Binder performance and testing

Particle Emission and Dispersion Test for the Early Planning Stage: New and Advanced Wear Measurement Technique for Characterization of Environmental Impacts of Roads

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Abstract

In modern times,the awareness around the impact of aerosols and nanoparticles on human health and the general ecosystem is growing. Due to this, it is becoming increasingly important to understand, isolate and study the source and dispersion of such particles into air, water and soil. There is extensive ongoing research in this field,to study the real time evolution of such particles from railway tunnels and roadways infrastructures. Although these existing techniques could be powerful tools in measuring the amount of such particles,they are time dependent and unable to identify the source of particle formation. In fact, particles can be discharged from various sources such as tires, exhaust gases, weather events, thereby reducing the ability and accuracy of existing systems to isolate and study the effects of surface abrasion. The proposed characterization technique offers an innovative and novel tool to investigate the effects of surficial abrasion from roads and predict the impact of bituminous materials, aggregates, microfillers and nanofillers on the general ecosystem and human health. The technique provides the ability to experimentally predict the effects of the aforementioned categories of materials in various dispersion mediums. The technique helps estimate the a)Loss of material from surface abrasion, b)Structural stability and integrity of the designed composition, c)The behavior of the material in various environmental and climatic conditions. Thus, providing road-engineers with additional material-indices for responsible road infrastructure design. This is achieved by providing a deeper understanding about the impact of material used on the environment and the responsible utilization and limitations of the material. The proposed technique works by generating, diffusing, isolating and analyzing the particles from specimens. Hence, unlike many existing techniques that require the road infrastructure to be present and functioning, the proposed technique helps isolate and predict the impact of materials during the planning and design phase of roads.

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1. Introduction

Every year about hundreds of tons of road dust is directly formed in the Nordic countries because of the abrasion of the road surface by studded tires [M Gustafsson, 1]. Winter and early spring are the time that the highest concentration of the road dust is recorded in urban areas, and often during these periods the concentration reaches the threshold level of the regulation for air quality. Owing to high concentration, the exposure to such dust has shown to have adverse health effects on the respiratory system and may cause premature death [2, 3]. As a result, various innovations and strategies were introduced over time to decrease the intensity of the road dust. The introduction of wear resistance pavements to studded tires showed to be an effective way to reduce the intensity of wear by studded tires [4]. Besides, tighter regulations have been sets in the past years by the governments to further control the dust (e.g., introducing low-emission zones, seasonal restrictions, and fee/tax implementation) [5].

Over the years there have been numerous publications that focused on road dust or generally on particle emission. If these publications were to be divided into categorizes based on the methods of study or equivalent laboratory characterization techniques, the publications can be broadly categorized into 2 approaches, as shown in Figure 1. First category in the figure involves bottom-up method of understanding the behavior and response of materials that are under tribological interactions. In engineering, tribology is defined as the field of engineering that studies friction, wear and lubrication of bodies in relative motion. Tribological techniques involve the replication of real frictional condition in laboratories. Techniques such as adhesion meter, pin-on-disk tribometer, ball-on-disk tribometer, DSR (dynamic shear rheometer) can be categories as potential techniques.

It is evident from the figure that environmental studies and impact of emissions are fairly complex in nature, and the original effects from road surfaces are combined with other sources of emissions. These studies that involve isolating individual effects from a compressive system falls into the second category of top-down research. Top-down studies are often performed using mass spectrometers, particle size analyzers, atomic absorption spectroscopy, X-ray fluorescence, atomic emission spectroscope, x-ray diffraction and small angle x-ray/neutron scattering [6]. Although techniques such as the ones mentioned could be both qualitative and quantitively in nature, the technique alone does not yield quantitively data. As a consequence, the results can be determined only when they are calibrated against set standards or benchmarks. In many such environmental tests, the samples are collected from sites, rather than being generated in labs. In such cases, samples are collected from certain sites by means of different techniques (e.g., vacuuming and sweeping) and then analyzed in-site or in labs. However, the collected samples from the sites carry various uncertainties that add to the complexity of the result since other sources of particle emissions and detachments can play a role in the production of the final test sample. So, the results from spectroscopy and diffractions alone cannot provide information about the individual sources of particles but rather the overall information of the final sample, irrespective of its origin, production mechanism behavior in isolation [7].

