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Stabilitet hos asfaltbeläggningar kornstorleksfördelning

- med inriktning mot inverkan av stenmaterialets

BERNARDITA LIRA

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KTH ROYAL INSTITUTE
OF TECHNOLOGY

Doctoral Thesis in Civil and Architectural Engineering

Influence of aggregates on permanent deformation of asphalt

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Stockholm, Sweden 2020

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ABSTRACT

One of the most common failure modes for asphalt pavements is the occurrence of permanent deformation on the wheel path. This leads to not only other distresses, such as potholes and stripping, but also decreases substantially road safety and increases maintenance costs. Resistance to permanent deformation of asphalt mixtures depends mostly on the aggregates, bitumen and air void content of the mixture. Mineral aggregates are the major component of asphalt mixtures, representing more than 90 % of the weight. The structure formed by the aggregates within the mixture depend highly on the size distribution, shape and texture of the aggregates. To manipulate the characteristics of the mineral aggregates is usually considered the most economical and convenient way to improve asphalt mixture performance.

The study presented in this thesis has investigated the influence of aggregate particles on the resistance to permanent deformation of asphalt mixtures. In the theoretical part, some pre-existing models have been considered and then further developed to obtain a framework able to characterise asphalt mixtures based on their aggregate gradation and relate these properties to performance. In the gradation-based framework two structures are identified: the primary structure, which provides the load-bearing capacity, and the secondary structure, which contributes with stability and durability. The experimental part has focused mainly on testing the assumptions included in the developed framework with regards to aggregates size distribution, gradation, and shape. Two series have been tested, one with varying aggregate gradation and one with varying flakiness index. All bitumen parameters and aggregate source have been kept constant for each series.

Results from the first series show that the aggregate gradation, especially the coarse fraction, has a significant influence on the resistance to permanent deformation as measured with the wheel tracking test. Mixtures where even tested with the cyclic compression test, where results were mostly able to identify good and bad, but no clear relationship to aggregate gradation. In the second series, the influence of particle shape was taken into account by varying the flakiness index of five, otherwise, identical mixtures. Results from the wheel tracking test showed no influence of flakiness index on the resistance to permanent deformation. Additionally, there was no higher breakage observed for the flaky particles than for the non-flaky particles.

The gradation-based framework has been applied using spheres representing aggregate particles. Even though the primary structure showed a certain correlation with permanent deformation, this was not statistically significant. Instead, the empirical findings in this study show a significant linear relationship between resistance to permanent deformation and the total coarse fraction of the mixtures, independent of its flakiness index.

Keywords: Asphalt mixtures, aggregate gradation, aggregate shape, flakiness index, permanent deformation, rutting.

SAMMANFATTNING

Permanenta deformationer är ett av de vanligaste problemen för asfaltsvägar och innebär att trafikrelaterad belastning trycker ihop eller omfördelar asfalten så att spårbildning uppstår vid ytan. Deformationer minskar trafiksäkerheten och ökar kostnaderna för beläggningsunderhåll, och kan även öka risken för andra problem som t.ex. potthål. Resistens mot permanenta deformationer påverkas mest av bitumentyp och halt, stenmaterialets sammansättning och beläggningens hålrumshalt. Stenmaterialet utgör huvudkomponenten i asfaltmassor och omfattar normalt mer än 90 % av vikten. Stenmaterialets struktur i blandningen beror på kornstorleksfördelningen samt form och textur hos partiklarna. Att manipulera egenskaperna hos stenmaterialet, främst fördelningen, anses vanligtvis vara det mest ekonomiska och fördelaktiga sättet att förändra och förbättra asfaltbeläggningars funktion.

Projektet presenterat i denna avhandling har undersökt inverkan av stenmaterialets sammansättning på permanenta deformationer hos bitumenbundna lager. I den teoretiska delen har existerande modeller studerats och vidareutvecklats till en mer generaliserad modell (*gradation-based framework*) i syfte att karaktärisera asfaltbeläggningar baserat på stenmaterialets sammansättning. Parametrarna från modellen har sedan använts för att prediktera provade asfaltbeläggningars funktion. I *gradation-based framework* identifieras två strukturer: den primära strukturen, som ger lastbärande kapacitet, och den sekundära strukturen, som bidrar med stabilitet och hållbarhet. Den experimentella delen har huvudsakligen fokuserat på att prova antagandena i den teoretiska modellen med avseende på kornstorleksfördelning och form. Två serier har testats, en med varierande kornstorleksfördelning och en med varierande flisighetsindex. Alla bitumenparametrar och stenmaterialets ursprung har hållits konstanta i respektive serie.

Resultat från den första provningsserien visar att hela stenmaterialets fördelning, särskilt den grova fraktionen, har ett signifikant inflytande på permanent deformationer mätt med wheel tracking test. Asfaltmassorna testades även med s.k. dynamisk kryp test, där resultaten identifierade bra och dåliga massor, dock utan tydligt samband med kornstorleksfördelningen. I den andra serien beaktades inverkan av partikelform genom att variera flisighetsindex på 5, i övrigt identiska, asfaltmassor. Resultat från wheel tracking test visade inget inflytande från flisighetsindex på resistensen mot permanenta deformationer. Dessutom har de flisiga partiklarna inte gått sönder under blandning och packning mer än de icke-flisiga partiklarna.

Sammanfattningsvis uppvisar den primära strukturen viss korrelation med permanenta deformationer, dock inte statistiskt signifikant. Istället, visar de empiriska resultaten i denna studie en signifikant linjär korrelation mellan resistens mot permanenta deformationer och den totala grova fraktionen av kornkurvan, oberoende av flisighetsindex.

Nyckelord: Asfalt, kornstorleksfördelning, flisighetsindex, permanent deformation, spårbildning.

PREFACE

The work presented in this thesis has been carried out in two stages. The first half was done between 2009 and 2012 at the division of Highway and Railway Engineering at KTH Royal Institute of Technology under the supervision of Professor Björn Birgisson and Docent Denis Jelagin. The second half was carried out between 2016 and 2020 as an industrial doctoral student at NCC Industry AB under the supervision of Docent Jonas Ekblad, Docent Robert Lundström and Professor Stefan Larsson at the department of Soil and Rock Mechanics at KTH Royal Institute of Technology, Sweden.

The Swedish construction industry's organization for research and development (SBUF) and NCC Industry AB are gratefully acknowledged for the financial support of this project.

I would like to express my gratitude to everyone at NCC that has helped or showed interest on my research. Thank you to Kenneth Vikström, Mona Teigen and everyone at the laboratory in Upplands Väsby, especially to Tomas Åström and Hassan Hakim, who have helped and assisted every time I have asked for.

Last but not least, thanks to my family and friends that have had to listen about this project for so many years.

Bernardita Lira

Stockholm, December 2020

SUMMARY OF APPENDED PAPERS

Paper I: Lira, B., Jelagin, D. & Birgisson, B. (2013). Gradation-based framework for asphalt mixture. Published in: Materials and Structures, 46 (8), pages 1401 – 1414

In the present study a generalized framework is developed to identify the range of aggregate sizes which form the load carrying structure in a hot mix asphalt and determine its quality. The method described in this paper is a numerical procedure based on packing theory of spheres. Parameters like porosity and coordination number have been used to evaluate the quality of the load carrying structure and relate it to resistance to rutting. The framework has been compared to the results from known field and laboratory mixtures and related to their rutting performance. The gradation analysis of the mixtures compared favourably with the performances reported from the field and laboratory testing proving to be a good tool to identify mixtures with a poor rutting performance based on the gradation of the aggregates.

Paper II: Lira, B., Jelagin, D. & Birgisson, B. (2015). Binder distribution model for asphalt mixtures based on packing of the primary structure. Published in: International Journal of Pavement Engineering, 16(2), pages 144 – 156

Film thickness describes the coating around aggregate particles on asphalt mixtures. The standard method of calculating film thickness has proven to present several limitations, such as assuming an average thickness independent of particle size, being completely independent to the porosity of the mixture and considering only one mineral type. In this paper, a binder distribution model is developed for aggregates according to size and role in the structure. The aggregates are separated into two different structures: primary structure, and secondary structure. A coating thickness for these two structures is calculated from a geometrical consideration that includes the packing arrangement of particles and the effect of overlapping as the film grows. The results were compared with known rutting performance of field mixtures and moisture conditioned laboratory mixtures, showing a good correlation between film thickness and resistance to failure.

Paper III: Lira, B., Ekblad, J. & Lundström, R. (2019). Evaluation of asphalt rutting based on mixture aggregate gradation. Published in: Road Materials and Pavement Design, pages 1 – 18

The study presented in this paper assesses, in an empirical way, the capability of the gradation-based framework to evaluate the susceptibility to permanent deformation of asphalt mixtures with varying aggregate gradation. The laboratory study was planned to isolate the effect of aggregate gradation by keeping the source of both the aggregates and the binder constant. The work consisted of testing six different asphalt mixtures with varying aggregate gradations using two different methods: wheel tracking and cyclic compression test. The combined normalized result shows a non-significant relationship between the gradation-based framework parameters and resistance to permanent deformation. Additionally, it was observed that the total amount of coarse material influences the mixture resistance to permanent deformation.

Paper IV: Lira, B., Ekblad, J. & Lundström, R. (2020). Influence of particle shape on permanent deformation of asphalt mixtures. Submitted to: Road Materials and Pavement Design (2020-09-18)

Particle shape is a fundamental property of mineral aggregates and plays an important role on particle arrangement and the structures they form. The following investigation assesses empirically the influence of particle shape defined by the flakiness index, on the resistance to permanent deformation of asphalt mixtures. The laboratory study isolated the effect of aggregate flakiness by keeping the source of both the aggregates and the binder constant. The study consisted of testing five mixtures with the same aggregate gradation and varying flakiness index of the coarse fraction, using the wheel tracking test, as well as evaluating particle breakage after mixing and compaction. Results show that there is no significant correlation between flakiness index and total rut depth of SMA mixtures. Additionally, there was no breakage observed for the flaky particles as previously stated in the literature.

Additional conference publication

Paper V: Lira, B., Lundström, R. & Ekblad, J. (2020). Influence of aggregate gradation on the permanent deformation of asphalt mixtures. Accepted for publication and presentation at: RILEM International Symposium on Bituminous Materials, December 14 – 16, 2020 – Lyon, France.

The study presented in this conference article aimed to correlate the measured resistance to permanent deformation of mixtures with varying aggregate gradation to the performance predicted by the Marshall stability test. The experimental study was performed on 6 mixtures designed with the Marshall mix design method and measured using the wheel tracking test. The total rut depth obtained with the wheel tracking test shows a high correlation to the Marshall flow values, as higher rutting corresponds to mixtures with higher flow. The study has shown the ability of Marshall flow value to predict the resistance to permanent deformation, independent of asphalt mixture type, as well as a close correlation between aggregate gradation and stability.

Contents

I. Description of Doctoral Work

This thesis comprise 3 main parts: a description of the work done during the doctoral project (chapter I), the stand-alone summary presented in chapters II through VII, including a general background, development of the gradation-based framework and the results of the experimental investigation, and finally the core of the work which consists of the five appended scientific papers, three of them already published in peer-reviewed scientific journals and a conference paper accepted for presentation and publication.

Problem statement

Asphalt mixtures as known today have been manufactured for over 100 years. It was early on understood the significance of the aggregate size distribution, or gradation, in terms of the functional properties of asphalt mixtures: it is the volumetric relation between aggregates, binder and air voids which determines the performance of a mixture. The asphalt mixture types, including aggregate gradation curves, that are in use today have been developed almost exclusively through empirical work. There has been no generally applicable theoretical framework for how gradations should be formulated to meet functional requirements set by the different road authorities.

Regarding road asphalt mixtures, it is possible to generally distinguish between 2 main types of aggregate gradations: (1) continuous gradations, also known as dense graded, which have a more or less continuous spectrum of particles sizes and (2) stone mastic asphalt (SMA), or gap graded, in which some particle sizes are excluded. Historically, the first type has been most dominant. During the late 1960´s the second type became increasingly popular, especially in the Nordic countries where wear from studded tyres became a growing source of rutting. It was also observed that SMA-type mixtures also contributed to comparatively reducing the mixtures susceptibility to permanent deformation.

Permanent deformation is one of the most important failure mechanisms and a major trigger of maintenance activities and costs for asphalt pavements. A vital part of choosing mixture type and assessing risks regarding pavement performance is adequate predictive tools to use in planning, tendering and subsequent construction, which emphasize on properties that can be evaluated and manipulated during the construction process. In this context, aggregates properties are instrumental for asphalt mixture design. However, still the amount of research and knowledge about aggregates is relatively limited compared to e.g. bituminous binders and additives.

Previous studies have both stated and tested the idea of a load carrying structures within the aggregate assembly. In cases where asphalt performance has been evaluated, this has predominantly been done in the laboratory varying multiple factors simultaneously, e.g. fraction of fines and source of the aggregates along with gradation. Field evaluation has also been done with test sections where the total rutting has been measured. However, the influence of the aggregate gradation and shape on asphalt performance has normally not been entirely isolated during these studies, which has resulted in other variables affecting the conclusions drawn.

Furthermore, many of the previous studies include asphalt mixtures with dense graded gradations and designs according to US standards. Consequently, prevailing empirical methods limited to these types of mixtures. But as stated earlier, SMA is an extremely popular type of mixture in the Nordic countries and in other parts of the world. Stone mastic asphalt is usually characterized by a dominant amount of coarse material, high binder content and low air voids. Hence, it is of large importance to expand the understanding of the influence of alterations to aggregate gradations and to define methods that can cover a wider range of asphalt mixture types.

Knowledge regarding the best use of the available materials in a more sustainable way is needed to produce better asphalt mixtures that can withstand distress and increase their service life. This is especially important for suppliers, e.g. when considering performance contracts where the contractor is responsible for providing mixtures that fulfil certain performance requirements and must assess the risks from deviations on asphalt production. In this context it is also important that properties can be manipulated in production and not only measured.

Project outline

The project presented in this study originated from the idea of characterizing asphalt mixtures based on their nominal properties to predict their performance as asphalt layers. The establishment of a framework based on parameters from the different components allows the asphalt mixture to be “engineered” as a starting point, reducing the trial-and-error period during mixture design and the uncertainties included in other empirical methods.

For this, all the components and their influence on the final product should be included. The first element to be included in the model is the mineral aggregates, as they are the most dominant component both by weight and volume. Aggregate gradation varies greatly between mixture types, hence the need to identify different structures and their role in the performance of a mixture. Subsequently, bitumen binder and how it distributes within the mixture in relation to the aggregate structures previously identified, was also included. This calculation could only be performed by taking into consideration all the volumetric properties of the mixtures, e.g. also including air void content.

