From outcrops to dust
−mapping, testing, and quality assessment of aggregates

Mika Räisänen

ACADEMIC DISSERTATION
IN GEOLOGY AND MINERALOGY

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To my Father

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Abstract

Aggregates can be defined as particles of rock that are used for various construction purposes, and they are produced mainly from sand and gravel deposits and increasingly from bedrock. The potential durability of an aggregate in a specific end-use application is often determined by mechanical tests. The petrographical properties of rocks, and the quarrying and crushing processes of aggregates have a controlling affect on the test results. While this study was carried out, many national standards and recommendations were being intensively substituted by European aggregate product and test standards. A major part of this study involved testing of raw materials and non-standardised aggregates. The results from five case studies, the objects of which range from *outcrops to dust*, bring new details to the relationships between petrographical and mechanical-physical properties of rocks. This study deals with four key topics: *evaluation of aggregate raw-materials, selective quarrying, laboratory crushing, and formation of mineral dusts from wearing of aggregates.*

In the *aggregate raw material study*, the modal composition and grain size distribution of hybridised rocks from the Jaala-Iitti complex were quantified from thin sections. Abundance of fine-grained matrix minerals (especially of hornblende), grain size distribution, uniform spatial dispersion of hornblende crystals, and grain boundary characteristics were found to have the greatest influence on the mechanical properties of these rocks.

In Finland, the extraction permit procedure, which has been implemented partly to help to protect the environment, can have opposite effects in geologically heterogeneous areas, because it is not advised to remove the topsoil from the whole extraction permit area before quarrying. Raw-material evaluation is environmentally sustainable and economically cost-effective because it supports *selective quarrying*. Based on the case study at the Pirkanmaa quarry, geology-based raw-material evaluation would facilitate more efficient utilisation of aggregate resources, so that high-quality aggregates would not be used for low-quality requirement applications.

Standardised mechanical tests are intended for testing end-products, not raw-materials that have been crushed with *laboratory crushers*. The results of this study indicate that, with regard to raw-material quality assessment it is crucial to pay attention to the running condition, setting, and capacity of laboratory crushers. Different laboratory crushers produce aggregates with varying shape properties and this has a distinctive impact on the results of mechanical tests. Consequently, a European working group on laboratory crushing and testing raw-materials should be established to set international directions for laboratory crushing.

The main theme of the road dust studies was: “Dust formation at tyre and asphalt pavement interface with various anti-skid and asphalt aggregates and tyre types in test conditions”. Anti-skid aggregates were tested with a road simulator, and dust samples were collected subsequently from the air, and analysed with SEM-EDX. *Mineral dusts* were classified according to their elemental composition, and the origin of dust particles (asphalt vs. anti-skid aggregate) was defined. This study indicates that, with regard to urban dust that the most important properties of anti-skid aggregates are their grading and resistance to fragmentation.

Keywords*: Aggregate; Anti-skid; Asphalt; Crushing; Flakiness index; Grain size distribution; Hybridisation; Los Angeles test; Petrography;* PM_{10}*; Quality assessment; Quantitative petrography; Resistance to wear by abrasion from studded tyres test; Urban dust.*

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Bedrock outcrops in Pernaja, winter 2000. This source area for high-quality asphalt aggregates was discovered during the course of geological mappings of this study.

Production of railway ballast and asphalt aggregates in the Pernaja quarry in summer 2004.

The brownish asphalt in front of the Helsinki city railway station is one end-use application of granite aggregates from the Pernaja quarry.

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During this study I have attended to aggregate research conferences in Gothenburg, Borås, Helsinki, Reykjavik, and Tampere. Discussions in these meetings with aggregate geologists and engineers have given me inspiration, information, and new friends as well. Thank you all, and especially to Mr. Urban Åkesson and Dr. Björn Schouenborg (SP Swedish National Testing and Research Institute), Mr. Mattias Göransson, Mr. Sven Lundqvist, and Dr. Lars Persson (Geological Survey of Sweden), Mr. Thorgeir Helgason (Petromodel Ltd.), Mr. Lars Stenlid (Skanska Sverige Ab), Mr. Mathias Jern (Chalmers University of Technology), Dr. Jarmo Eloranta and Mr. Jaakko Ruuskanen (Metso Minerals Oy), Mr. Olli Skyttä (Consolis Technology Oy), Mr. Pasi Niskanen (Lohja Rudus Oy Ab), and Mr. Tuomo Laitinen (Finnish Aggregates Producers Association).