This paper the propose a simple modification to a tribometer that could help bridge the evident gap that is exist in the approach used in environmental studies

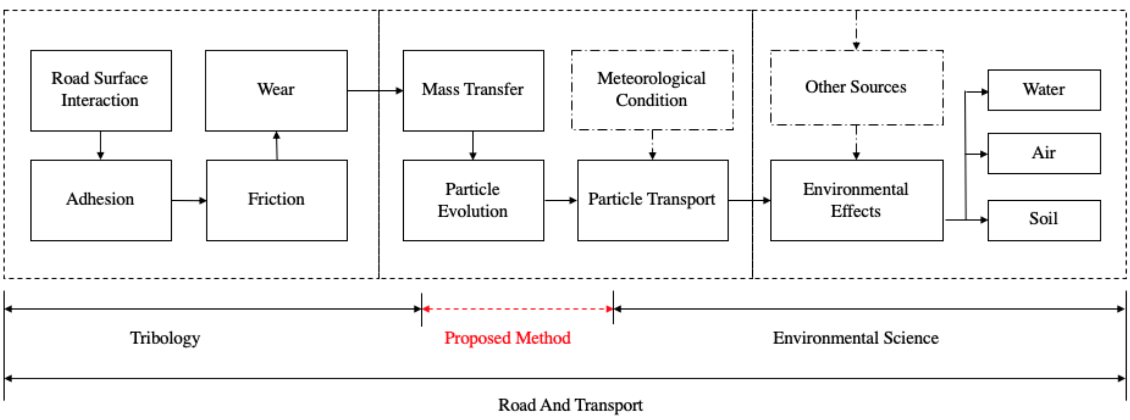


Figure 1: Holistic view of top-down and bottom-up categorization of publications that have contributed to the field of particle emission and the visible gap in the area of scientific reporting.

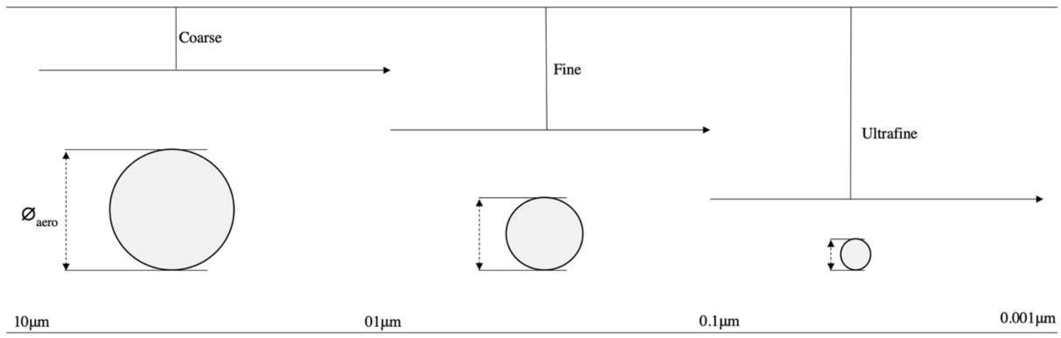


Figure 2: -Method to classify particulate matter based on the particle aerodynamic diameter.

of roads. To express the potential of the proposed modification, firstly a tribometer must be studied closely from an environmental perspective and how a modified tribometer becomes a prime candidate for studying roads. This would be performed through discussions of the merits and opportunities of adapting the characterization techniques for the field of road engineering, from a design and environment perspective.