As an initial step towards validation of the newly developed framework, mixtures from an existing database where used to evaluate performance with regards to permanent deformation and relate it to the parameters established by the proposed gradation-based framework. These results showed positive indication, which led to the decision to perform a laboratory study to evaluate these relationships.

The 1st experimental plan was outlined to test the parameters determined by the gradation-based framework, mainly the primary structure, with regard to the resistance to permanent deformation of asphalt mixtures. For this, 6 gradations covering a wide range of mixture types, and primary structure contents, were prepared and tested with different methods to assess rutting resistance. Of great importance was to keep all other variables, mainly bitumen type and aggregates source, constant. The results obtained led to very interesting conclusions, as even though they indicated impact of aggregate gradation on the resistance to permanent deformation, they did not show any significant correlation between primary structure content and rutting. One obvious simplification in the gradation-based framework is to assume aggregate particles as spheres, which may limit the primary structure range, as spheres are the particle shape with the lowest dense packing.

Based on the results from the first experimental study, the possibility to include varying particle shape in the framework was introduced. This was done by taking into consideration the only shape property nowadays included in the European standards for bituminous mixtures: flakiness index. A new experimental plan included 5 mixtures with the same gradation, stone mastic asphalt, but varying flakiness index. Once again, the bitumen and aggregates source were kept constant to isolate the effect of flakiness index on the resistance to permanent deformation of asphalt mixtures. Results from the wheel tracking test indicated non-existent, or very weak, influence of varying flakiness index between identical mixtures.

In summary, the experimental work showed that aggregate gradation has an overall influence on the resistance to permanent deformation of asphalt mixtures, particularly the total amount of coarse material. It was noted that limiting the flakiness index of the aggregates used on asphalt mixtures does not necessarily improve mixture performance, at least not for the stone mastic asphalts investigated.

In relation to the gradation-based framework, the determination of the primary and secondary structure did not improve performance predictions compared to the use of the total amount of coarse aggregate of a mixture. Further, parameters from the framework, like the binder thickness, would need to be redefined using coarseness instead of primary structure, and then tested to determine their relation to durability as theoretically stated in the framework.

Scope of the study

The main objectives of the study presented in this thesis are (1) to develop a framework to characterize asphalt mixtures based on the internal structure created by the mineral aggregates and (2) relate these characteristics to the resistance to permanent deformation and rutting performance of asphalt mixtures.

The work done in this project follows the basic scientific method by formulating a hypothesis, stating a mathematical framework and finally planning and executing experiments. The experimental part of this investigation aims to assess, empirically, the ability of the developed gradation-based framework to evaluate the susceptibility to permanent deformation of mixtures with different aggregate gradations and particle shapes.

Contributions

The basic ideas of this project were first stated by the main supervisor on the first part of the doctoral studies, Prof. B. Birgisson. The PhD candidate was responsible to formulate the hypothesis in mathematical terms and further developing the model by including variables to generalize the framework and mathematically include binder and air voids. Papers I and II were written by the candidate with the support, both in content and editorial, of both supervisors (Birgisson and Jelagin) which are also co-authors.

In the second part of the doctoral studies comprising original empirical research, the PhD candidate was responsible for planning and executing the experimental part of the study. In the empirical papers, III to V, the candidate manufactured all samples and performed all measurements at NCC´s laboratory in Upplands Väsby, Sweden, except for wheel tracking testing which was performed by Mona Teigen and Marita Åshammer at NCC´s laboratory in Lier, Norway. Furthermore, Lira made all the data compilation and calculations, as well as the statistical analysis. The manuscripts were all written by the PhD candidate with the support, both in content and editorial, of both supervisors (Ekblad and Lundström).

II. Introduction

Asphalt mix design has the purpose to determine the combination of the available materials to meet performance requirements. Asphalt mixtures consist mostly of four elements: mineral aggregates, bituminous binder, air voids and sometimes additives, of which aggregates typically represents more than 90 % of the weight, greatly influencing the mechanical properties and the performance of the mixture. Regardless of source, processing method, or mineralogy, the aggregates are expected to provide a strong load-bearing skeleton to resist different deterioration mechanisms and ensure adequate performance of the asphalt mixture (McGennis, et al., 1995).

Geometrically, sphere packing is defined as the arrangement of non-overlapping identical spheres within a self-containing three-dimensional space. For a certain mixture design and a given compactive effort, three main aggregate properties affect the packing characteristics: gradation, shape and surface texture. Aggregate gradation is the distribution of particles sizes and is the starting point of any mixture design. A change in the size distribution of the aggregates will influence the amount of void space in the aggregate skeleton and in the matrix itself which leads to a different load distribution through the asphalt layer. A mixture having a continuous gradation, in the sense that it contains particles of a wide range of sizes in uniform quantities, would generally have a relatively high packing density. Furthermore, a dense particle packing is usually also considered to increase the stability of the structure, reducing its susceptibility to permanent deformation and rutting, by providing more interparticle contacts and reducing the air voids compared to less dense mixtures. However, high stability still requires sufficient air void content in the mixture in order to ensure strength and durability combined with adequate proportions of bituminous binder.

The packing of aggregates is influenced not only by the aggregate gradations but also by the shape of individual aggregate particles (Kwan & Mora, 2001). There are many theories on how various shape parameters affect the packing of aggregates, partly due to the many shape parameters defined and partly because of the many methods for their characterization, which is a sign of the complexity involved. At the same time, the properties that are usually measured are single-valued properties rather than describing continuous distributions, which are more difficult to quantify and incorporate in theories or frameworks. There seems to exist a consensus regarding detrimental effect of increased flakiness (or non-cubical particles), however, empirical findings trying to estimate and quantify this effect are more scattered. The study presented in this thesis aims to contribute knowledge in this aspect.

Performance of asphalt mixtures relates mostly to the resistance to permanent deformation (rutting) and cracking, workability, permeability and durability (Brown, et al., 2009). In general, rutting of a pavement structure is the accumulation of permanent deformation caused by heavy traffic and wear of the top layer caused by studded tires. Permanent deformation typically occurs in the wheel path, decreasing road safety and contributing to other type of failures such as cracking and potholes. This type of distress has normally two main causes: 1) excessive repeated stress applied on the layers below the asphalt layers, and 2) accumulated deformation in the asphalt layers. The main factors affecting the resistance to permanent deformation in the asphalt layers is bitumen type and content, aggregates gradation, shape, size and texture, and the air void content (Sousa, et al., 1991).

The gradation-based framework presented in this study, paper I (Lira, et al., 2013), identifies the range of aggregate sizes of the total gradation which plays a key role in the load-bearing capacity of a specific asphalt mixture. This framework has been developed based on packing theory of spheres and is, in the empirical study, applied using common volumetric relationships. Included in the framework is the analysis of the binder distribution around the aggregate particles, paper II (Lira, et al., 2015).

The experimental part of this study consists of two test series: firstly, a series testing the ability of the gradation-based framework to evaluate the susceptibility to permanent deformation of mixtures with varying aggregate gradations, paper III (Lira, et al., 2019) and conference paper V, and secondly, a new test series investigating the influence of particle shape as described by the flakiness index on the performance of one and the same nominal asphalt mixture (paper IV). Both series have been tested to determine the resistance to permanent deformation of asphalt mixtures with varying gradation and flakiness index, respectively.

The thesis outline and scope are based on the following papers published and/or submitted in international scientific journals:

I. Lira, B., Jelagin, D. & Birgisson, B. (2013). Gradation-based framework for asphalt mixture. Published in: Materials and Structures, 46 (8), pages 1401 – 1414.

II. Lira, B., Jelagin, D. & Birgisson, B. (2015). Binder distribution model for asphalt mixtures based on packing of the primary structure. Published in: International Journal of Pavement Engineering, 16(2), pages 144 – 156.

III. Lira, B., Ekblad, J. & Lundström, R. (2019). Evaluation of asphalt rutting based on mixture aggregate gradation. Published in: Road Materials and Pavement Design, pages 1 – 18.

IV. Lira, B., Ekblad, J. & Lundström, R. (2020). Influence of particle shape on permanent deformation of asphalt mixtures. Submitted to: Road Materials and Pavement Design (2020-09-18).

Additional conference publication:

V. Lira, B., Lundström, R. & Ekblad, J. (2020). Influence of aggregate gradation on the permanent deformation of asphalt mixtures. To be presented at: RILEM International Symposium on Bituminous Materials, December 14 – 16, 2020 – Lyon, France.

III. General background

Several studies have been conducted to predict the performance of hot mix asphalt (HMA) based on aggregate properties, specially aggregates gradation, shape and texture. In 1931 Furnas wrote that on systems comprising more than two-sized components it may be assumed, as a starting point, that each component size exactly fills the voids of the preceding size, causing no increase in volume as a whole and leaving no excess material (Furnas, 1931). This holds true only for the specific case where the solid particles of the different sizes have the same shape so that the voids are the same for each size.

In particle assemblage there are two important relationships of volume: porosity and void ratio. Porosity (n) is the ratio of void volume to total volume and void ratio (e) is the ratio of void volume to solid volume. Void ratio can run to values greater than unity. Both, porosity and void ratio, indicate the relative portion of void volume in a soil sample and are related to each other (equation [1]). Equation [2] shows the expressions used to calculate both parameters in volumetric terms, where V is the total volume (voids + solid), V_v is the volume of voids and V_s is the solid volume (Lambe & Whitman, 1969).

$$n = \frac{e}{1+e} \qquad and \qquad e = \frac{n}{1-n} \qquad [1]$$

$$n = \frac{V_v}{V} \qquad and \qquad e = \frac{V_v}{V_s} \qquad [2]$$

Mathematicians have been studying sphere packings at least since the early 16th century, when Johannes Kepler conjectured that the densest way to pack equal-sized spheres together in space is the familiar pyramidal piling, also known as rhombohedral packing (Figure 1B), with a packing density of ≈0.74. For many years this has been accepted as true, but only in 1997 Thomas Hales finally proved Kepler's conjecture (Hales, 2005). On the other hand, the loosest packing arrangement is the simple cubic packing (Figure 1A) with a packing density of 0.52.

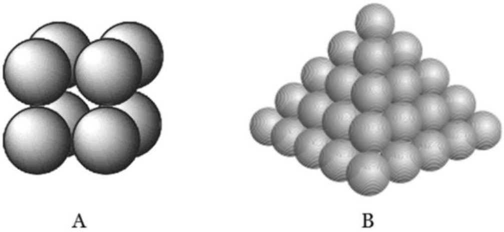


Figure 1. Sphere packing arrangements: A) simple cubic packing, B) rhombohedral packing.

Sphere packing has been used as a first step to characterize and optimize the packing density of mineral aggregates for a long time. This is done to be able to predict the response of a structure to loading. In particulate materials it is normally assumed that a vertically applied load is transferred through chains of particles while other particles play a secondary role of preventing the main chain from buckling (cf. e.g. (Santamarina, et al., 2001)).

Applications to asphalt mixtures

In the SuperPave mix design method, the Asphalt Institute (2001) has established control points through which aggregate gradations must pass, and restricted zones for gradation curves to control the air void content and provide better durability. By specifying coarse and fine angularity, the researchers were seeking to achieve hot mix asphalts (HMA) with a high degree of internal friction and thus, high shear strength for rutting resistance. At the same time, by limiting the number of elongated particles the resistance to aggregate breakage during handling, construction and under traffic will be limited.

In the USA, another important control parameter in asphalt mixture volumetric design is the percentage of voids in the mineral aggregate (VMA). However, under current specifications, many mixtures meeting all other formal requirements are subject to rejection solely on the basis of failing to meet the VMA requirement (Mohammad & Al Shamsi, 2007). Studies also show that a VMA requirement based on nominal maximum particle size (NMPS) does not consider the gradation of the mixture, ignores the film thickness of the asphalt binder and, thus, is insufficient by itself to correctly differentiate between good- and bad performing mixtures.

As mentioned before, several models have been developed to investigate and account for the influence of aggregates, specifically aggregate gradation, on the volumetric properties and performance characteristics of asphalt mixtures. Two of these models, which have served as background for the framework presented in this thesis, are: The Bailey method and the Dominant Aggregate Size Range (DASR).

The Bailey method

In the early 1980's Robert D. Bailey at the Illinois Department of Transportation presented a set of tools that would allow aggregate blends to be evaluated and to better understand the relationship between aggregate gradation and mixture properties. The Bailey method focuses on ensuring aggregate interlock and good aggregate packing (Vavrik, et al., 2002). The parameters in this method are related directly to VMA, air voids, and compaction properties.

In the Bailey method, aggregate interlock is selected as a design requirement, which will provide a rut-resistant mixture. To ensure that the mixture contains adequate binder content, the VMA is changed by modifying the packing of the coarse and fine aggregates. In this way, the asphalt mixture can have a strong skeleton for high stability and adequate VMA for good durability (Vavrik, et al., 2002). The basic principles of this method are firstly, the use of packing theory to define coarse and fine aggregate, and secondly, the use of volume instead of weight to determine the combination of aggregates.

According to this method, coarse aggregate is defined as the large aggregate that when placed in a unit volume creates voids, while fine aggregates are defined as the particles that fill the voids created by the coarse aggregate. In the Bailey method, the sieve which defines coarse and fine aggregate is known as the primary control sieve (PCS) and is based on the nominal maximum particle size (NMPS) of the aggregate blend, according to equation [3], where NMPS is one sieve larger than the first sieve that retains more than 10 %.

$$PCS = NMPS \times 0.22 \qquad [3]$$

The factor 0.22 in equation [3] was determined from analysis of the packing of different shaped particles. A two-dimensional analysis shows that the particle diameter ratio ranges from 0.155 (all round faces) to 0.289 (all flat faces) with an average value of 0.22. A corresponding three-dimensional analysis of the combination of particles gives a similar result with the particle diameter ratio ranging from 0.15 (dense/rhombohedral packing of spheres) to 0.42 (loose/simple cubic packing of spheres). For asphalt mixtures, packing of the aggregates is usually desired to be between simple cubic and rhombohedral, providing a stable configuration with a certain amount of voids, which makes the average value of 0.22 particle size ratio reasonable.