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I would like to express special appreciation to my mother Anita von Zansen, and to my late father Seppo Räisänen, who passed away before I could finish this study. Finally, My Family (Hannele Kauppinen, Tommi, Leo and Oona) is thanked for their never-ending support and enjoyable life outside the office.

Espoo, October 20th 2004

Contents

List of publications

This study is based on the following five papers, which are referred to by Roman numerals:

I Räisänen, M. 2004. Relationships between texture and mechanical properties of hybrid rocks from the Jaala-Iitti complex, southeastern Finland. *Engineering Geology* 74, 197-211.

II Räisänen, M. and Torppa, A. 2004. Quality assessment of a geologically heterogeneous rock quarry in the Pirkanmaa county, southern Finland. *Bulletin of Engineering Geology and the Environment (Submitted)*.

III Räisänen, M. and Mertamo, M. 2004. An evaluation of the procedure and results of laboratory crushing in quality assessment of rock aggregate raw materials. *Bulletin of Engineering Geology and the Environment* 63, 33-39.

IV Räisänen, M., Kupiainen, K., and Tervahattu, H. 2003. The effect of mineralogy, texture and mechanical properties of anti-skid and asphalt aggregates on urban dust. *Bulletin of Engineering Geology and the Environment* 62, 359-368.

V Räisänen, M., Kupiainen, K., and Tervahattu, H. 2004. The effect of mineralogy, texture and mechanical properties of anti-skid and asphalt aggregates on urban dust, stages II and III. *Bulletin of Engineering Geology and the Environment* (In press).

Räisänen has written all papers and carried out most of the laboratory work. Mertamo run most of the mechanical-physical tests reported in Paper I and helped with laboratory work reported in Papers III-V. Torppa participated in mapping, mechanical-physical tests, and petrographical work reported in Paper II. Kupiainen was mainly responsible for the single particle analysis with SEM-EDX and road simulator runs reported in Papers IV and V. Tervahattu participated in SEM-EDX work and in data interpretations reported in Papers IV and V.

1 Introduction

The Finnish bedrock is composed nearly entirely of Precambrian igneous and metamorphic rocks, which are overlain by Quaternary glacial sediments. Bedrock and the sediments are both used as raw materials for aggregates. Aggregates can be defined as particles of rock that are used for various construction purposes in bound or unbound conditions, such as roads, bridges, railroad beds, airports, houses, playgrounds, etc. In tons of product, quarrying is the largest industry in Finland, and the total amount of aggregates used annually is about 90 million tons, which is ca. 18 tons per inhabitant (Rintala 2003). Due to groundwater protection and reduced resources, the use of alluvial and fluvial aggregates is decreasing and other sources are needed (Britschgi 2001). According to Rintala (2003), the use of rock aggregates has doubled and the use of glaciofluvial aggregates has decreased ca. 30 % since the early 1980s.

In northern latitudes, some aggregates have special quality demands due to the climate. Cars use studded tyres during winter to obtain more traction on the icy road surfaces, and, therefore, asphalt aggregates need to have good resistance to abrasive wear. Frost may reach to a depth of 2.5 m, which affects the material choices in all layers of road construction. The quality of an aggregate, which is based on the rock texture and modal composition (e.g. Paper I), depends on the end-use application of aggregate. For example, high quality asphalt aggregates can have low-performance as concrete or as gravel road maintenance aggregates. Hereafter, in this thesis, when the quality of aggregates is discussed, the context has to be taken into account. The quality cannot be defined by a single test or petrographical analysis. Therefore, petrographic analyses cannot so far replace standardised tests, but they should be regarded as complementary (Smith and Collis 1993). Comprehensive understanding of material's behaviour in end-use and in aggregate quality assessment tests requires co-operation between material specialists and engineers. According to Vallius (2001), standardised tests of aggregates are not adequate in all construction applications. Road alignments are an example where the total costs, transport, logistics, and the lifetime of construction application etc. should be rated and the potential applicability of lower quality aggregates should be evaluated.

The importance of standardised testing and quality criteria for aggregates has increased. Due to bedrock heterogeneities, some areas lack high quality aggregates for most demanding construction applications, like railway ballast and asphalt aggregates for heavily trafficked roads. Therefore, it is vital to take into account the geological variation and utilise geological data in land-use planning, infrastructure, environmental and operational issues, and inventories of aggregate reserves (Vallius 1995; Nurmi et al. 2001; Räisänen and Vallius 2001; Persson et al. 2003; Suominen 2003; Paper II). In the future, the amount of small quarries will probably decrease due to increasing quality demands of aggregates, standardised testing, and productivity demands of aggregate production. It is easier to meet the environmental and production criteria in a large quarry. According to Suominen (2003), it is possible that some large quarries in Finland will be excavated underground in order to reduce environmental hazards, as for example in the USA; the increased costs of additional reinforcement for a certain end-use have to be taken into account.