1. Tribology and Particle Dislocation

Research led by Myshkin et al. [8] and Yoshizava et al. [9], studied the mechanism of adhesion, friction and mass-transfer in polymers. Myshkin, N.K and team performed a study on mechanistic scale, to understand the different friction-load mechanisms of polymers such as PMMA, PS, PTFE, PE and PC. Yoshizava and team performed a similar yet deeper study at a molecular scale to gain a better understanding of the behavior of monolayer surface of amorphous and liquid surfaces. In the both paper the teams studies the effect of various engineering factors on the phase transformation of polymers under the effect of temperature, loads, sliding velocities, and moisture. Others including the aforementioned, describe the underlying wear mechanisms of polymers as an influence of the above factors, and their effects on the phase transformation and the tribo-chemical changes on surfaces of polymeric materials during interactions [10-13]. Kaláska [14] displayed these theories through experimental methods. In the paper the author utilized a pin-on-disc tribometers to test the wear mechanism of 21 polymers and polymer composites. They demonstrated that the tribological behavior of the composites and the parent matrix (polymers) can be measured in a laboratory using a tribometer.

The same was displayed by researchers on other materials such as ceramics, metals and fluids [15-19]. Such tests show the dependents of all family of materials on time, temperature, sliding velocity and loads. Although the authors have utilized the potential of such techniques to understand the effect of external parameters on materials, researchers often concentrate on the wear surface rather than the emitted particles. The particles generated during these experiments is a direct product of mass-transfer during friction in a tribological study.

This often-overlook product has major significance in studying and understating the effects of particulate matter. These particles that are emitted from tribological studies contribute to the production of coarse, fine and ultrafine particulate matter. Particulate matter generated from road can be of various sizes, concentrations, shape and also chemical structure. Hence, the best method to follow is to organize them as per their aerodynamic diameter. According to aerosol definitions, aerodynamic diameter of an irregular particle is the diameter of a sphere particle with a density of 1000 kg/m^3 of the same setting velocity as the irregular particle. As shown in Figure 2 PM_{10} (particle size less than 10 µm) to $PM_{2.5}$ (particle size less than 2.5 µm) fall under such definition.

It is broadly accepted that the major source for particle emissions in urban zones is from the transportation sector. Amongst other sources of emissions are tires, motor components, road surfaces and road markings. Studies suggest that friction between two surfaces such as tire and road causes abrasion and wear of asphalt surface and cause the generation, transportation and increase of particles such as PM_{10}. Many scientific studies that suggest that such particles could pose a serious risk to human health [20].

Tribology is the field of engineering that studies friction, wear and lubrication of bodies in relative motion. In a road setting asphalt, vehicular breaks

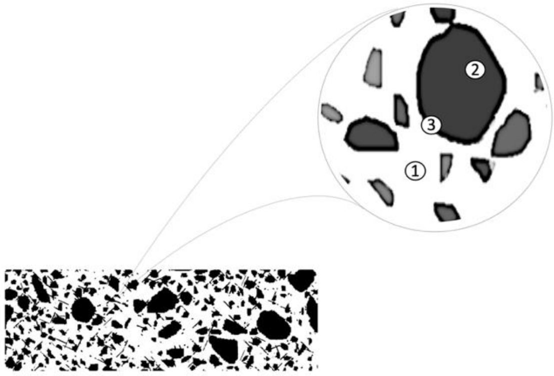


Figure 3: Cross section of the surface of asphalt pavement. 1). Bitumen 2). Aggregate and 3). Interface