To evaluate a mixture´s gradation using the Bailey method, three ratios are determined. The coarse aggregate (CA) ratio is used to evaluate packing of the coarse fraction of a gradation and to analyse the resulting void structure. In equation [4], HS represents the sieve with half the size of the NMPS.

$$CA\ ratio = \frac{(\%\ passing\ HS - \%\ passing\ PCS)}{(100 - \%\ passing\ HS)} \qquad [4]$$

The fine aggregate, below the PCS, is then considered as a gradation itself, which contains a certain portion of coarse and fine particles and may be evaluated in a similar way as for the coarse aggregates. Equation [5] describes the fine aggregate coarse ratio, FA_c, where SCS is the secondary control sieve and gives the break point between coarse–fine and fine–fine aggregates (equation [6]).

$$FA_c = \frac{\%\,passing\ SCS}{\%\,passing\ PCS} \qquad [5]$$

$$SCS = PCS \times 0.22 \qquad [6]$$

Finally, the fine aggregate fine ratio (FA_f) is calculated according to equation [7] where TCS is the tertiary control sieve (equation [8]).

$$FA_f = \frac{\%\,passing\ TCS}{\%\,passing\ SCS} \qquad [7]$$

$$TCS = SCS \times 0.22 \qquad [8]$$

An example of the analysis performed with the Bailey method is given in Figure 2 for two different mixture types to illustrate the theoretical and empirical implications of the Bailey method. The mixtures used are a dense graded mixture and a stone mastic asphalt (SMA) according to Swedish specifications (The Swedish Road Administration, 2013). Both mixtures have a nominal maximum particle size of 16 mm with a half size of 8 mm.

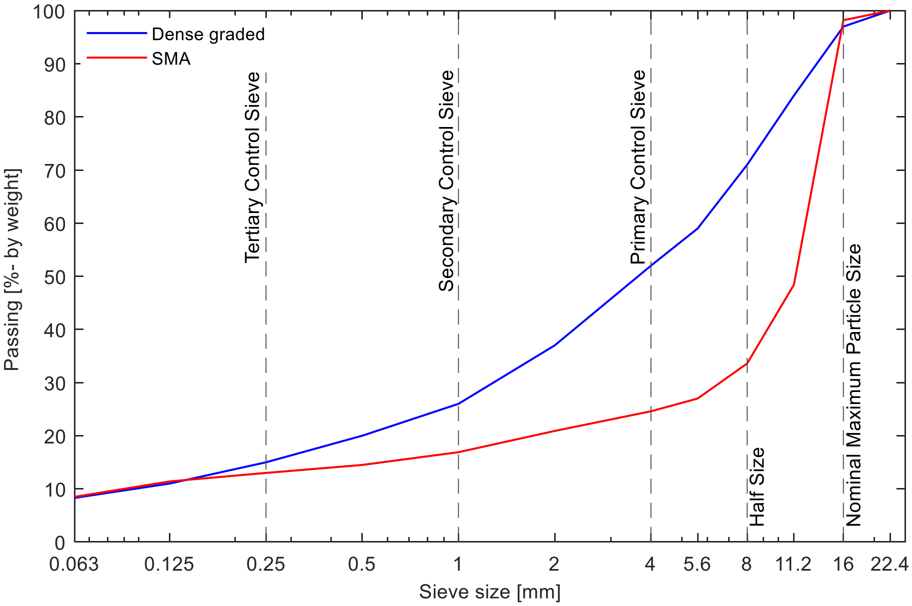


Figure 2. An example of the Bailey method implemented on 2 typical asphalt mixtures.

It may be observed in Figure 2 that, as the determination of coarse and fine aggregates only depend on the NMPS and not on the gradation, both mixtures will have the same control sieves. Table 1 presents the CA ratio, FA_c and FA_f for both, dense graded and SMA, according to the Bailey method. The limits given in the table for each mixture type and ratio are interpolations of the limits for NMPS 12.5 mm and 19 mm given in Vavrik, et al. (2002) for each mixture type.

Table 1. Ratios according to the Bailey method and interpolated limits for NMPS 16 mm

Mixture	CA ratio	FA_c	FA_f
Dense graded	0.66	0.50	0.58
Limits	0.55–0.70	0.35–0.50	0.35–0.50
SMA	0.14	0.69	0.77
Limits	0.30–0.45	0.60–0.85	0.63–0.87

It may be observed in Table 1 that for the dense graded mixture, the fine aggregate fine ratio (FA_f) is higher than the maximum allowed for that type of mixture. According to Vavrik, W. (2000), a number of normative conclusions can be drawn from the analysis. For example, high amounts of the fine portion of the fine aggregates risks to overfill the voids created by the coarse portion of the fine aggregates, thereby disrupting the contact between the particles. On the contrary, for the SMA mixture the coarse aggregate (CA) ratio is lower than the allowed values. A balanced coarse aggregate structure is suggested to give mixture that is easy to compact in the field and that adequately resist deformation under loading. A mixture with low CA ratio has smaller voids between the coarse aggregate, making it difficult to compact and prone to segregation. These issues are though not empirically supported when using either the dense graded or the SMA gradation curves presented in Figure 2.

The main limitation of the Bailey method is that no performance evaluation was done during its development, making all relations between performance and the different ratios only valid on a theoretical level, even though the procedure itself is largely based on experimenting and testing.

Dominant Aggregate Size Range

In 2006, a conceptual and theoretical approach to evaluate coarse aggregate structure based on gradation was developed by Roque, et al. (2006). The dominant aggregate size range (DASR) aims to identify the particles that will conform the main load carrying structure in asphalt mixtures and then relate the quality of this structure to performance. This approach limits the porosity of the DASR to guarantee contact between the load bearing particles, based on the porosity of the loosest state for spheres still in contact with each other (simple cubic packing arrangement, cf. Figure 1). All percentages are based on volume.

The main hypothesis of this approach is that the DASR must be composed of coarse enough particles while the DASR porosity must be no greater than 50 % for a mixture to effectively resist deformation. Particle size smaller than the DASR will serve to fill the void space between the DASR along with binder and fines (Kim, et al., 2008). The volume of material (binder, aggregate and air voids) that exists within the interstice of the DASR is denoted Interstitial Volume (*IV*), and the material filling the *IV* is called the Interstitial Components (*IC*). The *IV* serves to hold the DASR together and according to the authors it will strongly affect the durability of a mixture. Finally, a plane through the interstitial volume is called the Interstitial Surface (*IS*). The characteristics of this surface will affect the mixture´s resistance to deformation, particularly shear deformation associated with rutting.

As mentioned earlier, porosity is calculated as the ratio of the volume of void to the total volume. By assuming that a mixture has a certain effective binder and air voids content for a given gradation, porosity can be calculated for each aggregate particle size. The dominant aggregate size range is a range of contiguous sizes that are mutual interactive. To be interactive, the relative proportion between contiguous sizes should be less than 70/30 and larger than 30/70, which means that the relative proportions in any two contiguous sieve sizes should be within 70% from one sieve size and 30% from the contiguous sieve next in order for good coarse particle interaction. In other words, once the proportion exceeds the 70/30 ratio, the spacing of the particles with the smaller proportion increases so much that these particles are simply floating in the matrix and may no longer be an effective part of the load bearing structure (Kim, et al., 2009). When calculating the DASR porosities for the complete interactive range, the total volume will consist of particles that are equal to or smaller than the size of interest. In equation [9], i is the size of interest, $i-1$ is one sieve smaller than i, V_{TM} is total volume of the mixture and $V_{T(i-1,\,i)}$ is the total volume available for particles passing the sieve i and retained on the sieve $i-1$.

$$V_{T(i-1,i)} = V_{TM} - V_{agg(\geq i)} \qquad [9]$$

The volume of voids ($V_{V(i-1,\,i)}$) includes the volume of aggregates passing the $i-1$ sieve, plus the volume of binder and of air voids, as shown in equation [10].

$$V_{V(i-1,i)} = V_{agg(<i-1)} + VMA \qquad [10]$$

Finally, the porosity of the aggregate particle size between *i-1* and *i*, $\eta_{(i\text{-}1,\, i)}$, is calculated as:

$$\eta_{(i-1,i)} = \frac{V_{V(i-1,i)}}{V_{T(i-1,i)}} = \frac{V_{agg(<i-1)}+VMA}{V_{TM}-V_{agg(\geq i)}} = \left(\frac{V_{TM}-V_{agg(\geq i-1)}}{V_{TM}-V_{agg(\geq i)}}\right) \qquad [11]$$

Based on soil mechanics theory, the porosity of granular materials in the loose state is approximately constant between 45% and 50% regardless of particle size or distribution (Lambe & Whitman, 1969), therefore, Kim, et al. (2009) have chosen that the porosity of the DASR must be no greater than 50% for the particles to be in contact with each other.

An example of the analysis performed with the dominant aggregate size range approach is given in Figure 3 with the same mixtures used to exemplify the Bailey method (cf. Figure 2): a dense graded mixture and a stone mastic asphalt (SMA) according to Swedish specifications (The Swedish Road Administration, 2013). In the original DASR approach, the particle size passing the 2.36 mm but retained at the 1.18 mm sieve was selected as the smallest particle coarse enough to contribute to aggregate interlocking. However, these limits have been re-defined to particles passing the 4 mm sieve but retained on the 2 mm sieve for the European sieve system.

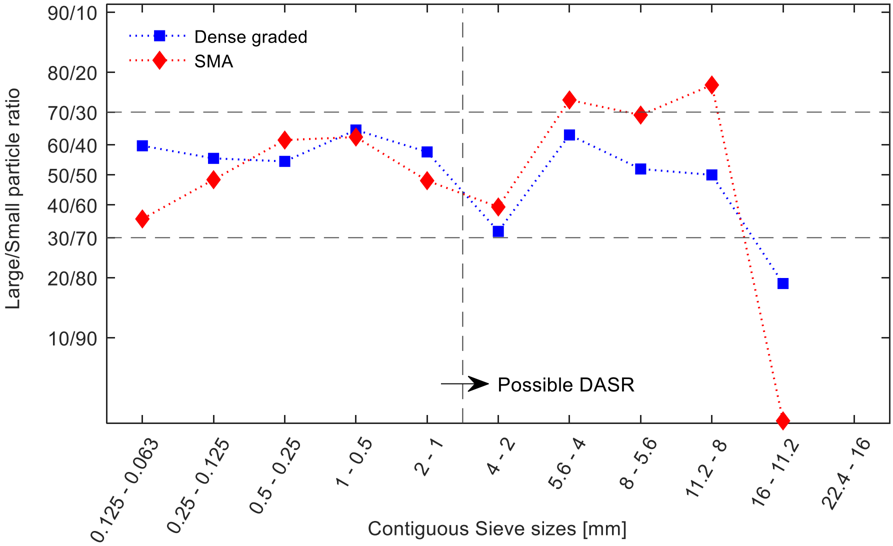


Figure 3. Dominant aggregate size range approach, interaction diagram for dense graded and SMA mixtures, respectively.

As it may be observed in Figure 3, the dense graded mixture has a continuous DASR from 2 to 11.2 mm, which means that almost all of the coarse aggregate interact with each other forming the load bearing structure of the mixture. In the case of the SMA mixture there is interaction between sieve sizes 2 and 4 mm and between 5.6 and 8 mm. Table 2 presents these results together with mixture properties and the porosity for the determined range.

Table 2. Analysis according to the DASR approach

Mixture	**Binder content [% by weight]**	**Air voids [% by volume]**	**DASR [mm]**	**% by volume of aggregate in DASR**	**DASR porosity [% by volume]**
Dense graded	6.0	1.6	2 – 11.2	60	42.9
SMA	6.2	3.2	2 – 4	6.1	83.7
			5.6 – 8	6.6	85.0
			11.2	49.8	54.2

It may be observed in Table 2 that the dense graded mixture has a DASR porosity below 50 %, representing good stone-to-stone contact between all the particles that comprise the dominant aggregate size range. The SMA mixture on the other hand, shows that neither of the identified ranges satisfies the condition of at least simple cubic packing. In this case, the model indicates that the porosity of individual particle sizes may be used instead, as for SMA and gap-graded mixtures it is not uncommon that a large part of the aggregates are concentrated on only one fraction. In the case presented in Figure 3, 49.8 % of the aggregate material passes the 16 mm sieve and is retained in the next sieve, 11.2 mm. This means that the porosity of the individual sieve size 11.2 mm is 54.2 %, making this sieve the DASR for the given SMA mixture.

The DASR approach has been evaluated by its developers using an extensive range of mixtures from existing databases and the results indicate that mixtures identified as having a poor gradation, with DASR porosity greater than 50 %, resulted in poor rutting performance (Kim, 2006). However, the experience with Swedish mixtures do not support those results, as the presented SMA mixture normally, from experience, shows a good resistance to permanent deformation. Another note is that, and an important limitation of the approach, the DASR identification procedure is valid strictly for gradations composed of discrete particle size with a sieve size ratio 2:1, with uniform distributions within each sieve and considering aggregates as spheres.

Shape of particulate materials

Both the Bailey method and the DASR approach, use packing of spheres as the backbone to calculate the different parameters involved. Packing theory is a tool that allows the analysis of aggregate gradations based on a geometric and systematic arrangement of uniform spheres. Spheres have previously been used to understand how mixtures of particles build internal structures influencing macroscopic characteristics.

It may however be noted that, for example, most aggregates are not uniform spheres of the same size, nor can they be arranged in a cubic structure naturally, presenting a wide range of porosities, both in dense and loose state. Table 3 presents the porosity and void ratio for uniform spheres as well as for some typical granular soils in both the loose and dense states.

Table 3. Maximum and minimum volume properties for granular soils (Lambe & Whitman, 1969)

Description	**Porosity [% by volume]**		**Void ratio**	
	***n* min**	***n* max**	***e* min**	***e* max**
Uniform spheres	26	48	0.35	0.92
Standard Ottawa sand	33	44	0.50	0.80
Clean uniform sand	29	50	0.40	1.0
Uniform inorganic silt	29	52	0.40	1.1
Silty sand	23	47	0.30	0.90
Fine to coarse sand	17	49	0.20	0.95
Micaceous sand	29	55	0.40	1.2
Silty sand and gravel	12	46	0.14	0.85

As it may be observed in Table 3, granular materials can reach porosities both lower and higher than uniform spheres. According to McGennis, et al. (1995), cubical, rough-textured aggregates provide more strength than rounded, smooth-textured aggregates. Even though both cubical and rounded particles may possess the same inherent strength, cubical aggregate particles tend to lock together, resulting in a stronger mass of material than that by rounded pieces. Instead of locking together, rounded aggregates particles tend to slide by each other. When a bulk of aggregates is subjected to loading, there may occur a plane within the composite structure where aggregate particles begin to slide by or "shear" with respect to each other, which results in particle reorganization, densification and deformation of the mass.