While this study was carried out, European standards and directives were intensively substituting many national standards and recommendations. These standards have been implemented by CEN (Comité Européen de Normalisation, European Committee for Standardization). The standards have been developed for production control and products, such as aggregates, to set convergent quality criteria for construction materials, so that construction materials that are tested according to the harmonised standards can be transported and used in all EU countries.

According to new production standards (e.g. CEN 2002, EN 13043), the aggregate producer needs to assess the nature of the raw material. For evaluation of conformity of aggregate products, the producer shall undertake initial type testing and factory production control. This can be implemented only by geology-based production of aggregates. In Finland quarrying has generally been based on the average quality of rocks, because geological mapping of quarries has not previously been required. It is possible to perform selective quarrying in geologically variable areas where rock units are sufficiently large, logistically attainable, and separable. Operational problems can occur unless the quarry plan is based on detailed geological mapping.

Directives are also implemented to protect people from unwanted health effects and environmental hazards. European Council Directive (1999/30/EC) defines new European limiting values for PM_{10} (thoracic particles <10 µm) concentrations in the air. In Finland this directive is of current interest during springtime dust episodes that mainly originate from resuspension particles from wearing of asphalt and anti-skid aggregates (Kukkonen et al. 1999; Pakkanen et al. 2001; Räisänen et al. 2002, 2004a and 2004b; Kupiainen et al. 2003 and 2004; Tervahattu et al. 2004; Papers IV and V). During crushing and handling of rock, large amounts of dust can rise into the air. This dust may contain harmful minerals, such as asbestos and quartz, and, therefore, the concentration, composition, and size distribution of dust should be monitored at appropriate intervals during major rock handling operations (Junttila et al. 1994). Fibrous silicates are found in metamorphic mafic-ultramafic rocks. The particle size of amphibole and serpentine asbestos minerals have the following shape and size criteria: the thickness of asbestos mineral needle must be < 3 µm, length > 5 µm, and length/thickness ratio > 3 (Valtioneuvoston päätös 1380/94).

The correlation between mechanical and petrographical properties from various rock types has been studied in numerous investigations using various methods (e.g. Irfan and Dearman 1978; Brattli 1992; Shea and Kronenberg 1993; Ersoy and Waller 1995; Vallius 1995; Tugrul and Zarif 1999; Åkesson et al. 2001; Åkesson et al. 2003). Because petrographical properties vary significantly, and various properties can have opposite effects on mechanical properties, additional studies are still needed. Mechanical tests are the key method when the quality of aggregates is defined. However, petrographical information assists in understanding the mechanical test results and in quality estimation of aggregates, and it is essential when bedrock quarrying and crushing are being planned and performed. This holds true even for laboratory crushing.

This study consists of various sub-studies focusing *from outcrops to dust*. The studies bring new data on the relationships between mechanical-physical properties of aggregates and petrographical rock characteristics. The results of this study emphasise that detailed geological mapping and petrographical analyses assist in all stages of aggregate production (exploration, quality assessment, initial testing, extraction permit procedure, quarrying and crushing, factory production control, and end-use). Determination of petrographical properties helps to understand the behaviour of various materials in mechanical tests, which can further help to develop improved test methods. Although standardised European test methods have been implemented for many types of aggregates, modifications of test methods are still needed, for example, for aggregates with different particle sizes. However, even though standardised tests are a key method in aggregate research, they do not necessarily correlate with properties of aggregates in construction applications in practice. Understanding of these factors is vital when the functionality of an aggregate in an end-use application is evaluated. This study also evaluates the current research methods and quality assessment of aggregates, and suggests improvements and modifications in order to promote the use of aggregate reserves according to principles of sustainable development.

This study includes petrographical studies (texture and modal composition of aggregates) and mechanical tests (resistance to fragmentation and abrasion), and is composed of five papers: *Paper I,* petrographical and mechanical properties of aggregates in a geological formation; *Paper II,* selective quarrying in a geologically heterogeneous quarry; *Paper III,* laboratory crushing and testing aggregates; *Papers IV and V,* quality of anti-skid and asphalt aggregates, and formation of urban dust.

2 Methods

A major part of this study involves testing of raw materials and non-standardised aggregates. Recommendations of national organisations have been used, if European Standards were not available.