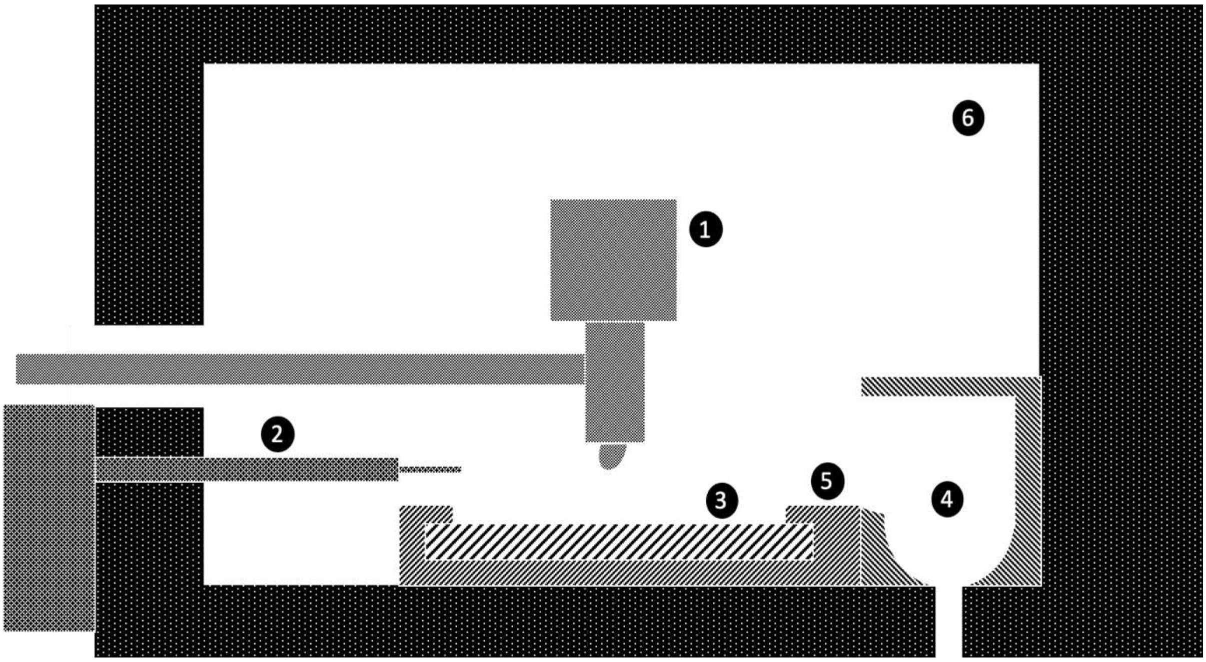
and tires are entangled in a tribological cycle of adhesion and deformation that ultimately leads to the wear of all three materials and cause the evolution of particles. Friction between surfaces such as tire and road or tire and break can cause abrasion, this leads to the wear. If the wear mechanism of asphalt surfaces were to be isolated, some of the major influencing factors that contribute to this wear mechanism are traffic volume, tire texture, vehicle speed, weight, pavement wear characteristics and weather.

3. Tribological behavior of asphalt

When studying the structural integrity (microstructural) and generation of particles in asphalt there are three regions of interest, i.e. matrix, filler and interface, as shown in Figure 3. Asphalt comprises of 4-6% of bitumen, 90-95% aggregates and other fine particles such as fillers. The percentage of bitumen in asphalt is selected depending on the functional conditions of the road [21]. The primary purpose of bitumen is to act as a glue to hold the aggregates in place. Due to this, in a simplified setting, asphalt can be seen as a composite. With bitumen acting as an organic matrix and aggregates acting as inorganic fillers, where $\varphi_f > \varphi_m$, with φ being the volume fraction and f and m representing the filler and matrix, respectively. In asphalt the failure could occur in three possible stress modes, i.e. tensile, in-plane shear and out-of-plane shear. Depending on the interfacial bonding strength between the matrix and filler, the failure could occur either in the bulk of the matrix or throughout the composite, through the filler. This means that the interfacial qualities of asphalt will determine if the generated fracture will propagate through bitumen into aggregate providing high structural integrity or weather the fracture will pass around the aggregate causing it to detach immediately from the road and propagate into the environment. From earlier discussions it is evident that asphalt is a composite, and this means that similar to conventional composites the overall wear mechanism of an asphalt surface is a collective of independent wear response of the three regions of asphalt. Thus, to understand particle emission from asphalt surface the tribological response of the different regions of asphalt have to be studies separately and in tandem with one another.

3.1 Bitumen

Similar to polymers, bitumen is known to display viscoelastic properties, such as both fluid-like and solid-like behavior. This means that the properties of bitumen are a function of time and temperature, and the material processes a fading memory of the magnitude and frequency of loading conditions it experienced. By this context, on a macroscopic scale, asphalt can be further categorized as a polymeric composite [22]. The viscoelastic properties of bitumen can be divided into five regions, i.e. glassy, transition, rubbery, rubbery-flow and liquid flow. Unlike other polymeric materials, bitumen has a complex chemical structure and thus the existence and influence of the five regions could vary and sometimes even overlap, for different compositions. A good understanding of these five regions in bitumen is essential to predict the structural integrity of the matrix phase of bitumen. One method to study the influence of these regions on the viscoelastic properties of bitumen can be studied using creep compliance. Creep compliance is a slow and progressive deformation of a bitumen under constant load. All polymers creep to a certain degree and this is influenced by the type of polymer, magnitude of load, temperature and time [22, 23]. If bitumen is assumed to have uniform macroscopic properties and the influence of varying chemical composition and complex molecular structure is