Investigations have indicated that the packing properties of non-spherical particles are considerably different from spherical particles, and even a slight difference in particle shape will increase the packing density notably. ShuiXiang, et al. (2010) applied sphere assembly models and relaxation algorithms to simulate the random packing of several geometrical forms in 3D, and the results are given in Table 4.

Table 4. Packing density in loose and dense state for 3D objects according to ShuiXiang, et al. (2010)

Shape	**Packing density**	
	Random (loose)	**Ordered (dense)**
Sphere	0.64	0.74
Cone	0.67	0.78
Tetrahedron	0.68	0.78
Spherocylinder	0.69	0.91
Cylinder	0.72	0.91
Ellipsoid	0.74	0.77
Cube	0.78	1

As can be observed in Table 4, the sphere is the geometrical shape that has the lowest packing density, both loose and as ordered packing, of the typical geometrical shapes evaluated. Simulations show, once again, the difference in the achievable packing between cubical-like particles and rounded particles. The granular materials presented in Table 3 also show that, more than once, their minimum porosity could be better simulated by other geometrical forms that allow a denser packing and might represent more accurately the reality of mineral aggregates.

Film thickness

Another important parameter affecting the durability and resistance to deformation of asphalt mixtures is the film thickness of bitumen around the aggregate particles. Even though film thickness per se is not included in mixture design methods, such as SuperPave, it may be considered as a parameter that is reflected in the characteristics of the aggregate gradation, voids in mineral aggregate (VMA) and bitumen content (Brown, et al., 2009). Elseifi, et al. (2008) investigated the concept of asphalt binder film thickness experimentally on the basis of measurements obtained by image analysis techniques. Their results showed that the coating material surrounding large aggregates is actually asphalt mastics, i.e. mixture of asphalt binder and fine aggregates.

Cooke and Rowe (1999) developed a method to evaluate the porosity and specific surface of a porous media coated with an accumulating film. The calculations take into account the limitations to film growth imposed by contact between particles and the film overlapping, as it develops around the particle. The parameters used are calculated based on spheres of equal diameter and assuming that the porous media can be represented by a regular or geometrically systematic packing arrangement, in which the arrangement of the rows of spheres can be repeated in all directions. A deeper review of the model by Cooke and Rowe and its use on the calculations of film thickness for asphalt mixtures is presented in paper II (Lira, et al., 2015).

IV. Gradation-based framework

Mineral aggregates in asphalt mixtures are particles of different sizes and shapes, characterized by a size distribution, normally called gradation curves, based on sieve analysis. Considering a group of particles of different sizes and shapes, the structure that these particles create will be more or less stable depending on the number and position of their neighbours.

Particle packing theory states that large single sized particles, when filled into a container, will have voids, which in turn can be filled with smaller particles, thereby reducing the voids or increasing the packing density. This packing density in turn can be further improved by introducing a third component of still smaller size and so on. The concepts from packing theory can be applied to size distribution of aggregates by considering them as an arrangement of solid units in which each constituent is supported and held in place by a tangent contact with another solid unit. By applying an analysis based on three-dimensional packing theory to a complete aggregate distribution, it is possible to find the range of sizes where stone-to-stone contact is assured, with the minimum density of a simple cubic packing. Following is a summary of the main assumptions and calculations of the framework, for a detailed description of the gradation-based framework, see Paper I (Lira, et al., 2013).

The gradation-based framework is a generalized version of the DASR approach, where the limitations of a pre-determined sieve size relation of 2:1 has been changed to accommodate for any relationships. Furthermore, the distribution within each sieve fraction (assumed as uniformly distributed in DASR) and shape of the particles (spheres) have been made variable. The procedure, which is described in the following sections, takes each of these parameters into account as further research or relevant information becomes accessible.

Main assumptions

The framework developed during this project is a tool for analysing asphalt mixtures by identifying two main structures within the aggregates in a mixture: the primary structure (PS) and the secondary structure (SS), as shown in Figure 4. The primary structure is the range of sizes that constitutes the mixture´s skeleton by providing the main load-bearing capacity. The secondary structure is formed by the particles smaller than the primary structure but larger than the filler fraction (> 63 µm), providing support to the load carrying structure. Particles larger than the primary structure are called oversized.

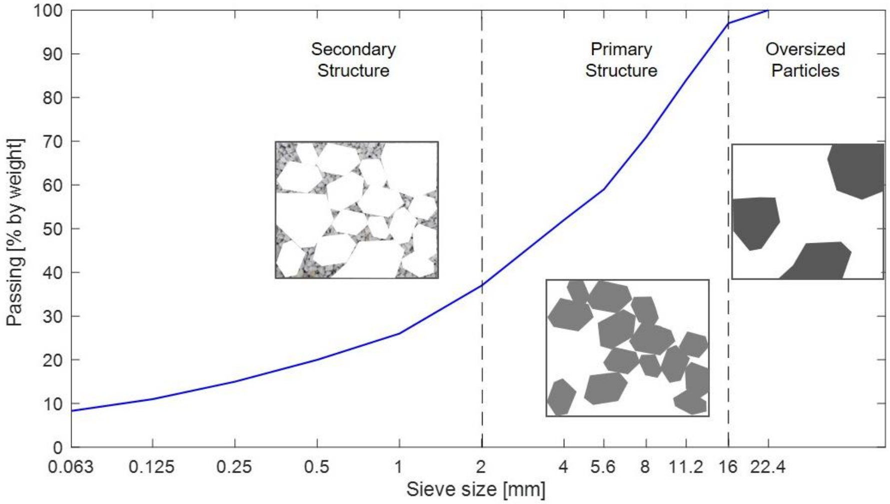


Figure 4. Gradation-based framework with inserts in grey visualizing the various fractions of the particle assembly.

Figure 4 shows an illustration of a particle size distribution (same dense graded gradation as in Figure 2) and the different structures that the gradation-based framework identifies. In this case, the primary structure comprises the material retained between sieve sizes 2 and 11.2 mm (included), while particles below the 2 mm sieve are part of the secondary structure and all particles larger- or equal to 16 mm are oversized and do not contribute to the load bearing capacity.

The interaction between particles of two consecutive sieve sizes is based on three main assumptions:

1. The particles within a sieve have a continuous distribution of sizes characterized by the parameter B. The mean sieve size $\overline{D_n}$ with material retained at D_{min} (opening of the n sieve) and smaller than D_{max} (opening of the previous/larger sieve), is defined as:

   $$\overline{D_n} = B \cdot (D_{min} + D_{max}) \qquad [12]$$

   where B is a dimensionless parameter representing the mean value for a distribution between 0 and 1. In this study, as for the DASR approach, all calculations have been made assuming a uniform size distribution (B=0.5) for each sieve.

2. The maximum and minimum concentration for the particles is known, either from theoretical calculations or laboratory measurements. When considering the particles as spheres, the maximum concentration (φ_{max}) for two consecutive

sizes is equivalent to a rhombohedral packing configuration: 74% of the unit cell is filled. The maximum concentration in the calculations may be varied if other shapes are considered.

3. The aggregate particles are uniformly distributed in the total volume. There is no segregation in the mixture.

Calculations

The ranges for primary and secondary structure, respectively, are determined through an analysis based on the percentage of particles retained at each sieve, defining the higher and lower limits for particles between two consecutive sieves to be in contact with each other. To determine these ranges, it must be kept in mind that all particle arrangements between the densest and loosest packing are considered as providing stone-to-stone contact.

Normally, aggregate gradations for asphalt mixtures are composed of several particle sizes and only in specific cases, such as SMA and gap-graded mixtures, just one of the fractions contains enough particles to create a load–bearing structure. Otherwise, a combination of several particle sizes is needed to assure a stable structure. The following analysis consists of an iterative process between two contiguous sieve sizes at a time, until the complete gradation has been analysed.

Considering an aggregate gradation where φ_n and φ_{n+1} are the concentrations for two contiguous sieves with mean particle size $\overline{D_n}$ and $\overline{D_{n+1}}$ respectively (with $\overline{D_n} > \overline{D_{n+1}}$). The weighted average size (D_{avg}) is calculated as:

$$D_{avg} = \frac{\varphi_n \cdot \overline{D_n} + \varphi_{n+1} \cdot \overline{D_{n+1}}}{\varphi_n + \varphi_{n+1}} \qquad [13]$$

The interaction between particles of different sizes can be defined as the possibility for all particles to be in contact with each other. Assuming spheres, Figure 5 shows the threshold cases for contact between particles of two different size: case A shows the maximum distance between the larger particles where smaller particles are needed to ensure contact and create a structure. Figure 5B, on the other hand, shows particles with mean size $\overline{D_n}$ in simple cubic packing that create a void that may still be filled by the smaller particle with mean size $\overline{D_{n+1}}$. If particles $\overline{D_n}$ have a denser packing, there is no space for the closest next size particle to be part of the load bearing structure.

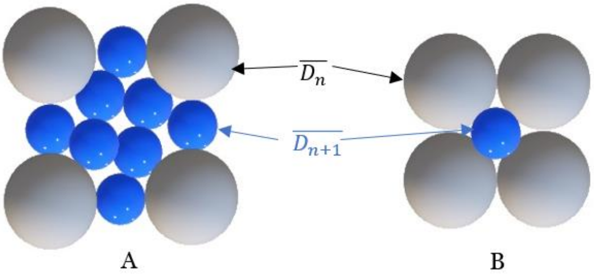


Figure 5. Threshold cases of contact between spheres of two contiguous sieve sizes. A) the structure is created with a combination of both particle sizes, B) the larger particles create a structure on their own.

From Figure 5B, considering perfect spheres of uniform size $\overline{D_n}$ in a simple cubic packing, the concentration (φ) in the total volume can theoretically be calculated to 52 % (φ_{min}=0.52). Now, considering the spheres in a rhombohedral packing (densest) the concentration increases to 74 % of the total volume (φ_{max}=0.74). This means that to reach maximum density, a maximum of $\varphi n+1=0.22$ (difference between φ_{max} and φ_{min}) of the smaller size can be added to a simple cubic arrangement. For there to be interaction for two contiguous sieve sizes, their concentrations must then be between these extreme cases, as expressed in equation [14].

cf. Figure 5A cf. Figure 5B

$$\frac{0.22 \cdot \overline{D_n} + 0.52 \cdot \overline{D_{n+1}}}{0.22 + 0.52} \leq D_{avg} \leq \frac{0.52 \cdot \overline{D_n} + 0.22 \cdot \overline{D_{n+1}}}{0.52 + 0.22}$$

$$0.297 \cdot \overline{D_n} + 0.703 \cdot \overline{D_{n+1}} \leq D_{avg} \leq 0.703 \cdot \overline{D_n} + 0.297 \cdot \overline{D_{n+1}} \qquad [14]$$

Equation [14] is valid only when spherical particles are considered. i.e. is equivalent to the 70/30 ratio presented by the DASR approach. To determine the primary structure, the analysis is done in a systematic way until the last sieve size and a list of interaction ranges is obtained. The interaction range might include several consecutive sieve sizes or be interrupted by a non-interactive size range, giving several possible ranges for the primary structure. To select which one of these ranges is the strongest or most influential, the total concentration of material at each range is determined. The range of sieve sizes that has the highest concentration will be the primary structure. The smallest sieve size that can be part of the primary structure will be the one retained at the 1.18 mm or 2.0 mm, depending on the sieve system used.

A schematic summary of the procedure to identify the primary structure is given in Figure 6. An example with the same two mixtures, dense graded and SMA, used previously is given in Figure 7 and Figure 8, respectively.

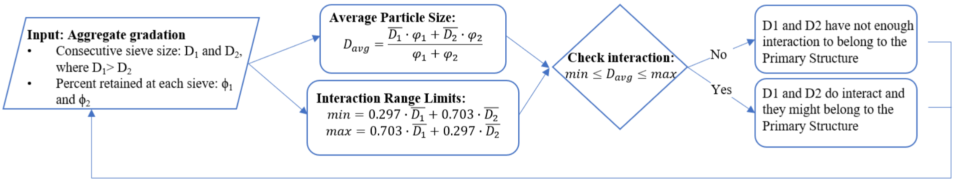
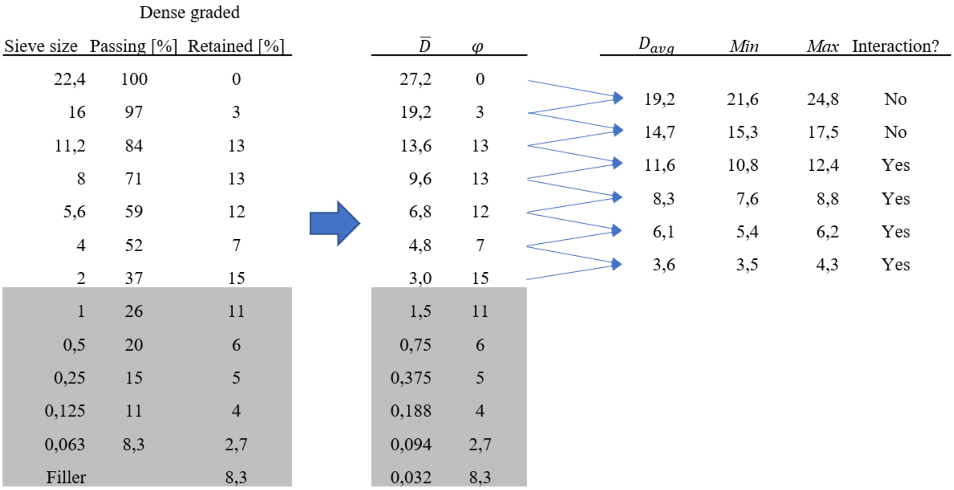


Figure 6. Flowchart of the procedure to identify the primary structure.