2.1 Sampling

Samples for this study have been collected from various geological environments. In total, 190-200 polished thin sections were studied. One sample for mechanical-physical tests weights > 50 kg and this study includes 90-100 of such. Polished thin sections have been made from all of these. Sampling sites were selected after detailed geological mapping in order to secure representative sampling of raw materials and aggregate products. Rock samples were taken from locations near the quarry face, road cuttings, outcrops, and products. Weathered surfaces were removed, because they do not represent the bulk of the rock material. In this comparative study of petrographical and mechanical properties the importance of representative sampling for both thin sections and mechanical-physical tests cannot be overemphasised. The main criteria for all test samples were homogeneity and soundness (lack of micro-cracks). According to Jern (2001), the damage zone of blast holes can be up to 3 m for some rock types. When explosives were used I this study, the test material was collected so that the samples contained no evident blast hole remnants. Dust samples were collected with a high-volume particle sampler (PM_{10} –gravimetric Wedding & Associates).

2.2 Crushing and size reduction

A hydraulic press was used to reduce the size of boulders in order to obtain material that could be crushed with laboratory jaw crushers and then tested with mechanical tests. Laboratory crushing is not a standardised procedure, even though many products need to be tested from laboratory-crushed samples. For example, large end-products, such as armourstones, need to be crushed prior to the testing (CEN 2002, EN 13383-1). According to this standard, laboratory crushing must be carried out with a laboratory jaw crusher, and flaky particles must be removed with bar sieves. This way the effect of particle shape on mechanical properties can be lowered. The standard does not define the crushing method in detail. According to Vallius (1995), crushing method has a great influence on the shape of aggregates, and, therefore, on the fragmentation resistance as well. In this study, crushing was carried out in two stages; the second stage by choke-feeding the crusher.

2.3 Testing

Samples were reduced in size according to CEN (1999, EN 932-2), and sieved according to CEN (1997a, EN 933-1). Samples were homogenised by removing weathering surfaces and other heterogeneities.

The flakiness index, which describes the shape of particles, was measured according to CEN (1997b, EN 933-3), and is reported as the transmission percentage of flaky particles. In the test the particles are either flaky or not, and, therefore, the degree of flakiness is not described and the surface roughness is not determined.

Tests to determine the resistance to wear from studded tyres were performed according to CEN (1998a, EN 1097-9) and according to the Finnish national method (PANK 1995, PANK-2207). The latter method is intended for testing raw materials and is run using a bar-sieved sample. The Los Angeles test (CEN 1998b, EN 1097-2) determines the resistance of an aggregate to fragmentation.

2.4 Petrography and compositional analyses

The modal composition and the textural properties of rocks were determined with a polarising microscope in transmitted and in reflected light. A scanning electron microscope (SEM-ZEISS DSM 962) coupled to an energy dispersive X-ray microanalyser (EDX-LINK ISIS with ZAF-4 measuring programme) was used for identifying mineral compositions from rock and dust samples in anti-skid aggregate studies. The single particle analysing method is described in Kupiainen et al. (2003), and Papers IV and V. XRD (X-Ray Diffraction) was also used in mineral identification.

3 Review of papers

3.1 Paper I

This paper focused on relationships between petrographical and mechanical properties of rock aggregate raw materials from the unmetamorphosed Jaala-Iitti complex, which is a subvolcanic rapakivi granite intrusion. Rapakivi granites are common in southern Finland, but the hybridised Jaala-Iitti complex is of an exceptional type (Salonsaari 1995). The Jaala-Iitti complex was an ideal study area for rock aggregates and for their mechanical properties, because it consists of several isotropic granite types with distinct modal compositions and grain boundary textures. Therefore, anisotropic weaknesses did not have an influence on the results. The study is based on point counting analyses of modal composition, grain size distribution, average grain size, and especially the dispersion of quartz, hornblende, and biotite. These, and other petrographical properties, were compared with the mechanical properties of rock aggregates from the Jaala-Iitti complex.

Rocks with different modal compositions are likely to have different mechanical properties due to the various physical characteristics of minerals, but variations in the modal composition typically reflect changes in the texture of rock as well. Therefore, it is crucial to quantify both textural and compositional properties. Overall, the abundance of fine-grained matrix minerals (especially of hornblende), grain size distribution, spatial dispersion of hornblende crystals, and intense micrographic intergrowth texture with interlocking grain boundaries were found to have the greatest influence on the mechanical properties. Furthermore, Fe-Mg minerals have strong influence in resistance to fragmentation, because these minerals can form complex grain boundaries and/or interlocking textures in rocks. In small quantities, Fe-Mg minerals can also have a positive impact on the resistance to abrasion despite their relatively low hardness. The reason for this is that these minerals can prevent breakage of aggregates, and, therefore, decelerate the formation of specific surface area (abrasive area) of aggregates.