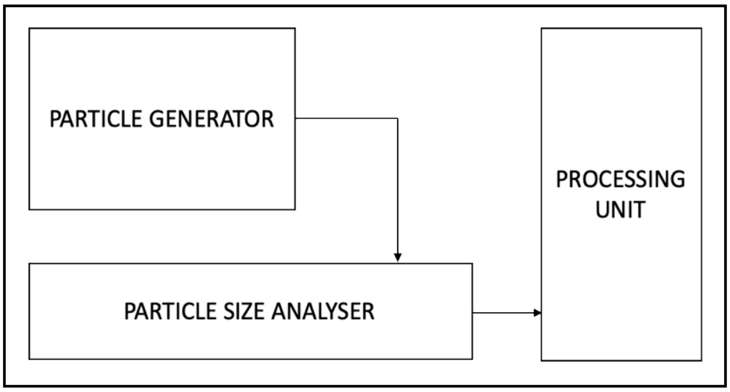


Figure 4A: Proposed design of a particle generator. 1). Pin-on-plate tribological particle generation unit 2). Compressed air outlet 3). Test sample 4). Sample collection and transportation unit 5). Sample holder 6). Controlled chamber. 4B: Schematic representation of an integrated lab setup for a study of particle generation and analysis from roads. The particle generator is connected to a particle size analyzer which will provide information about the physical nature of the particles.

ignored, then the tribological response of the matrix phase of asphalt is purely a function of time, temperature, magnitude and frequency of load during cyclic loading and creep.

3.2 Aggregate

The reinforcement in asphalt is made up of aggregates. Aggregates have a different physical response to load, wear characteristics when compared to bitumen. Aggregates are in general minerals. Minerals are naturally occurring inorganic solids with a defined chemical composition and microstructure. The minerals used in asphalt can be generally categorized into gritstone, limestone, flint, basalt, granite and quartzite. Wear and particle detachment in aggregates have a different mechanism due to their microstructure. In asphalt pavements, wear of aggregates is mainly influenced by the movement of traffic, tires and the sand particles that can be entrapped between the lining of tires. The ability of aggregate to resist wear depends on the gross hardness of the surface that is under tribological interaction. It is widely accepted that aggregates with varying surface hardness have higher resistance to wear when subjected to varying magnitude and frequency of cyclic loading [24].

3.3 Interface

The third and most important region of asphalt is the interface between the matrix and filler. In many polymeric matrices, it is common to have van der walls force and hydrogen bonds in the interface. With the right conditions for phase change, the matrix and filler will join through interfacial attraction and form a stable bond with each other. During frictional force a tangential force is applied on this interfacial bond that is formed between the two materials, and this causes it to break. Factors that affects the strength of the bond or the growth and formation of the fracture at the interface is the surface characteristics and microstructure of the materials [25].

4. Modifying a tribometer into a particle generator

To conduct a successful study to deduce the tribological response of asphalt pavements, all the above-mentioned conditions must be converted into engineering factors such as frequency and magnitude of load, rotational rates, temperature, time and hydration. There are two types of cracks that can propagate in asphalt a) top-down and b) bottom-up. As the names suggest they indicate the direction of the crack propagation. Top-down cracks are those that start off as a surface deformation during loading. In asphalt it is theorized that surface cracks initiate and propagate due to a combination of two stress-modes, i.e. out-of-plane shear and tensile. With shear acting as the dominant mode. The other type of surface cracking is thermal fatigue which is also caused due to interaction of loads. Researchers have found that in thermal fatigue is more influential in crack formation of thin asphalt when compared to thick asphalts. It is evident that particle detachment that leads to environmental emissions is a consequence of top-down cracking of asphalt at a microscopic scale. Myers and De Beer at el. [26], have shown that during loading of asphalt the load is most concentrated on the edge of the tire and that this load extends 10mm into asphalt. These two finds have major significate in tribological studies. This would suggest that to recreate tribological conditions in a laboratory setting a small sample has to be concentrated with high cyclic load at various hygrothermal conditions to observe the surface response of asphalt under tribological conditions. From these engineering factors and the influence of these aforementioned factors on the material properties of asphalt or its parent constituent, will provide a better understanding of the wear characteristics and particle dislocation.