Dense graded

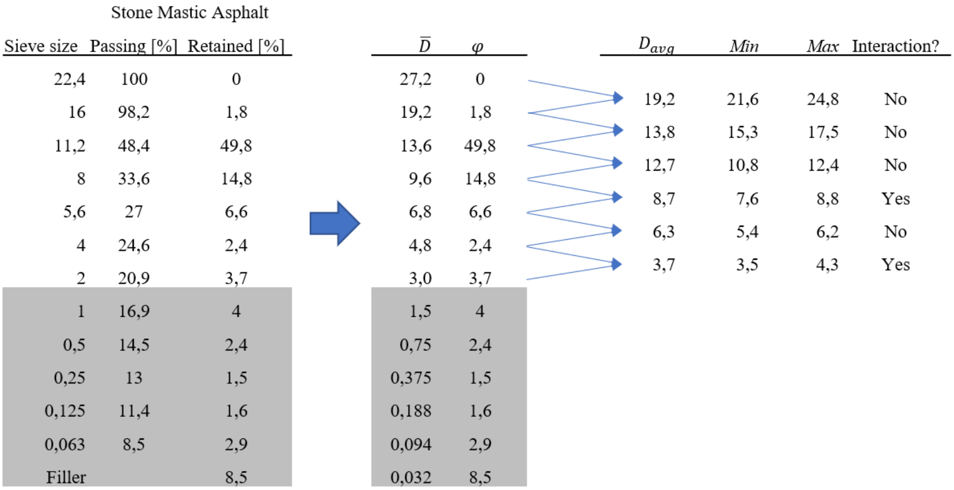
Sieve size	Passing [%]	Retained [%]
22,4	100	0
16	97	3
11,2	84	13
8	71	13
5,6	59	12
4	52	7
2	37	15
1	26	11
0,5	20	6
0,25	15	5
0,125	11	4
0,063	8,3	2,7
Filler		8,3

$\overline{D}$	φ
27,2	0
19,2	3
13,6	13
9,6	13
6,8	12
4,8	7
3,0	15
1,5	11
0,75	6
0,375	5
0,188	4
0,094	2,7
0,032	8,3

D_{avg}	*Min*	*Max*	Interaction?
19,2	21,6	24,8	No
14,7	15,3	17,5	No
11,6	10,8	12,4	Yes
8,3	7,6	8,8	Yes
6,1	5,4	6,2	Yes
3,6	3,5	4,3	Yes

Figure 7. Identification of the primary structure for a dense graded gradation.

In Figure 7 the calculations for the primary structure are presented for a dense graded type of gradation. It is possible to observe in the figure, that particle sizes from 11.2 mm sieve down to the 2 mm are interactive. The total concentration of the interactive sieves is 60 %, which is larger than any individual size, which means that the interactive range is the primary structure of the gradation.



Stone Mastic Asphalt

Sieve size	Passing [%]	Retained [%]
22,4	100	0
16	98,2	1,8
11,2	48,4	49,8
8	33,6	14,8
5,6	27	6,6
4	24,6	2,4
2	20,9	3,7
1	16,9	4
0,5	14,5	2,4
0,25	13	1,5
0,125	11,4	1,6
0,063	8,5	2,9
Filler		8,5

$\bar{D}$	φ
27,2	0
19,2	1,8
13,6	49,8
9,6	14,8
6,8	6,6
4,8	2,4
3,0	3,7
1,5	4
0,75	2,4
0,375	1,5
0,188	1,6
0,094	2,9
0,032	8,5

D_{avg}	*Min*	*Max*	Interaction?
19,2	21,6	24,8	No
13,8	15,3	17,5	No
12,7	10,8	12,4	No
8,7	7,6	8,8	Yes
6,3	5,4	6,2	No
3,7	3,5	4,3	Yes

Figure 8. Identification of the primary structure for a stone mastic asphalt gradation.

On the other hand, the calculations presented in Figure 8 show the case of an SMA gradation, where interaction is found in two groups: particles retained on 8 mm down to 5.6 mm (included), and particles retained on 4 mm sieve down to 2 mm sieve. The concentrations of each group are 21.4 % and 6.1 %, respectively. In this case, the individual sieve size 11.2 mm has a concentration (percent retained) of 49.8 %, which is higher than the identified interactive groups, therefore making this individual sieve size the primary structure of the gradation.

It may be observed that the results of the given examples are equal to the ones obtained by the dominant aggregate size range approach. This is due to the fact that particles have been considered as spheres, the distribution assumed within each sieve has been considered to be uniform (B=0.5) with discrete particle size, and that every other sieve size in the European sieve system has a ratio of 2:1. The gradation-based framework presents, however, the possibility to vary these three parameters.

Porosity of the Primary and Secondary Structure

Porosity has been used in packing theory as a parameter to evaluate the packing density of an arrangement. The calculation of the primary structure porosity (n_{PS}) is based on the general definition of porosity (equation [2]) where the total volume is calculated as the combination of the volume of all the mixture´s components (aggregates, binder and air voids) minus the volume of the aggregate larger than the PS ($V_{agg}^{oversized}$). The volume of voids will be represented by the total volume minus the volume of aggregate belonging to the primary structure range (V_{agg}^{PS}).

$$n_{PS} = \frac{V_T - V_{agg}{}^{oversized} - V_{agg}{}^{PS}}{V_T - V_{agg}{}^{oversized}} \quad [15]$$

To calculate the porosity of the secondary structure (η_{SS}) it is necessary to look at the total volume as a system formed by bitumen binder (V_b), fines ($V_{agg}{}^{<SS}$), SS and air voids (V_{av}). The volume of voids in this system is everything except the secondary structure (equation [16]).

$$n_{SS} = \frac{V_b + V_{agg}{}^{<SS} + V_{av}}{V_T - V_{agg}{}^{\geq PS}} \quad [16]$$

Binder distribution on the Primary and Secondary Structure

In the framework presented in this thesis and described in paper I (Lira, et al., 2013), particles with size below the smallest sieve size and the bitumen binder are considered to form a composite material called mastic. This mastic will be the material that coats the secondary structure (SS) with thickness t_{SS}. It is expected that if this coating is too thin, there will be insufficient 'glue' between the particles of the SS, making it react as granular material instead of an asphaltic composite, which may lead to a brittle response under loading. The mixture of mastic and SS will then cover the PS, coating it with thickness t_{PS}. The thickness of this coating will be related to the packing configuration of the PS and the percentage of air voids in the mixture, as the coat will represent the distance between the air void/binder interface and the aggregate/binder interface.

This hierarchical distribution system considers two parameters: coating thickness of the SS (t_{SS}) and coating thickness of the PS (t_{PS}). To be able to use the concepts introduced by Cooke & Rowe (1999), the packing arrangements of the mixture must be determined. This is obtained from the coordination number (m'). The coordination number (equation [17]) is the continuous relationship between contact points and porosity, and it has been defined based on the four theoretical packing arrangements, making it valid only within these cases (extrapolation is not valid).

$$m' = 2.827 \cdot \eta^{-1.069} \quad [17]$$

In Table 5 all the parameters from the gradation-based framework have been calculated for the two example mixtures presented earlier in this thesis. In the table, d_p represents the weighted average diameter for respectively the primary and secondary structure and t is the coating thickness around each structure.

Table 5. Calculated parameters from the gradation-based framework for a dense graded and a stone mastic asphalt mixture type

Mixture	Range [mm]	η	m'	d_p [mm]	*t* [mm]
			Primary Structure		
Dense graded	2 – 11.2	0.481*	<6	8.9	3.06
SMA	11.2	0.584*	<6	13.8	5.61
			Secondary Structure		
Dense graded	0.063–2	0.483*	<6	1.3	0.45
SMA	0.063–2	0.430	7.0	1.1	0.02

* The porosity is higher than for a simple cubic arrangement.

It may be observed on Table 5 that the SMA mixture presents a thin film of mastic around the secondary structure, but a relatively thick film around the primary structure. This may be attributed to the fact that all aggregate material smaller than 11.2 mm acts as coating material for the primary structure. In the case of the primary structure, the thickness of the coating depends mostly on the difference in porosity between mixtures, where the dense graded mixture presents almost a simple cubic packing while the SMA has a higher porosity with more space between particles to be filled. On the other hand, for the secondary structure it is the SMA that presents a structure slightly denser that the simple cubic packing arrangement, decreasing the amount of space between particles, though obtaining a much lower film thickness. To calculate the coating thickness for cases with porosities higher than the simple cubic arrangement (* in Table 5) the distance between coated particles must be taken into account, as explained on paper II (Lira, et al., 2015).

V. Experimental study

The main objective of the experimental part of this study is to assess, empirically, the ability of the gradation-based framework to evaluate the susceptibility to permanent deformation of mixtures with different aggregate gradations. The framework as calculated in this thesis, as well as the DASR approach, is based on two main premises: (1) the response of an asphalt mixture can be inferred from a model based on a system of different sized spheres and, (2) concepts from the packing theory of spheres may be applied to granular assemblies as in an asphalt mixture.

The experimental plan was divided in two parts: test the influence of gradation on permanent deformation and the ability of the gradation-based framework to predict laboratory performance when using the same parameters as the DASR approach, and secondly, investigate the assumption that spheres can be used to identify the load-bearing structure of mineral aggregate gradations. The first experiment investigates the influence of varying gradations and the second varying particles shapes.

Test methods

All mixture design has been done using the Marshall mix design method by which the optimal binder content is determined for a given gradation to achieve a target air void content. The Marshall stability test has been performed on all mixtures in this investigation.

To have a broad characterization of resistance to permanent deformation, two different laboratory methods representing different modes of testing, have been used during the experimental part of this study: wheel track and cyclic compression test. To characterize the particle shape for the second part of the experimental study, the Flakiness Index method was used. In the following chapter all of these methods are described in detail.

Marshall stability test

The Marshall mix design method was originally developed in the 1900’s by Bruce Marshall of the Mississippi Highway Department and then modified by the U.S. Army Corps of Engineers from a need to design/manufacture asphalt mixtures that could resist heavier loads. The Marshall mix design method selects the optimal binder content at a desired air void content that satisfies minimum stability and range of flow values. As a part of the Marshall mix design method, the Marshall stability test has been widely used to assess the performance of asphalt mixtures. The stability value has been considered as a measure of the resistance of the specimen to develop internal shear planes and the flow value is considered to measure the plasticity of an asphalt mixture (White, 1985).

The Marshall mix design method consists of 6 steps:

1. Select the aggregate gradation.
2. Select the bitumen binder type.
3. Prepare the samples. In this investigation, 3 different binder contents were tested for every gradation with 3 samples for each case, in accordance with EN 12697:30.
4. Test with the Marshall stability apparatus at 60 °C.
5. Report the results for stability, flow, air void content and density.
6. Select the optimum bitumen binder content.

Figure 9 presents a graphical representation of the definitions for stability, S, and flow, F, based on the results of the Marshall stability test.

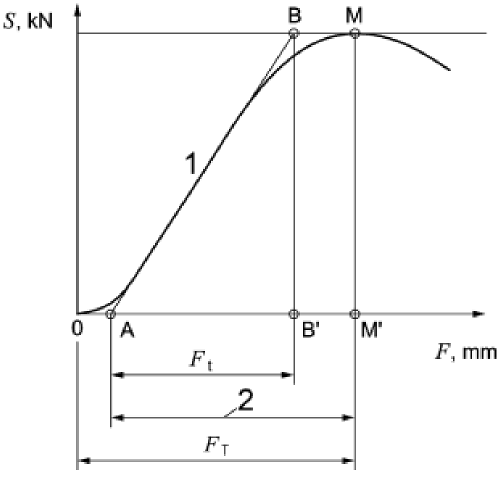


Figure 9. Marshall stability and flow; definitions of measured parameters from EN 12697-34 (2020).

The Marshall mix design method is widely used around the world, even though the type of testing involved is most suitable for dense graded mixtures, which give the highest stability values. Deciding whether the asphalt mixture will be satisfactory at the selected design bitumen binder content is guided by applying certain limiting criteria to the mixture test data. The Marshall method mix design criteria in Table 6 are recommended by the Asphalt Institute.

Table 6. Typical Marshall design criteria, ESALs: equivalent standard axles (Asphalt Institute, 2014)

	< 10^4 ESALs		**10^4 –10^6 ESALs**		**> 10^6 ESALs**	
Mix Criteria	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Compaction (nr. of blows on each end)	35		50		75	
Stability [N]	2224		3336		6672	
Flow (× 0.25 mm)	8	20	8	18	8	16
Air Voids [% by vol.]	3	5	3	5	3	5
VFA [% by vol.]	70	80	65	78	65	75

The optimum binder content of the asphalt mixture is selected by considering all of the data given in Table 6 (plus VMA, which also depends on maximum nominal aggregate size and target air void content). For example, the Asphalt Institute recommends choosing the binder content at the median of the percent air voids limits chosen. If all of the calculated and measured mixture properties at this binder content meet the mix design criteria, then this is the optimum bitumen binder content for the mixture. However, if not all of the design criteria are met, then some adjustment or compromise is necessary, or the mix may need to be redesigned.

In this investigation and based on the defined gradations at each case, binder contents were determined according to the Marshall mix design procedure with a target air void content of 3 % by volume.

Wheel tracking test

Wheel track testing is a simulative type of test used to assess the susceptibility of bituminous material to deform by measuring the rut depth formed by repeated passes of a loaded wheel at a fixed temperature (EN 12697-22, small size device, procedure B in air). The load is applied by a rolling wheel (700 ± 10 N) for 10 000 cycles (20 000 crossings) and the rut depth is measured on 25 points along a 10 cm line in the middle of the specimen. In addition to the final rut depth, the wheel-tracking slope [WTS_{air}, mm/1000 cycles] is computed as:

$$WTS_{air} = \frac{(d_{10000} - d_{5000})}{5} \qquad [18]$$

where d_{10000} and d_{5000} is the rut depth after 10 000 and 5 000 cycles, respectively. Initial deformation is defined as rutting after 500 cycles. Figure 10 shows the device used in this investigation to the left and to the right one of the slabs after being tested.

Figure 10. Wheel tracking test device (left) and specimen after testing (right).

In this study, the specimens were manufactured at 160 °C and compacted with a roller compactor in moulds to a final thickness of 60 mm for the gradation analysis and 50 mm for the particle shape analysis. Testing temperature was 50 °C. The results were expressed as the mean proportional rut depth, PRD, as a way to make all results comparable. The mean proportional rut depth is the mean value of the final rut depth normalized by the specimen's thickness.

Requirements for the maximal rut depth vary between different authorities. As an example, Table 7 gives the requirements from the Norwegian Public Road Administration for maximal allowed rut depth, expressed as a percent of the sample´s thickness (PRD, %).

Table 7. Requirements for resistance to permanent deformation measured with the wheel tracking test (The Norwegian Public Roads Administration, 2018)

	Annual daily traffic	
Asphalt layer	**5001–10 000**	**> 10 000**
Wearing course	7	5
Binder course	7	5

Cyclic compression test

The cyclic compression test (EN 12697-25, with confinement) is a type of test which makes it possible to rank various mixtures or to check the acceptability of a given mixture. This test does not easily allow for making quantitative predictions of rutting in the field, as neither do the wheel tracking test.

In this investigation method A1 was used, which determines the creep characteristics of bituminous mixtures by means of a uniaxial cyclic stress applied on cylindrical test specimens. To achieve a certain confinement, the diameter of the loading platen is smaller than that of the test specimen (Figure 11). The applied load, in this method, is done by square shaped stress pulses.

Figure 11. Uniaxial cyclic compression test with confinement.