Hybridisation between mafic and felsic melts has led to complex microtextures and to decreased grain size in the Jaala-Iitti complex (Salonsaari 1995). Accordingly, hybridised rocks have more resistant mechanical properties than non-hybridised hornblende granites. The results demonstrated the suitability of hybridised rocks as raw materials for high quality aggregates that can resist fragmentation and abrasion. Aggregates from the Jaala-Iitti complex are an excellent source of aggregates for high-speed roads and railway ballast. They have great local importance.

Quantifying petrographic examination of thin sections can give a more reliable estimate of the durability of rocks than a macroscopic study or a single mechanical test. The present study shows how quantitative petrography with optical microscopy can assist in aggregate quality assessment and exploration of aggregates. It also helps to describe petrographical properties of aggregates and to interpret the results of mechanical tests (resistance to fragmentation and abrasion), and to assess their validity.

3.2 Paper II

In Finland, quarrying is generally based on the average quality of rocks, because geological mapping of quarries has not previously been required. According to the new product standards (e.g. CEN 2002, EN 13043), an aggregate producer needs to assess the nature of the aggregate raw materials. Geological mapping of quarries is an important part of initial type testing and factory production control. It also facilitates selective quarrying in areas where rock units are sufficiently large, logistically attainable, and separable. Operational problems can occur unless the quarry plan is based on detailed geological mapping. This study draws attention to the importance of detailed quality assessment of rock quarries.

This case study on the Pirkanmaa quarry draws attention to the importance of detailed quality assessment of rock quarries. It is a part of a larger study in which geological mapping and quality assessment of five quarries were carried out and was performed in an area where metamorphosed supracrustal rocks prevail. The original quarry planning was not based on geological units. Our quality assessment was done about five years after the opening of the quarry. The intention was to help to stabilise aggregate production and to determine, if it was possible to produce a wider quality-range of aggregates from the same quarry for various construction purposes. The assessment of each rock unit was based on texture, mineralogy, and mechanical-physical properties.

Our results indicated that the Pirkanmaa quarry consists of a number of rock units that are large enough to be extracted separately. Therefore, aggregates for various end-use applications can be quarried according to the market demand. On one hand, abrasion and fragmentation resistant aggregates are available, for example, for asphalt pavements of heavily trafficked roads or for railway ballast. On the other hand, mica-rich aggregates with low resistance to abrasion and high weathering susceptibility are good as maintenance aggregates of gravel roads. Unless, selective quarrying is applied at the Pirkanmaa quarry, aggregates from various rock units may be mixed. This will have an effect on the average quality of aggregates produced, and it can also lower the lifetime of the end-use application. For example, pyrrhotite-bearing aggregates are likely to weather rapidly and, if mixed with carbonate bearing aggregates, can react to form sulphates. This may cause deterioration of, for example, the un-bound base course layer of a road. We concluded that, the quarrying stages and the direction of extraction should be changed, and, therefore, new extraction permits should be applied for. The quarry can become economically more profitable, if quarry planning and extraction are based on detailed geological data.

In Finland, 10-year extraction permits are most common. They demand extraction and rehabilitation in stages which are defined when the extraction permit is applied for. Due to communal decision-making, it is difficult to change accepted extraction plans. Detailed geological mapping is difficult to perform in areas covered with topsoil and vegetation, because removal of the topsoil from the whole extraction permit area is not allowed. Therefore, the permit procedure that has been developed to help to protect the environment can have opposite effects in geologically heterogeneous areas. We argue that this undermines sustainable use of aggregates.

It is possible to utilise aggregate resources in a cost-effective way so that high-quality aggregates are not used for applications in which low-quality aggregates are satisfactory. Geology-based quarry planning and mapping demand removal of the topsoil layer from a large area during quarry planning and extraction, marking of geological units, and careful planning of blasting and crushing. Our study demonstrates that in geologically heterogeneous areas quarrying should be based on the local geology for two reasons. First, it is possible to produce a wider range of aggregate products for different construction purposes from the same quarry, and, therefore, obtain maximal profits from production during the whole life span of the quarry. Second, the crushing process can be more stable and more easily adjustable, the capacity can be higher, good shape properties of aggregates can be more easily achieved, the amount of fines can be minimised, and unexpected changes in quality of aggregates can be prevented.