As shown before a tribometer is designed to simulate the external conditions a body or a surface under motion would experience during friction. There exist scientific standards to designing a tribometer. Most importantly ASTM G99-17 and ASTM G133 are aimed for design of pin-on-disc and ball-on-disc tribometers [27, 28]. This is important because protocols provided in standards such as ASTM are designed to produce results with 95% confidence. This number directly reflects on the figures of merit of a characterization technique. Figures of merit are criteria that are set-up ensuring that a result can be replicated across laboratories across the world. They are namely accuracy, precision, repeatability, reproducibility and uncertainty. Thus, the existence of ASTM standards for a tribometer adds to the capability of such a proposed modification. A good example of modifications of a tribometer can be seen in the work by Poulios et al. [29], in the publication the authors designed a reciprocating pin-on-plate design from a conventional pin-on-disc.

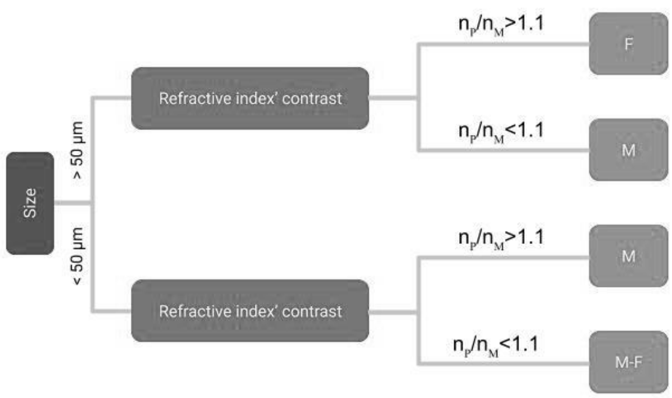


Figure 5: Guidelines for selecting appropriate scattering theory

A particle generator can be designed by modifying a commercially available pin-on-disc tribometer with an air-blower and a collection chamber unit, shown in Figure 4A. A sample of asphalt, bitumen or aggregate can be housed in a hygrothermal chamber and held in place by a sample holder. A probe is selected for the experiment. The selected probe must have a shear modulus greater than that of the sample. During this experiment particles will dislocate from the substance with lower shear modulus. A load would be attached to the probe to simulate the tribological influence of tire and the probe would in a horizontal cyclic motion to simulate that on the surface of the sample. During this interaction particles will be generated as expected in a tribometer. When a source for controlled and compressed air is introduced, it will force the generated particles to flow in the desired direction, causing the particles to collect. Since compressed air will contain water-vapor, this will confine the particles to the surface of the water droplets. This collected sample can be then transferred to a material characterization unit to analyze the content, Figure 4B. Since the particles are generated from a controlled system, with figures of merit, collected particles can be compared with the surface of the sample to verify the mass loss.

The collected sample can be directly transported to the particle analyzer to study the particle size and distribution or to a mass spectroscope to study the chemical composition. Since the composition of bitumen and aggregates can be determined, diffraction is of more interest in this paper and will be discussed in detail. Diffraction techniques are versatile and thus both dry and wet samples can be analyzed in diffraction techniques. To be able to quantify the scattering of a particle during a diffraction, the phase function must be defined. The phase function depends basically on the direction of the incident light and the refractive light; hence, the phase of the scattering depends only on the scattering angle. Therefore, it can be said that the phase function is defined as the angular cross-section per particle, this can be written as 'A'. Particle phase also function depends on the size relative to the wavelength of the incident ray, λ, which intern gives you size particle 'X'. Based on the size particle there are 3 main scattering techniques. When the particle size X >> 1 the principle of scattering is Raylength scattering, but when particles are X = 1 it is Mie scattering and finally when X << 1 the best principle is Fraunhofer diffraction theory [30].