Figure 12 presents a typical example of stages that may be distinguished when performing the cyclic compression test, where *n* is the number of loading cycles and ε_n is the cumulative axial strain.

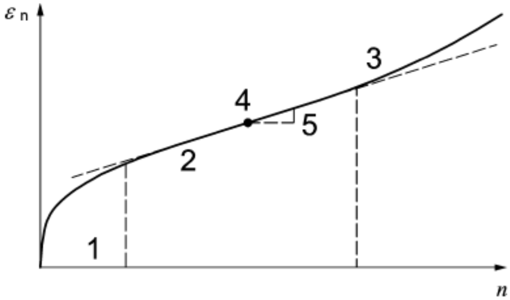


Figure 12. Creep curve from cyclic compression test: vertical strain as a function of load pulses.

In Figure 12, stage 1 represents the initial part of the creep curve where the slope decreases with increasing number of loading cycles, stage 2 is the part of the curve where the slope is quasi constant and can be expressed by the creep rate, f_c (nr. 5 in the figure), and stage 3 is the last part of the creep curve where the slope increases with increasing number of loading cycles. Point 4 in the figure represents the inflection point of the creep curve. It may be added that none of the samples tested during this study reached stage 3 of the creep curve.

To be able to evaluate rutting susceptibility at similar levels of compaction between the cyclic compression test and the wheel tracking test, i.e. comparable results at the same air void content, specimens for cyclic compression testing were manufactured with a gyratory compactor at 6 different packing levels (Figure 13). In this case, the specimens were compacted with a gyratory compactor at different number of gyrations: 25, 50, 80, 120, 160 and 200, respectively. The specimens were cylindrical with a diameter of 150 mm and height 60 mm. Cyclic loading was applied as square shaped loading, 0–100 kPa on a plate with a diameter of 96 mm, at a frequency of 0,5 Hz for a total of 3600 pulses. Testing temperature was 40 °C. The cumulative permanent deformation is the vertical displacement after *n* loading cycles, and the creep rate is calculated as the slope of axial strain between 500 and 3600 cycles, which is assumed to be the end of stage 2.

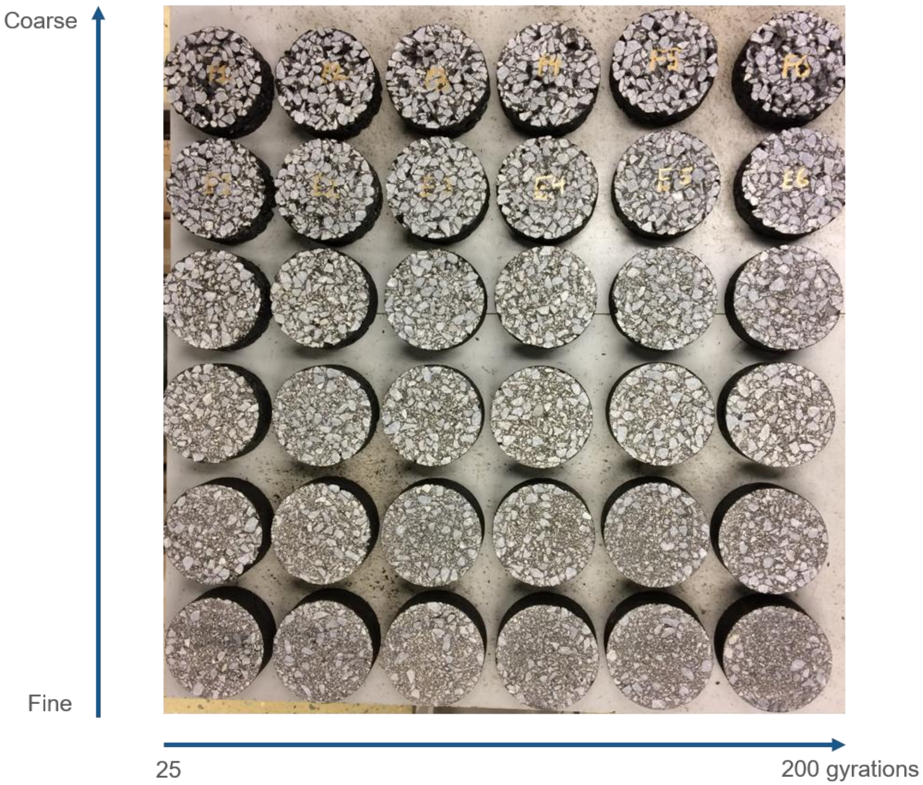


Figure 13. Samples tested with the cyclic compression test, mixtures A to F with varying gradations and compacted using varying number of gyrations.

Figure 13 shows all the samples tested with the cyclic compression test, from mixture A in the bottom to mixture F on the top, and with the least packing effort on the left to the highest on the right.

Flakiness Index

The flakiness index of aggregates is the percentage by weight of particles whose smallest dimension (thickness) is less than three fifths of their mean dimension (European Committee for Standarization, 2012). The determination of flakiness index is a characterization of particle shape and not a performance test.

According to EN 933-3, the test is performed in two sieve operations. The first one done with square sieves to separate the sample into various particle size fractions d_i/D_i, minimum/maximum particle size, and the second one is performed with bar sieves which have parallel slots of width $D_i/2$, as shown in Figure 14. The overall flakiness index is calculated as the total mass of particles passing the bar sieves expressed as a percentage of the total dry mass of particles tested. The flakiness index of each particle size fraction d_i/D_i is calculated as the mass of particles passing the corresponding bar sieve, expressed as a percentage by mass of that particle size fraction.

Figure 14. Square sieve (left) and bar sieve (right) for flakiness index.

The particle shape analysis performed during this investigation has focused mainly on fraction 11.2–16 mm, which means that the flakiness index has been determined to the sieve sizes summarized in Table 8.

Table 8. Sieve sizes for measuring flakiness index according to EN 933-3

Particle size fraction di/Di [mm], square sieve	**Width of slot in bar sieve [mm]**
12.5/16	8±0.2
10/12.5	6.3±0.2

Results

As previously mentioned, the experimental part of this investigation has been divided in two parts. The first part aims to validate the basic principle of the gradation-based framework: there is a load-bearing structure within the aggregate material that is related to the ability of a mixture to resist permanent deformation, and is presented in paper III (Lira, et al., 2019). The second part of the laboratory investigation is based on mixtures with the same aggregate gradation but varying flakiness index, as described in detail in paper IV.

Aggregate gradation experiment

The aggregate gradation experiment covered 6 aggregate gradations ranging from fine-dense to gap graded, where laboratory prepared specimens of each mixture were tested with the wheel tracking test and cyclic compression test. Each mixture had aggregate material from the same source and the gradation had a maximum nominal aggregate size of 16 mm. The gradations that were tested were determined based on the two most common gradations used in Sweden as a wearing course: a dense graded gradation (B and C) and a stone mastic asphalt (E). One additional mixture was included between these curves (D), and two extreme mixtures (A and F) that are outside of the specifications (The Swedish Road Administration, 2013), as shown in Figure 15.

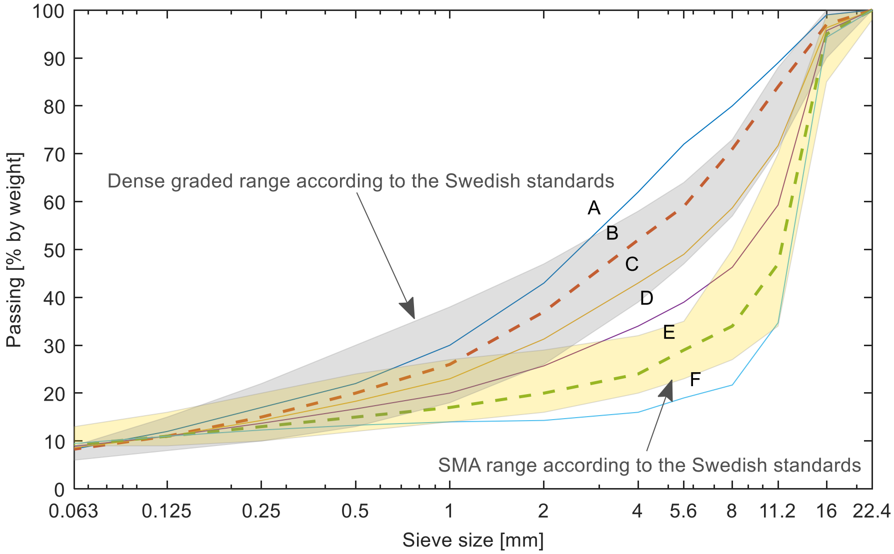


Figure 15. Gradation curves for mixtures A to F of the aggregate gradation analysis.

As it may be observed in Figure 15, the distance between the gradation curves has been chosen to challenge the limits given by the specifications. It can be noted that expanding the study to more mixtures in between becomes irrelevant as such precision does not exist in the production of asphalt mixtures where tolerances are usually around ± 5 % by weight. The difference between the mixtures can also be compared to the specification ranges; all gradations that are within the range are denoted the same and should presumably show similar functionality.

Mixtures A to F were characterized according to their aggregate gradation using the gradation-based framework and the results are given in Table 9. In the same table, characterization by the Bailey method and the DASR approach have been included for comparison.

Table 9. Aggregate gradation characterization of mixtures in the experiment

	Mixture					
	A	**B**	**C**	**D**	**E**	**F**
Gradation-based framework						
Primary Structure content [%]	56.0	60.0	65.0	36.4	48.0	59.6
Primary Structure range [mm]	2–11.2	2–11.2	2–11.2	11.2	11.2	11.2
Secondary Structure content [%]	34.7	28.7	22.7	50.4	37.8	25.2
Secondary Structure range [mm]	0.063–2	0.063–2	0.063–2	0.063–8	0.063–8	0.063–8
PS/SS	1.61	2.09	2.86	0.72	1.27	2.37
Bailey method						
CA ratio	0.90	0.66	0.38	0.23	0.15	0.07
FA_c	0.48	0.50	0.53	0.59	0.71	0.88
FA_f	0.57	0.58	0.62	0.69	0.76	0.88
DASR						
DASR Porosity [%]	44.0	40.0	35.0	63.6	52.0	40.4
DASR range [mm]	2–11.2	2–11.2	2–11.2	11.2	11.2	11.2

As mentioned earlier, the design of the mixtures was done to obtain a large variance in aggregate gradation. This can be observed once more on the primary structure content presented in Table 9, which ranges from only 36.4 % for mixture D to 65 % for mixture C. It may be noted that the minimum and maximum PS mixtures actually correspond to gradations that are right close to each other in the visual presentation of the gradations in Figure 15. Mixture D has a primary structure that does not represent even a simple cubic packing according to packing theory, which is the minimum concentration for the particles to even be in contact and form a structure. This means that mixture D might be outside of the boundaries where the gradation-based framework may be applied.

The Bailey method defines limits for the different ratios, with different limits in case of SMA mixtures (in this case mixture D, E and F are considered as SMA), and for NMPS according to the sieve system used in the USA. To be able to apply this method, the limits for a mixture with NMPS 16 mm has been determined by interpolating between 12.5 mm and 19 mm limits, as given in Table 10. The results show that there is no mixture that has all of the ratios within the given limits. The DASR approach gives quite similar results to the gradation-based framework, considering that *DASR porosity = 1 – PS content*, when using spheres and uniform distributions within sieve sizes.

Table 10. Bailey method limits for NMPS 16 mm (interpolation)

	NMPS 16 mm	
	General	**SMA**
CA ratio	0.55–0.70	0.30–0.45
FA_c and FA_f	0.35–0.50	0.63–0.88

The Marshall mix design method was used to determine the optimal binder content for each mixture (Table 11). All mixtures have the same bitumen binder type 70/100 from the same provider.

Table 11. Key Marshall properties for mixtures A to F of the aggregate gradation analysis

	Mixture					
	A	**B**	**C**	**D**	**E**	**F**
Binder content [% by weight]	5.8	6.0	5.8	5.9	5.9	5.9
Marshall air voids [% by vol.]	3.6	1.5	1.2	1.2	2.6	6.4
Marshall stability [N]	11800	11400	10000	7900	6300	3500
Marshall flow [mm]	3.33	4.24	4.48	3.82	2.85	2.91
Stability/flow [kN/mm]	3.54	2.69	2.23	2.07	2.21	1.20

As noted in Table 11, there is only a small difference in binder content between the mixtures, which is also reflected on the air void content, except for gradation F. The Marshall stability decreases steadily with increased coarseness of the mixtures, while the flow value reaches its maximum for mixture C and minimum for mixture

E. The ratio of stability to flow has been called the Marshall stiffness, and has been used as a measure of the material´s resistance to permanent deformation (Tapkin, et al., 2010). The load-bearing capacity of an asphaltic mixture is a function of the flow value as well as the stability, and reveal the inadequacy of the usual specifications which call for only a minimum stability and maximum flow (Metcalf, 1959). In this case the Marshall stiffness decreases with increased coarseness, except for mixture E which has a higher stiffness than mixture D.

Particle shape experiment

The particle shape experiment is based on 5 mixtures with the same aggregate gradation, but varying flakiness index of the coarse fraction. In this case, a stone mastic asphalt (SMA) type of mixture has been chosen due to its high amount of coarse aggregate, which allows for a stricter control of the amount of flaky particles in the mixture. An SMA mixture type has been chosen for this experiment as it is generally assumed to be more sensitive to small deviations in the coarse particle fractions compared to continuously graded asphalt mixtures, as its resistance to permanent deformation relies on the stone-to-stone contact.

In this case, two different sources for the aggregates were used: aggregates smaller or equal to 4 mm from a quarry outside of Stockholm (Arlanda), and material larger or equal to 5 mm from a quarry in Karlstad (Alster). As the aggregate gradation curve in this case is fixed, the optimum binder content according to the Marshall mix design method was determined only for a reference mixture, with unmodified flakiness index. Results from the Marshall mix design gave an optimal bitumen content of 6.2 % by weight with an air void content of 3.2 % by volume. All mixtures tested have a 0.3 % by bitumen weight of fibre to prevent drainage.

The SMA curve used in this part of the study corresponds to the same aggregate gradation curve used as an example during the background chapter (Figure 2). This curve has 64 % of the aggregate material within the fraction 11.2–16 mm. To be able to change the flakiness index, this fraction was separated into 2 smaller groups using square sieves: 10–12.5 mm (30 % by weight) and 12.5–16 mm (70 % by weight), respectively. Subsequentially, these 2 fractions were sieved one more time using bar sieves, as given in Table 8, to separate the flaky particles from the non-flaky particles. The flakiness index of the entire fraction is 11, with a FI of 7 for the 10–12.5 mm fraction and 13 for fraction 12.5–16 mm. The 5 tested mixtures were designed by using relative proportions of flaky and non-flaky aggregates from each subfraction, creating mixtures with total nominal flakiness as given in Table 12.