3.3 Paper III

This paper deals with laboratory rock crushing and testing of aggregate raw materials. It also describes the crushing procedure of tested aggregates reported in Papers I and II. The aim of this study was to show the importance of the procedure of non-standardised laboratory crushing in testing raw materials, because EN standards are applied to test products, not raw materials. Geological properties are decisive in rock comminution (Lizotte and Scoble 1994; Briggs and Bearman 1996). Furthermore, the shape properties of laboratory crushed aggregates and the sample preparation can cause variation and uncertainty in the results of mechanical tests. The quality of rock aggregate raw materials is often established using aggregates that have been crushed with a laboratory crusher, even though the EN test standards are intended for testing the products. However, laboratory crushers are not standardised, and there are no official and uniform instructions for laboratory crushing. According to product standards (e.g. CEN 2002, EN 13043), an aggregate producer needs to assess the nature of the raw materials. For evaluation of conformity of aggregate products, the producer must undertake initial type testing and Factory Production Control. The first step in this is detailed geological mapping of quarries followed by laboratory crushing and mechanical testing as part of the initial type testing and quality estimation.

In the present study, we tested three laboratory crushers, a small industrial crusher, and three resistance to wear by abrasion from studded tyres test (A_N test) mills. The aim was to compare the mechanical and shape properties of aggregates produced with different laboratory crushers. Both bar-sieved and normal samples were tested.

The results of this study indicate that the standard deviation of the A_N test for different crushers is lower with bar-sieved samples than with normally sieved samples. The results of the bar-sieved samples give a minimum A_N test value. The flakiness index determined from the A_N test specimens provides a quality control between test specimens, and its effect on mechanical properties of aggregates on each rock type can be used in quality evaluation. We also found out that a low-powered laboratory crusher with close setting cannot crush high-quality rock aggregate materials efficiently; they can produce aggregate particles, which are too rounded. Overall, when the quality of aggregate raw materials is evaluated using tests that are designated only for products, the shape properties of aggregates have to be considered. The reason for this is that different types of laboratory crushers have different types of crushing parts, and they are in various running conditions and settings. It is vital that the setting of laboratory crushers is adjustable, and it should be just above the required particle size of a particular mechanical test. Otherwise, the grading and amount of flaky particles of test material can be non-representative. Therefore, we call for standardisation of laboratory crushing in order to minimise uncertainties of mechanical tests of aggregates.

3.4 Paper IV

It has been generally accepted in the Nordic countries, Japan, and North America that studded tyres and anti-skid aggregates are mainly responsible for formation of inorganic urban dust. However, studies on the cause of urban dust are usually focused on either anti-skid aggregates or on studded tyres. In the present study, both factors have been considered. This study is part of a project consisting of three stages. The first stage is reported in this paper, and the second and third stages in Paper V. The main theme of these studies is: “Dust formation at tyre - pavement interface with various anti-skid materials and tyre types under test conditions”. The aim of these studies was to find out which properties of aggregates affect the formation and concentration of PM_{10} mineral dust in urban areas, and to find out whether the composition and amount of urban dust can be controlled by the right selection of aggregates.

We investigated the effect of the particle size distribution, mechanical-physical properties and petrography of rock and blast furnace slag aggregates on the generation of urban dust. We spread anti-skid aggregates on the asphalt pavement of a road simulator. The asphalt pavement was made up of homogeneous rock aggregates that were mainly composed of different minerals compared with anti-skid aggregates. Dust was collected from the ambient air. The particle size distribution and the proportions of dust from the pavement and the anti-skid aggregate were analysed with a scanning electron microscope coupled with an energy dispersive X-ray microanalyser by single particle analysis.

In our study, PM_{10} consisted mainly of particles generated by wearing of the anti-skid and asphalt aggregates. The anti-skid aggregate is worn at the tyre-road interface and the asphalt pavement is worn both by studs and by mineral material originating from the anti-skid aggregate and the pavement surface. The wear on the asphalt pavement depends on the tyre types used, properties of the anti-skid and asphalt aggregates (particle size distribution, mechanical-physical and textural properties), pavement surface condition (wet or dry), and traffic (volume and speed).

According to this study, proper aggregate selection can assist to decrease the total amount of urban dust and concentration of potentially harmful minerals. The 0/2 mm fraction should be wet-screened from anti-skid aggregates that are used in densely populated areas. Furthermore, the successive particle breakage into smaller particles with more wearing surface can be minimized by using anti-skid aggregates with good resistance to fragmentation. Therefore, anti-skid aggregates, which have poor resistance to fragmentation and contain mainly hard minerals (for example medium to coarse-grained granites), should be used with caution in densely populated areas. They are likely to break down and form fine-grained particles with high specific surface area; such particles can be abraded and can also wear the pavement.