Raylength scattering is used to describe the scattering of the light by a particle smaller than the wavelength of light. In this context the particles could also be the size of atoms or molecules. Raylength scattering is mainly used for gases but is useful to study solids and liquids as well. When the particles studied are similar or exceed the size of the wavelength of light then Raylength scattering cannot be used to describe the particles, instead the Mie scattering serves best. Mie scattering is an analytical solution to particle analysis. Fraunhofer diffraction theory is a simplified version of the diffraction formula provided by Kichoff. It can be used when the light source and viewing phase are both at infinity with comparison to the aperture. Fraunhofer diffraction has a lower precision when compared to Mie scattering. ISO 9276 standard parts 1-5 describe the mathematics and statistical method to choosing the right scattering technique for proposed characterization technique for particle analysis as shown in Figure 5. To cover a wide range of particle sizes a light scattering diffraction technique such as particle size analyzer can be utilized as the technique utilizes a combined Mie-Fraunhofer scattering [31].

5. Conclusion

In the paper the authors propose an adaptation to existing tribometers to utilize the characterization technique to study particle evolution and its environmental impacts. The proposed method is a lab-based technique that can be utilized in the planning phase of road design to generate and understand the influence of various road designs on its nearby environment. The method will help

a. Study the behavior of bitumen, aggregates, interface of asphalt both independently and in a completed road design.
b. Study particles of various pm sizes, ranging from 10µm to 0.001µm.
c. Study surface wear of test samples at various temperatures, loads, load frequencies, moisture and wear mechanisms.

A simplistic design was presented and the potential for an integrated system with a diffraction technique was also discussed.

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7. References

[1] M Gustafsson, Review of Road Wear Emissions, Non-Exhaust Emissions, 2018, pp. 161-181, doi:10.1016/B978-0-12-811770-5.00008-X

[2] K Kupiainen, B R Denby, et al., Road dust and PM 10 in the Nordic countries, Nordic Council Of Ministers, 2017, doi:10.6027/ANP2016-790

[3] B Snilsberg, Pavement wear and airborne dust pollution in Norway, 2008, ISBN: 978-82-471-8706-7

[4] P Bellin, Stone mastic asphalt in Germany, The Institute of Asphalt Technology, 1998, pp. 61-70

[5] Swedish Transport Agency, Low-emission zone, 2019, Available at: https://transportstyrelsen.se/sv/vagtrafik/Miljo/Miljozoner/. (Accessed: 13th August 2019)

[6] R Horn, Modern Methods in Heterogeneous Catalysis Research. [ebook] Dep. of Inorganic Chemistry, Group Functional Characterization, Fritz-Haber-Institute of the Max-Planck-Society, pp.3-5, http://www.fhiberlin.mpg.de/acnew/department/pages/teaching/pages/teaching__wintersemester__2004_2005/horn_analysis_291004.pdf.

[7] N K Myshkin, M I Petrokovets, Tribology of polymers: Adhesion, friction, wear, and mass-transfer, Tribology International, Vol. 38, 2005, pp. 910–921, doi: 10.1016/j.triboint.2005.07.016

[8] H Yoshizawa., Y-L Chen, et al., Fundamental mechanisms of interfacial friction. 1.Relation between Adhesion and Friction., The Journal of Physical Chemistry A, pp. 1993, 4128-4140, doi: 10.1021/j100118a033

[9] J Israelachvili, S Giasson, et al., Some fundamental differences in the adhesion and friction of rough versus smooth surfaces, Tribology Series, Volume 38, 2000, pp. 3-12, doi: 10.1016/S0167-8922(00)80107-8

[10] D-H Choa, B Bhushana, et al., Mechanisms of static and kinetic friction of polypropylene, polyethylene terephthalate, and high-density polyethylene pairs during sliding, Tribology International, Vol. 94, 2016, pp. 165-175, doi: https://doi.org/10.1016/j.triboint.2015.08.027