Table 12. Nominal flakiness index for mixtures F0 to F40

Mixture	**Flakiness Index (FI)**		
	10–12.5 mm	**12.5–16 mm**	**Total**
F0	0	0	0
F10	7	13	10
F20	16	22	19
F30	26	32	28
F40	36	42	37

In Table 12, mixture F10 represents the reference mixture i.e. the mix using unmodified aggregate fractions with default shape properties. The other mixtures were composed of bar sieve separated particles to reach predetermined flakiness levels. The Marshall stability for the reference mixture was 5.5 kN and the flow value was 4.22 mm, giving a ratio of 1.3 kN/mm.

Table 13 presents the aggregate gradation characterization according to the gradation-based framework. In this part of the investigation, the bitumen binder and aggregates from the Marshall samples were extracted (according to EN 12697-1) after testing to determine the gradation curve and flakiness index after mixing, compaction and testing. The values presented in Table 13 are the results after extraction.

Table 13. Aggregate gradation characterization, particle shape analysis after sample manufacturing and testing

	Mixture				
	F0	**F10**	**F20**	**F30**	**F40**
Gradation-based framework					
Primary Structure content [%]	49.7	48.5	46.9	47.9	48.4
Primary Structure range [mm]	11.2	11.2	11.2	11.2	11.2
Secondary Structure content [%]	37.9	38.6	41.2	40.1	39.8
Secondary Structure range [mm]	0.063–8	0.063–8	0.063–8	0.063–8	0.063–8
PS/SS	1.31	1.26	1.14	1.19	1.22

As it may be observed in Table 13 there is almost no difference between mixtures, showing that mixing, compacting and testing according to the Marshall produce does not significantly change the gradation curve or the parameters calculated by the framework.

Summary of findings

In this section all the results from both parts of the experimental study are presented and analysed. Two factors were investigated: gradation and particle shape. For this, cyclic compression tests and wheel tracking tests were performed to evaluate resistance to rutting.

In both parts of the experimental study the wheel tracking test was used to characterize the resistance to permanent deformation of the different mixtures. Table 14 summarizes results from all mixtures tested in this project.

Table 14. Wheel tracking test results for all mixtures

Mixture	Air voids [% by vol.]	Initial rut, d_{500} [mm]	Slope, WTS_{air} [mm/1000 cycles]	Final rut, d_{10000} [mm]	PRD [%]
A	2.3	2.3	0.13	4.7	7.6
B	1.6	4.5	0.36	10.4	17.1
C	1.2	4.1	0.20	7.9	13.0
D	1.0	3.3	0.11	5.7	9.3
E	2.1	1.6	0.09	3.2	4.8
F	4.8	2.6	0.18	5.7	8.5
F0	1.0	1.5	0.08	3.4	6.6
F10	1.0	1.4	0.06	2.9	5.5
F20	1.9	1.4	0.07	3.1	5.9
F30	1.4	1.2	0.06	2.6	5.1
F40	2.1	1.3	0.08	3.0	5.7

As it may be observed in Table 14, the air void content in both experiments vary within a small range, where mixtures with similar gradation (SMA: mixture E and mixtures F0 to F40) have similar levels. The wheel tracking slope represents the deformation rate that the sample experiences during testing after a certain initial stage. It may also be observed that the mixtures from the second experiment show a much lower value for the slope compared to the mixtures from the first experiment. Overall, the mixture that showed the worst resistance to permanent deformation is mixture B followed by mixture C, both with a dense graded gradation. The highest resistance to rutting is achieved by mixture E, followed by F30. Both these mixtures have a standard SMA gradation. When just observing the results from the second part of the experimental study, it may be noted that varying the flakiness index of a mixtures when having the same gradation, produces almost no difference as compared to the influence of the aggregate gradation curve in relation to the resistance to permanent deformation.

Figure 16 shows the results from the wheel tracking test for all the mixtures investigated in this study. The left side of Figure 16 shows the parameters air void content, initial rut, slope and percent rut depth on each individual axis plotted versus primary structure content on the x-axis. The right side shows the same parameters plotted versus the amount of coarse material in the gradation in the x-axis instead. To determine which fraction is to be considered as coarse, the primary control sieve (PCS) from the Bailey method has been used, obtaining that for a mixture with maximum nominal particle size of 16 mm the PCS is 4 mm.

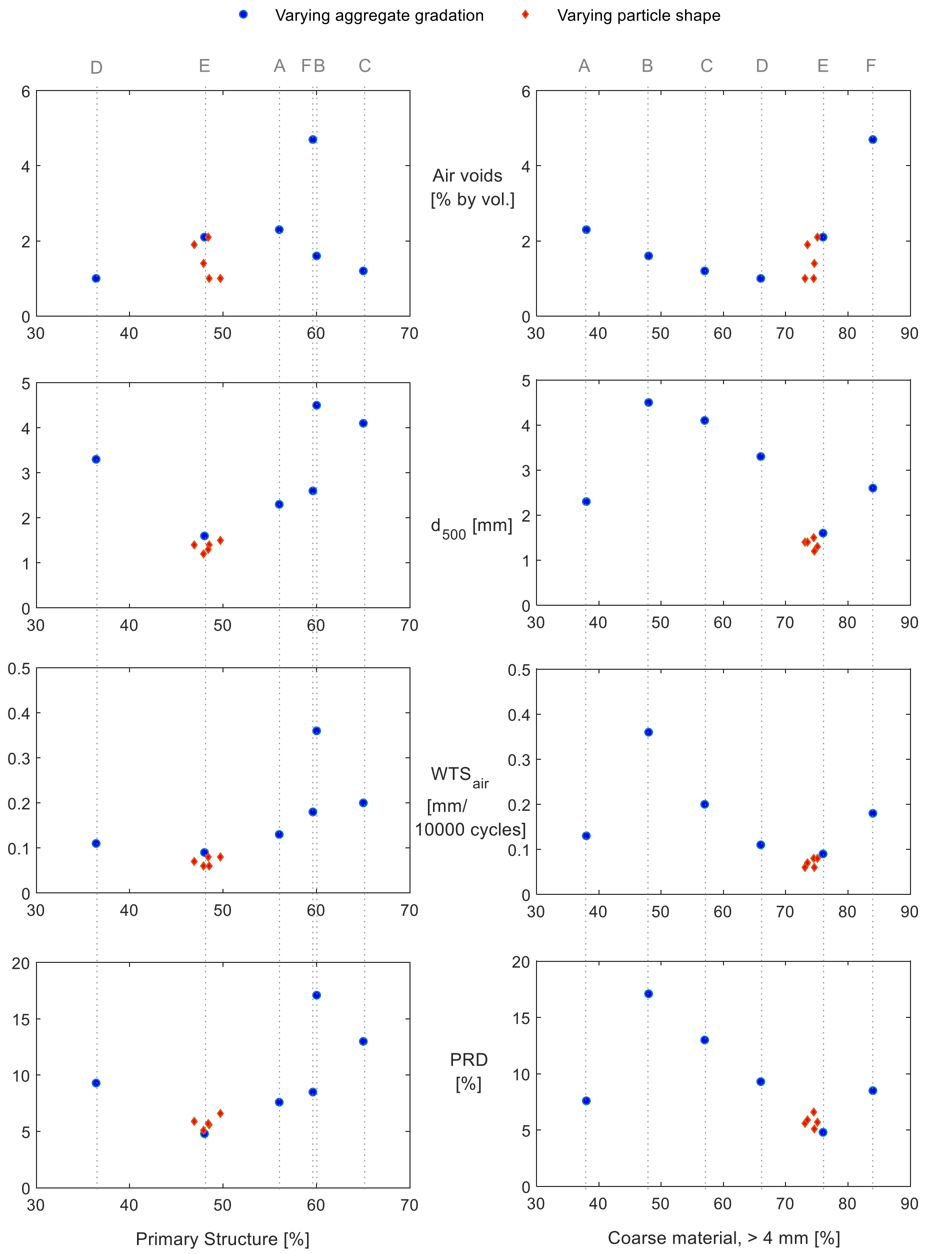


Figure 16. Wheel tracking results for all mixtures versus primary structure (left) and percent coarse material (right).

According to the gradation-based framework, mixtures with similar primary structure are expected to perform in a similar way, however, and as observed on the left side of Figure 16, mixtures B and F differ in almost all of their wheel tracking test results, despite having similar primary structure (60 %). Mixture F shows, for example, half of the total deformation (PRD) as compared to mixture B, and more than double of the air voids content. Mixture E, with a PS content of 48 %, presented the highest resistance to permanent deformation. By using instead, the amount of coarse material as a classification system for the different mixtures, a clear difference between mixtures with varying gradation may be observed. It is important to remember that mixtures A and F are cases outside of the specifications, representing mixtures that are not actually being produced (in Sweden). This means that, if these two mixtures are removed from the analysis, then a significant linear relationship may be found between amount of coarse material and the resistance to permanent deformation. Furthermore, including the mixtures from the second part of the experimental study shows that mixtures with similar aggregate gradation curve perform similarly, even when having significantly different flakiness index.

Included in the first part of the experimental study was also testing the different mixtures with the cyclic compression test. Results from the cyclic compression test are summarized in Table 15. The values presented in Table 15 are calculated based on the air void content from the wheel tracking test samples. This was achieved using a linear regression of rutting parameters as a function of air voids giving the possibility to determine the permanent deformation and strain, as well as the creep rate, for a specific air void content.

Table 15. Cyclic compression test results for mixtures A to F at wheel tracking air void level

Mixture	Initial cumulative permanent deformation, u_{500} [mm]	Creep rate [mm/1000 cycles]	Total cumulative permanent deformation, u_{3600} [mm]
A	0.20	0.29	0.26
B	0.21	0.39	0.27
C	0.22	0.41	0.30
D	0.15	0.16	0.18
E	0.23	0.26	0.28
F	0.39	1.39	0.65

It may be observed in Table 15 that mixture D shows the lowest cumulative permanent deformation, both initial and total, as well as the lowest creep rate, while mixture F shows the highest cumulative permanent deformation, both initial and total, as well as the highest creep rate. Figure 17 plots the results from the cyclic compressive test versus primary structure (left) and the total amount of coarse material (right).

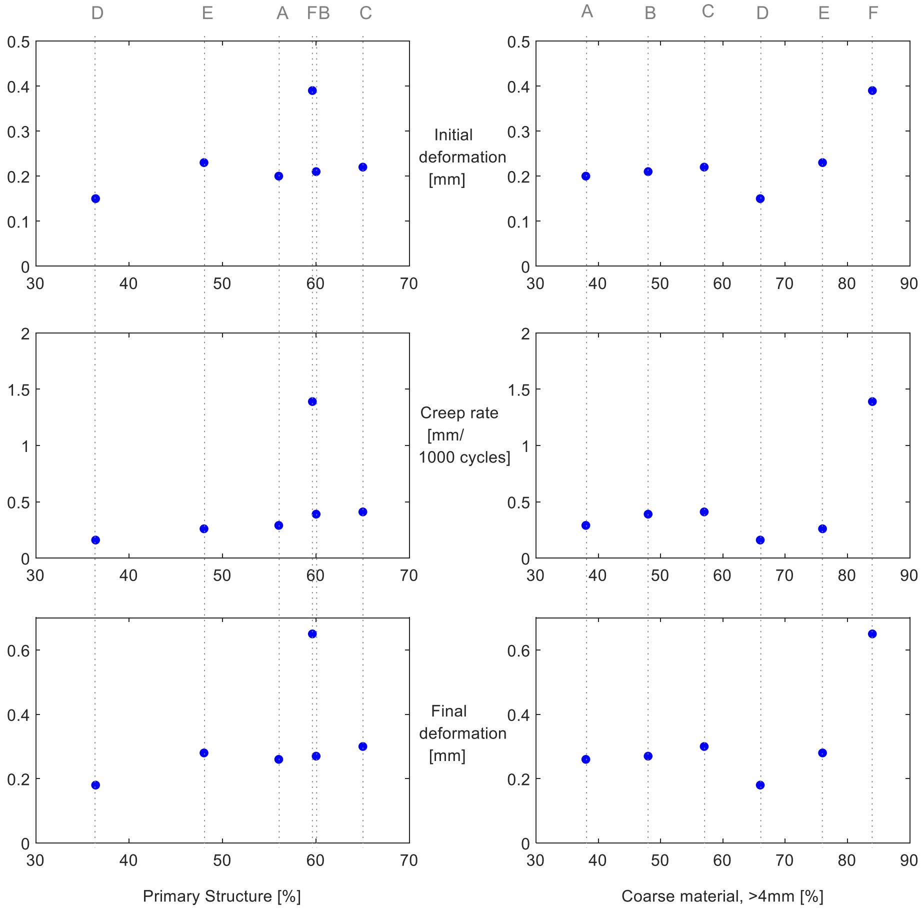


Figure 17. Cyclic compression test results for mixtures A to F versus primary structure (left) and percent coarse material (right).

In general, in Figure 17 it may be observed that results for neither initial nor final deformation show any clear difference between varying levels of primary structure. It is clear that mixture F behaves differently as its results are almost double than the rest of the test series, as also observed from the wheel tracking results. Furthermore, no clear relationships may be established when comparing the cyclic compression test results to the amount of coarse material (right side of Figure 17).

As mentioned earlier, the Marshall stability test is not considered a performance test, but it has been used in the past as a performance predictor or for qualitative assessment where the stability value is used as a measure of the resistance of the specimen to develop internal shear planes and the flow value as a measure of the plasticity of an asphalt mixture (White, 1985). The Marshall stability test has been performed to all mixtures in this investigation and the results are given in Figure 18.