The present study also claims that anti-skid aggregates should be classified according to their quality and the location of use. In order to be able to test the product, the anti-skid aggregate, new modifications for EN standard testing methods for mechanical properties need to be developed for finer particle size aggregates, because the correlation between mechanical properties and test fractions with different particle size distribution is not linear. Our results bring new information on the formation process of dust particles, and can assist to determine cost-effective means to decrease urban road dust concentrations in the air and the negative health effects, and discomfort factors caused by urban road dust.

3.5 Paper V

This paper reports the second and third stages of the anti-skid aggregate studies with a road simulator and is a continuation of Paper IV. Additional anti-skid aggregates were tested and the asphalt pavement of the road simulator was changed in order to test previous results and to determine (1) the effect of modal composition of asphalt aggregates on the formation of urban road dust and (2) source contributions of dust from asphalt and anti-skid aggregates.

This study focused on the particle size distribution of anti-skid aggregates and on new anti-skid aggregates with varying mechanical properties and origin (glaciofluvial and crushed rock). Comparison between two asphalt aggregates was also carried out. Our results lend support to the conclusions in Paper IV. Anti-skid aggregates which contained a fine fraction, produced a clearly higher amount of dust under test conditions than the wet-screened anti-skid aggregates. Successive breakage of particles into smaller particles with more wearing surface and the consequent increase of mineral dust in the air can be minimized by using wet-screened (2mm) anti-skid aggregates with good resistance to fragmentation. Kanzaki and Fukuda (1993) and Lindgren (1998) state that asphalt-originated particles act as grinding material. Therefore, the grading and the amount of fine fraction (0/1 mm and 1/2 mm fractions) are crucial, because anti-skid aggregate particles wear the pavement and are worn themselves. The importance of anti-skid aggregate grading is more pronounced with larger anti-skid material amounts. Räisänen et al. (2004a and 2004b) verified the importance of the anti-skid aggregate grading on the formation of urban dust in practice. This study was performed in actual conditions, and it was also based on single particle analysis.

Glaciofluvial anti-skid aggregates, which are often medium- to coarse-grained granitic rocks, were tested because they are widely used in Finland. Such granitic rocks often have a poor resistance to fragmentation (cf. Paper IV), and, therefore, the results of our study indicate that the use of glaciofluvial materials as anti-skid aggregates should be carefully considered in inhabited areas. We argue that if these aggregates are used, they should be wet-screened, and their resistance to fragmentation should be defined. As emphasised in Paper IV, new standardised testing method modifications for anti-skid aggregates are needed.

The PM_{10} concentrations were lower in test series with asphalt pavement made using fine-grained Pernaja granite compared to asphalt pavement made using mafic volcanic rock. Both of these asphalt aggregates have good resistance to fragmentation and to abrasive wear by studded tyres, but their modal compositions are quite different. The average hardness of the Pernaja granite is higher compared with that of the mafic volcanic rock. Furthermore, we found that the relative proportions of minerals in anti-skid and asphalt aggregates were not the same as in the PM_{10} dust. Due to higher average hardness of the quartz-rich asphalt pavement (stage III) compared with the hornblende-rich asphalt pavement (stage I and II), stage III asphalt pavement was not worn homogeneously. Heterogeneities were observed between quartz and alkali feldspar concentrations in the PM_{10}.

4 Summary

4.1 Conclusions

This study of aggregates from outcrops to dust leads to the following conclusions:

1. In the Jaala-Iitti complex, hybridisation between mafic and felsic melts has locally formed complex microtextures, whereupon the grain size has decreased and mechanical strength of the rock has increased. Abundance of fine-grained matrix minerals (especially hornblende), grain size distribution, uniform spatial dispersion of hornblende crystals, and intense micrographic intergrowth texture with interlocking grain boundaries were found to have the greatest influence on the mechanical properties of aggregates. Fe-Mg minerals have formed complex grain boundaries and interlocking textures that markedly increase resistance to fragmentation. Hybridised rocks are a potential source of high-quality aggregates that can resist fragmentation and abrasion as well.

2. The mechanical test result values of aggregates are affected, besides petrographical properties of aggregates, also by the size, shape, and surface roughness of the aggregate particles tested. However, the relationships are complex. For example, the shape of the aggregate particles is partly dependent on mechanical-petrographical properties of aggregates and rock disintegration. The particle size of test material has a great influence on the mechanical test results, but the correlation between these factors is non-linear.

