaces exceeded the 0.8 µm ‘hygiene’ level. An R_a of 0.8 µm is generally used to describe a hygienic surface (Verran 2001). Because the cleaning indices of the industrial plastic surfaces soiled with organic oil soil and inorganic particle soil had no clear correlation with the R_a values (III) and only weak correlations with the parameters R_a (first moment), R_q (second moment), R_{sk} (third moment) and R_{ku} (fourth moment), these values cannot predict the cleanability in general. It is thus evident that none of the integral roughness parameters (first, second, third or fourth moment) are sufficient to correctly describe the topography of surface and therefore no correlations were observed. However, it is expected that possible random unevenness of the surface should play a role in soiling tendency or cleaning capability. Possibly local measures of surface unevenness are more sensitive to different spatial scales and are able to distinguish between morphologies in different scales. For this, several methods have been developed within the theoretical methodologies for surface characterisation, most of them based on power spectra or Fourier-transforms of surface morphology (Barabasi and Stanley 1995).

However, when individual materials and their cleanability were examined, the profilometric measurements were useful in order to illustrate differences between materials. In summary, the measurements of surface topography can be used for examination of wear and cleanability, but in order to properly evaluate surfaces, valid 2D profilometric measurements should be used only in conjuction with other, e.g. SEM measurements. The results of this study can be used when developing new industrial soil-resistant plastic surfaces. In this study physical methods were developed and adapted from other fields. The pilot equipment and definition methods that were developed for the cleanability research proved to be useful and reliable. These devices and methods can be utilized both in materials research and product development.

7 CONCLUSIONS

1. Contact profilometry, scanning electron microscopy (SEM) and atomic force microscopy (AFM) were suitable for studying the topography of laboratory- made PVC model surfaces and industrial plastic surfaces. These methods have their own limitations but together they are an effective tool, providing useful information on surface topography, especially when studying laboratory-made PVC model surfaces with known chemical compositions and structures. Valid 2D profilometric measurements should be used only in conjuction with other, e.g. SEM measurements in order to evaluate surfaces. The SEM technique yields high resolution pictures of the microtopography of surfaces but does not readily provide quantitative information. The numeric information from the AFM measurement is different from that obtained from the profilometric parameters because AFM gives only a numerical height profile.

2. When studying wearing of plastic surfaces, the Soiling and Wearing Drum method and the Frick-Taber method represent different kinds of wear mechanisms. The Soiling and Wearing Drum Tester (EN 14565) simulates better the wear caused by sand contamination than the Frick-Taber method (EN 660-2) which uses heavy wearing. Both the examined wearing methods can be used to compare the wearing of different plastic materials using appropriate evaluation methods of wearing and industrial use.

3. According to the results only a weak correlation between plastic surface topography and cleanability was observed. The colorimetric method proved to be suitable for examining the cleanability of the industrial plastic surfaces. However, other methods, e.g. the radiochemical method would provide more detailed information of cleanability. The industrial plastic surfaces are a complex group of materials because of their chemical and topographical heterogeneity. However, topography measurements were useful for examining the topography and cleanability of individual materials.

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