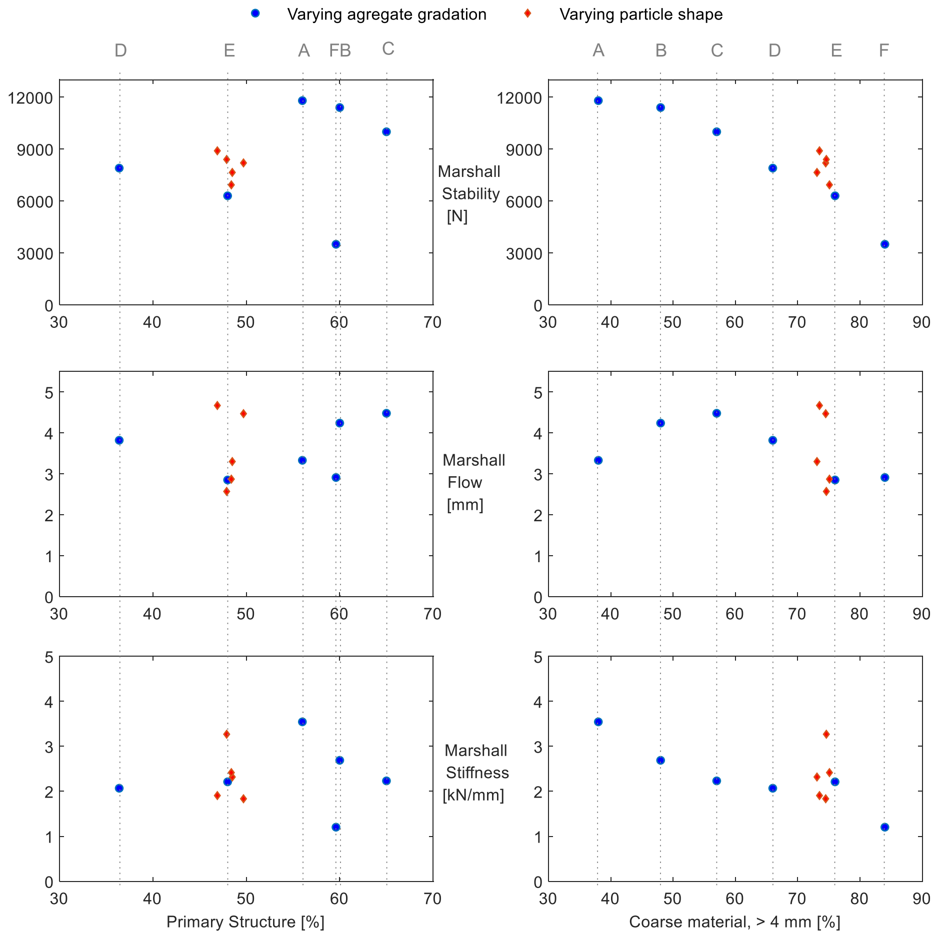


Figure 18. Marshall stability test results for all mixtures versus primary structure (left) and percent coarse material (right).

In general, it may be observed that none of the Marshall parameters show any correlation to the primary structure (left side of Figure 18). However, Marshall stability has a clear linear relation with the amount of coarse material in the gradation, where the coarser a gradation, the lower the Marshall stability becomes. It may also be observed that all mixtures satisfy the lower and medium traffic requirement for stability according to Table 6, and mixtures A to D and F0 to F40 satisfy even the requirement for high traffic roads.

On the other hand, the minimum limit for the Marshall flow according to the Asphalt Institute (2014) is 4 mm, which only mixtures B, C, F0 and F20 achieved. An interesting observation on the Marshall flow results is that, for the first time in this investigation, a difference may be observed between the mixtures with varying flakiness index, showing that the amount of flaky particles within the aggregates influences the deformation resistance according to the Marshall stability test.

Figure 19 shows an asphalt mixture sample with three defined axes to the left and the Marshall stability test device to the right with a sample after testing. A Marshall sample is commonly compacted with a hammer that applies a certain amount of blows on the z-direction, which is believed to produce a certain alignment of the aggregate particles, especially if these are flaky and/or elongated.

Figure 19. Marshall sample (left) and Marshall stability device after testing (right).

When the samples are tested on the Marshall stability apparatus, the load is applied on the radial axis (y-axis in the figure), which means that if the particles are aligned mostly horizontally after compaction, the load will be applied perpendicular to the particle’s main axis direction. However, whether this holds true was not investigated in this project.

The results from this investigation shows no agreement on regards to prediction of the resistance to permanent deformation between cyclic compression and wheel tracking test. This may be explained by three major differences in the testing procedure: (1) compaction of the specimen, (2) confinement during testing and (3) type of loading. A full analysis of these aspects and their implications is given in paper III (Lira, et al., 2019).

VI. Discussion

The gradation-based framework developed in the first part of this investigation provided a system to identify the range of aggregates that represents the load-bearing structure of an asphalt mixture. Other parameters were also included in the framework to represent all the components of a mixture, such as disruption factor and binder film thickness. These parameters are directly related to the primary structure content. Therefore, the bearing structure hypothesis is the first part to be empirically validated.

The results presented in the initial validation, with mixtures from an existing database (Lira, et al., 2013), identified that mixtures from the WesTrack field test, with a primary structure content of 83 %, showed a relatively high rut depth per million equivalent standard axles, while mixtures from the NCAT field test with PS content between 55 % and 75 % showed much lower rutting. There was no significant difference within the NCAT mixtures. The initial validation process also included laboratory mixtures which were evaluated according to their primary structure and compared to rutting results from the Asphalt Pavement Analyzer (APA). In this case, the mixtures had a primary structure between 27 % and 67 %. The results, however, showed no significant correlation between PS content and total rut depth.

The thickness of material around the PS was also considered during the first validation process. The theoretical development assumes that if the film thickness is too thin the mixture will be more susceptible to rutting and moisture damage, affecting the durability of the mixture. However, it is also assumed that above a certain thickness, the propensity for rutting and bleeding is increased as well as it may disturb the contact between load-bearing particles. Results of the field mixtures showed, once again, that the WesTrack mixtures with high rut depth grouped together on the lower end of the PS film thickness, while the NCAT mixtures, with low rutting, had all a film thickness greater than 1 mm around the PS.

The largest limitation of performing a validation from an external database is the lack of control of the variables and details of the experimental plan. In this case, for example, the field test mixtures are not only different in regard to the bitumen binder used and the overall mixture design, but they are also highly dependent on the environmental conditions of the test sites. In the case of the laboratory mixtures, different aggregate sources were used, granite and limestone, with different mineralogical composition, which influences the chemistry of the mixture, negatively affecting the ability to draw conclusions.

A second validation process was therefore included in the project, by testing mixtures in a controlled laboratory environment. The study included the evaluation of resistance to permanent deformation through 2 different test methods: the cyclic compression test and the wheel tracking test. The results showed no significant correlation in deformation between cyclic compression and wheel tracking. This may be due to 3 major differences in the testing procedures: compaction of the specimen, confinement during testing and type of loading. This results also highlights the importance of the test method used, and the limitations of the conclusions drawn from previous studies.

Even though the results obtained with the different test methods did not fully agree, a normalized analysis showed that there is an influence of aggregate gradation on the measured deformation of asphalt mixtures in the laboratory. The most influential assumption of the gradation-based framework is assumed to be particle shape. During the development of the framework it has been assumed that all particles are spherical and that the response of a system with spheres may represent the response of asphalt mixtures. However, it is likely that shape differences will affect the packing characteristics of a mixture, which is usually neglected in models assuming spherical particles. The development of an aggregate structure in asphalt mixtures and, most important, the resistance of a mixture to deform, is a combination of factors such as the gradation of the aggregates, their shape, surface texture and mineral composition, as well as the applied compaction that will arrange the aggregate matrix and the bitumen binder used.

As stated previously, the main objectives of this project were to develop a framework to characterize asphalt mixtures and give a statistical correlation to performance. This framework defined a parameter, the primary structure, that would describe the range of aggregate sizes that constitutes the load-bearing structure in a mixture. However, results have indicated that it is the total amount of coarse aggregate that might provide the load-bearing structure. The results from the original empirical research are summarized in Figure 20. The figure also includes results from the 2nd test series investigating influence of flakiness index.

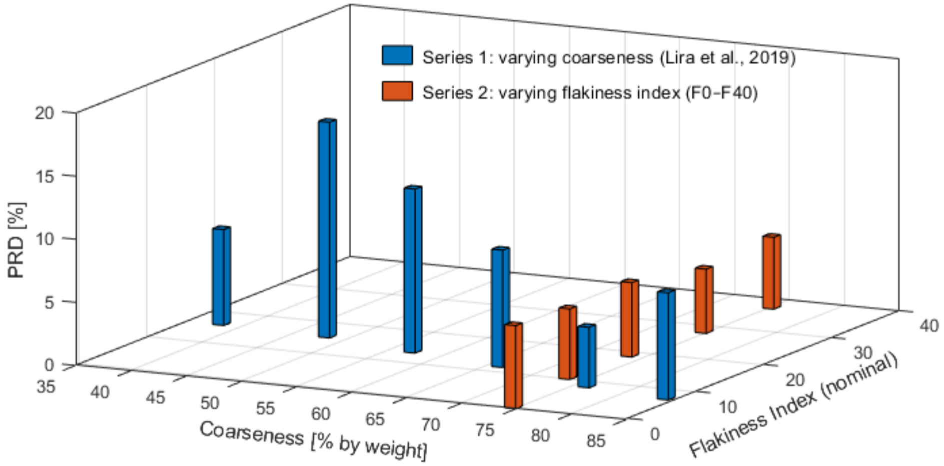


Figure 20. Summary of the results from wheel tracking test for all the laboratory mixtures included in the second validation process.

The wheel tracking test was used in both series for the experimental part. Figure 20 presents the percent rut depth (PRD) versus the amount of material greater than 4 mm (coarseness) and the flakiness index of the mixture. As it may be observed in the figure, the PRD measured in series 2 fits in accordance with the results from series 1 for mixtures with similar amount of coarse material. This indicates coarseness to be more influential than flakiness index with regard to resistance to permanent deformation.

Research is normally defined as a creative and systematic work performed to increase the stock of knowledge. Many times, this is made by further developing and/or testing already existing theories. By developing a framework and then testing its main assumptions, the researcher must always remember that there is a chance that results do not agree with the initial hypothesis. This is also considered as new knowledge, as knowing that something does not work is as important as knowing that it does. Results from this project have not entirely falsified the concept of an existing load-bearing structure within the aggregate gradation, but it has led to understanding that by directly using the amount of coarse fraction as the primary structure, a greater degree of explanation might be achieved in regards with permanent deformation of asphalt mixtures.

VII. Conclusions and future work

The work presented in this thesis has been divided in two parts, firstly the development of a gradation-based framework, and secondly, the experimental evaluation of the same framework and its assumptions.

The gradation-based framework is a tool to identify the range of aggregate sizes which presumably play a key role in the mechanical response of an asphalt mixture, denoted the primary structure, and the range of sizes that support the load-bearing structure, denoted the secondary structure. This framework can be applied regardless of the sieve system used, considering a continuous size distribution within each sieve size, and using common volumetric relationships. The framework has been developed so that different shapes may be considered to represent aggregates in asphalt mixtures. The mathematical expression in this thesis are though based on packing theory of spheres. The calculation of the binder coating thickness for the primary and secondary structure has been based on the relationship between film thickness and porosity of the different packing arrangements developed by previous researchers.

The experimental part of this study has focused on the evaluation of the relationship between resistance to permanent deformation of asphalt mixtures and the parameters determined using the gradation-based framework. Two experiments were carried out in this study: evaluation of resistance to permanent deformation for mixtures with varying aggregate gradation and for mixtures with varying aggregate particle shape.

The first experiment comprised laboratory measurements of rutting with six different asphalt mixtures, all of them with the same maximal nominal aggregate size and the same bitumen type and aggregate source, using wheel tracking and cyclic compression test. Hence, the main difference between the tested mixtures was aggregate gradation which was varied in a systematic way to represent mixtures from fine dense to coarse gap graded. The second experiment focused on the influence of particle shape, as quantified by the flakiness index, on resistance to permanent deformation of asphalt mixtures, tested with the wheel tracking test. All the tested mixtures had the same aggregate gradation and source, and bitumen type and content, but varying flakiness index on the coarse aggregate fraction, which was varied in a systematic way from 0 % to 38 %.

Based on the results obtained from the laboratory analysis and presented in this thesis, the following conclusions can be drawn:

- Primary structure showed no significant correlation with total permanent deformation on the 95% confidence level.
- For mixtures within the commonly specified limits, there is a significant linear relationship between coarseness and resistance to permanent deformation.
- Flakiness index showed no significant correlation with total rut depth from wheel tracking test.
- Empirical findings do not offer overall support for the hypothesis that particle shape strongly influence resistance to permanent deformation of SMA-type mixtures.
- Empirical findings do not offer overall support for the gradation-based framework.

Results from this investigation indicate limitations of the gradation-based framework to evaluate the susceptibility to permanent deformation of mixtures with different aggregate gradations. By considering the complete coarse fraction, improved relationships were established. This might be a consequence of the use of spheres in the calculated framework parameters. Spheres have been proven to reach the least density even when being packed in their densest way possible, resulting in a limiting criterion for determining the primary, or load bearing, structure of a mixture. In an attempt to challenge this theory, influence of particle shape on permanent deformation was also studied. The laboratory results showed nevertheless, only a weak influence of flakiness index on the resistance to permanent deformation of stone mastic asphalt.

The binder distribution model was developed within the gradation-based framework and based its calculations on the porosity and content of the primary and secondary structures. However, the concept of primary structure was not verified on the first part of the experimental study, showing that the total coarseness of a gradation had better prediction capabilities than the limited range determined by the primary structure. This means that the definitions and calculations for the binder coating thickness need to be redefined based on the total coarseness.

The main contributions from this project can be summarized as:

1. generalizing and extending an existing approach for asphalt mixtures, and
2. performing original empirical research through carefully planned experiments.

The first contribution has been already achieved as the framework has been further used at KTH in other doctoral student projects regarding e.g. binder aging

(Das, 2014) and cracking (Dinegdae, et al., 2015). In regards with the second contribution, the original experimental research isolated the influence of single factors to a degree not previously found in the literature.

Further research and laboratory experimentation is needed to determine the range of validity of the gradation-based framework. As a start point, calculations for primary and secondary structure could be made with other shapes with known minimum and maximum porosities and compared to the results obtained in the first part of the experimental study in this thesis. To further test the influence of shape, parameters other than flakiness index may be used to describe different mixtures. A very interesting aspect would be to investigate how varying shape properties influence the resistance to permanent deformation of other type of mixtures, for example dense graded mixtures.

This investigation has kept the influence of bitumen binder constant by always using the same bitumen type and having very small differences on bitumen content. But bitumen binder also plays an important role on asphalt mixture´s performance. An important next step to keep developing the understanding of asphalt mixture performance is to include bitumen type on the test series.

As mentioned in the introduction to this thesis, asphalt mixtures consist mostly of four elements: mineral aggregates, bituminous binder, air voids and sometimes additives. Each element has its inherent properties and they may be modified in endless ways. By understanding the way each and every one of these properties influence and affect the performance of asphalt mixtures can we, hopefully, produce more sustainable mixtures and more long-lasting roads.

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APPENDED PAPERS