3. In geologically heterogeneous areas, sustainable use of aggregates is undermined by the current extraction permit procedure that often demands definition of the direction of extraction before detailed geological mapping has been completed. When an extraction plan is based on the prevailing geology, it is possible to produce a wider range of aggregate products from the same quarry for different construction purposes during the whole life span of a quarry, and the crushing process can be more easily adjusted. The running conditions of a quarry can become more profitable, when quarry planning and extraction is based on geological data.

4. Rock properties (composition, texture, size, and shape) and laboratory crusher properties (type, capacity, setting, and running condition) affect the shape and mechanical properties of aggregates, and hence, the quality assessment of aggregate raw-materials.

5. By using high-quality anti-skid aggregates it is possible to reduce the amount of urban dust. Overall, the 0/2 mm fraction should be wet-screened from high-quality anti-skid aggregates that are used in populated areas, because fine-grained anti-skid aggregate particles increase the formation of dust both from anti-skid aggregates and from asphalt aggregates. Furthermore, the successive particle breakage into smaller particles with more wearing surface can be minimised by using anti-skid aggregates with good resistance to fragmentation. The importance of fragmentation resistance of anti-skid aggregates is emphasised with anti-skid materials that have high average hardness.

6. Our road simulator tests indicate that the wearing process of aggregates is not homogeneous. The relative proportions of minerals in anti-skid and asphalt aggregates were not the same as their proportions in the PM_{10} dust. This was recorded in tests with various anti-skid aggregates and without anti-skid aggregates, and with various tyre types (studded and friction tires).

4.2 Recommendations for practice

1. The procedure for *simplified petrographic description* is described by CEN (1996, EN 932-3). The standard is used when initial type testing is carried out at quarries. This EN standard is inadequate; it does not require thin section studies, which means that modal composition, texture, weathering susceptibility, identification of sulphide and asbestos minerals, alkali-silica reactivity etc. cannot be estimated or defined. However, thin section studies are currently included in the *petrographic*

examination standard for natural stones (CEN 2000, EN 12407). Given that the results of thin section studies can give an assessment of aggregate performance in mechanical tests and in various end-use applications of aggregates, this standard could be applied also for aggregates to update the standard to "petrographic examination of aggregates".

2. In Finland, the communal permit procedures for aggregate extraction should be changed. The geological constraints need to be taken more fully into account when the extraction permit is applied for and in the production of aggregates. Furthermore, extension of the validity of larger extraction permits, for example to 20 years, would help to establish factory-type production areas. In the long run, it would also favour sustainable use of aggregates and assist in production and environmental planning.

3. Geological data should be more extensively utilised in aggregate exploration both on local and on regional scale. For example, the reports on a contact aureole and roof pendants in the Wiborg rapakivi granite massive (Vorma 1972, Vorma 1975) led to the discovery of the Pernaja quarry area in the beginning of this study in 1999. As a result, the Pernaja quarry was established in 2000 and, currently, it produces high-quality asphalt aggregates and railway ballast.

4. The particle shape of laboratory-crushed aggregates should always be determined. The flakiness index determined from the A_N test specimens can act as quality control between the test specimens. A European working group on laboratory crushing (including detailed descriptions of used laboratory crushers) and testing raw-materials should be established in order to set international directions for laboratory crushing. This is of great importance in the initial testing, in evaluation of aggregate reserves and raw materials, and in testing large sized end-products, such as armourstones or large sized side-products of dimension stone quarries.

5. Proper aggregate selection can assist in decreasing the amount of urban dust. Wet-screened (2mm) aggregates that have high resistance to fragmentation should be used as anti-skid aggregates in populated areas. For example, the 1/4 mm (1-4 mm) anti-skid aggregates that are used in Helsinki city can have up to 50 % < 2 mm particles. Poor resistance to fragmentation of this anti-skid aggregate emphasises the need for improvements of aggregates in use. Our results from anti-skid aggregate studies (the characteristics of road dust formation in test conditions) can be used in practice to help to determine cost-effective means of lowering the urban road dust emissions, negative health effects, and discomfort factors caused by urban road dust.

6. Standardised testing method modifications and quality criteria are needed for anti-skid aggregates as well as for many other yet non-standardised aggregates.

7. The use of salt for winter maintenance causes wet conditions, and a wet asphalt pavement is worn substantially faster than a dry one (Folkeson 1992). A mixture of water and asphalt-originated mineral particles acts as grinding material and enhances the wearing process of the asphalt pavements and the formation of dust. If salt is used as the main anti-skid method close to densely populated areas (for example, on the motorways of Helsinki and Espoo), intensive spring-cleaning of these roads is required to lower the amount of urban dust. The cleaning costs should be recognized as unavoidable expenses related to the using of salt.

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