[11] E Gustafsson, Investigation of friction between plastic parts, Chalmers Reproservice, Vol. 30, 2013, ISSN 1652-8557

[12] E Z Li, W L Guo, Research on Tribological Behavior of PEEK and Glass Fiber Reinforced PEEK Composite, Physics Procedia, Vol. 50, 2013, pp. 453 – 460, doi: 10.1016/j.phpro.2013.11.071

[13] G Kalácska, An engineering approach to dry friction behaviour of numerous engineering plastics with respect to the mechanical properties, eXPRESS Polymer Letters Vol.7(2), 2013, pp. 199–210, doi: 10.3144/expresspolymlett.2013.18

[14] J J Tang, K Liu, et al., The influence of size and distribution of graphite on the friction and wear behavior of Ni–graphite coatings, Technology, Vol. 252, 2014, pp. 48-55, doi: 10.1016/j.surfcoat.2014.04.063

[15] C Novak,D. Kingman, Tribological properties of paraffinic oil with nanodiamond particles, Tribology Transactions , Vol. 57 (15), 2014, pp. 831-837, doi: 10.1080/10402004.2014.916371

[16] M Grandin, Tribology of Metal-Graphite Composites, Acta Universitatis Upsaliensis Uppsala, 2017, pp. 75, ISBN 978-91-513-0079-5

[17] G P Ostermeyer, M Muller,New, Insights into the tribology of brake systems, Proc. IMechE Part D: J. Automobile Engineering, Vol. 222, pp. 1167-1200, doi: 10.1243/09544070JAUTO595

[18] J Keller, V Fridrici, et al., Surface topography and tribology of cast iron in boundary lubrication, Tribology International, Vol. 42, 2009, pp. 1011–1018, doi: 10.1016/j.triboint.2009.02.008

[19] C Muhlfeld, B Rothen-Rutishauser, et al., Interactions of nanoparticles with pulmonary structures and cellular responses, American Journal of Physiology: Lung Cellular and Molecular Physiology, Vol 294, 2008, pp 817–829, doi: 10.1152/ajplung.00442.2007.

[20] B Singh, S Taheri, et al., Estimation of tire–road friction coefficient and its application in chassis control systems, Systems Science and Control Engineering, Vol. 3(1), 2015, pp. 39-61, doi: 10.1080/21642583.2014.985804

[21] R Taylor, G Airey, Rheology of bitumens, Shell handbook, 2015, pp. 123-133, doi: 10.1680/tsbh.58378.119

[22] ASTM D7405-15 Standard Test Method for Multiple Stress Creep and Recovery (MSCR) of Asphalt Binder Using a Dynamic Shear Rheometer, ASTM International, 2015, doi: doi.org/10.1520/D7405-15

[23] R Allen, Aggregates in asphalts, Shell handbook, 2015, pp. 244-247, doi: 10.1680/tsbh.58378.217

[24] Y X Gan, Effect of Interface Structure on Mechanical Properties of Advanced Composite Materials, International Journal of Molecular Sciences, Vol. 10, 2009, pp. 5115-5134; doi:10.3390/ijms10125115

[25] S Xu, K Wang, et al., Influence of Binder Properties on the Performance of Asphalts page, Shell handbook, 2015, pp. 520-522, doi: 10.1680/tsbh.58378.503

[26] ASTM G99-17 Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus, ASTM International, 2017. doi: 10.1520/G0099-17

[27] ASTM G133-05(2016) Standard Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear, ASTM International, 2016. doi: 10.1520/G0133-05R16

[28] K Pouliosa, N Dragob, et al., A reciprocating pin-on-plate test-rig for studying friction materials for holding brakes, Wear, Vol. 311 (1-2), 2014, pp. 40-46, doi: 10.1016/j.wear.2013.12.023

[29] Zi Ye, Measurement of particle size distribution based on Mie scattering theory and Markov chain inversion algorithm, JSW, Vol.7(10), 2012, pp. 2309-2316, doi: http://doi.org/10.4304/jsw.7.10.2309-2316

[30] ISO 13320:2009, Particle size analysis — Laser diffraction methods, ISO, 2009, doi:10.1520/ISO13320:2009