Investigation of asphalt compaction in vision of improving asphalt pavements

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Licentiate thesis

Stockholm, November, 2015

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TRITA-BYMA 2015:5
ISSN 0349-5752
Printed in Sweden by USAB, Stockholm, 2015

Akademisk uppsats som med tillstånd av Kungliga Tekniska Högskolan I Stockholm framlägges granskning för avläggande av teknologie licentiatexamen fredagen den 24 novemeber kl. 13:00 i sal B3, KTH, Brinellvägen 23, Stockholm.

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Abstract

Asphalt joints are potentially weakest parts of every pavement. Despite of their importance, reliable tools for measuring their mechanical properties for design and performance assessments are still scarce. This is particularly true for cold joints when attaching a new hot pavement to a cold existing one as in case of large patches for pavement repair. In this study, three static fracture testing methods, i.e. indirect tensile test (IDT), direct tension test (DTT) and 4 point bending (4PB), were adapted and used for evaluating different laboratory made joints. The results suggested that joints with inclined interfaces and also the ones with combined interface treatments (preheated and sealed) seemed to show more promising behaviors than the vertical and untreated joints. It was also confirmed that compacting from the hot side towards the joint improved the joint properties due to imposing a different flow pattern as compared to the frequent compaction methods. The latter finding highlighted the importance of asphalt particle rearrangements and flow during the compaction phase as a very little known subject in asphalt industry. Studies on compaction are of special practical importance since they may also contribute to reducing the possibility of over-compaction and aggregate crushing.

Therefore, in this study, a new test method, i.e. Flow Test (FT), was developed to simulate the material flow during compaction. Initially, asphalt materials were substituted by geometrically simple model materials to lower the level of complexity for checking the feasibility of the test method as well as modeling purposes. X-ray radiography images were also used for capturing the flow patterns during the test. Results of the FT on model materials showed the capability of the test method to clearly distinguish between specimens with different characteristics. In addition, a simple discrete element model was applied for a better understanding of the test results as a basis for further improvements when studying real mixtures. Then, real mixtures were prepared and tested under the same FT configuration and the results were found to support the findings from the feasibility tests. The test method also showed its potential for capturing flow pattern differences among different mixtures even without using the X-ray. Therefore, the FT was improved as an attempt towards developing a systematic workability test method focusing on the flow of particles at early stages of compaction and was called the Compaction Flow Test (CFT).

The CFT was used for testing mixtures with different characteristics to identify the parameters with highest impact on the asphalt particle movements under compaction forces. X-ray investigations during the CFT underlined the reliability of the CFT results. In addition, simple discrete element models were successfully generated to justify some of the CFT results.

Key words: Cold asphalt pavement joints, asphalt joint laboratory production, IDT joint evaluation, DTT joint evaluation, 4PB joint evaluation, joints FEM analysis. Discrete Element Modeling (DEM), X-ray Computed Tomography (CT), Compaction Flow Test (CFT), Compactability

Sammanfattning

Asfaltsfogar är de potentiellt svagaste delarna av en vägkonstruktion. Trots detta är pålitliga verktyg för att bedöma deras mekaniska egenskaper för konstruktion och prestandabedömning fortfarande sällsynta. Detta gäller särskilt för kalla fogar när en ny varm beläggning läggs intill en kall befintlig beläggning som i fallet vid större lagningar av asfaltsbeläggningar. I denna studie applicerades tre statiska testmetoder för brott, dvs. indirekt dragprov (IDT), direkt dragprovning (DTT) och 4-punktsböjning (4PB) för att utvärdera olika laboratorietillverkade fogar. Resultaten visade att fogarna med lutande gränssnitt och även de med kombinerat behandlade gränssnitt (förvärmda och förseglade) uppvisar ett mer lovande beteende än de vertikala och obehandlade fogarna. Kompaktering från den varma sidan av fogen gav även bättre resultat på grund av ett annat strömningsmönster jämfört med den konventionella packningsmetoden. Det senare betonade även vikten av att förstå materialuppbyggnaden och partikelströmningarna under kompakteringsfasen vilket är ett outforskat område inom asfaltbranschen. Studier av kompaktering är av särskild praktisk betydelse eftersom de också kan bidra till att minska risken för överkompaktering och krossning av stenmaterialet.

En ny flödestestmetod har därför utvecklats i denna studie för att simulera materialflödet under packningen. Inledningsvis ersattes asfalt av modellmaterial för att sänka graden av komplexitet i syfte att kontrollera genomförbarheten av den nya testmetoden samt för modelleringsändamål. Geometriskt enkla material med tätast möjliga kombinationer testades för både torra och ytbehandlade blandningar. Röntgenbilder användes för utvärdering av materialflödet under packningen för olika modellblandningar. Resultat visade att testmetoden möjliggjorde en tydligare urskiljning av blandningar med olika egenskaper och att metoden potentiellt skulle kunna användas som ett verktyg inom området. Dessutom applicerades en enkel diskret elementmodell för att öka förståelsen av flödet av modellmaterialet under kompaktering som grund för ytterligare förbättring vid övergång från modellerade material till verkliga blandningar. Därför mixades och testades verkliga blandningar under samma förutsättningar som för det modellerade materialet. De övergripande resultaten av de verkliga blandningarna bekräftade resultaten från de modellerade materialen. Testmetoden visade även en potential för att simulera flödet på ett sätt så att skillnaden mellan blandningar kan detekteras även utan inspektion med röntgen. Därför gjordes även ett försök att utveckla testmetoden till en systematisk testmetod med god användbarhet som fokuserar på flödet av partiklar i tidiga skeden av packning, i detta fall benämnd kompakteringsflödestest (CFT).

CFT tillämpades för olika blandningar i syfte att identifiera de parametrar med störst inverkan på partikelrörelserna vid kompakteringskrafter. Röntgendatortomografi (CT) vid CFT underströk tillförlitligheten hos CFT-resultaten. Dessutom har enkla diskreta elementmodeller (DEM) framgångsrikt tagits fram för att bekräfta en del av CFT-resultaten.

Nyckelord: Kalla asfaltsfogar, laboratorieframställda asfaltsfogar, IDT-fogutvärdering, DTT-fogutvärdering, 4PB-fogutvärdering, finit elementmodellering (FEM), diskret elementmodellering (DEM), röntgendatortomografi (CT), kompakteringsflödestest (CFT), kompakterbarhet

Preface

The work in this licentiate thesis has been carried out at Royal Institute of Technology (KTH), Department of Architecture and Built Environment. The thesis is a part of a research at KTH building materials with the aim of developing Real time in-situ quality evaluation methods for asphalt mixtures at their virgin stages.

First of all, I would like to thank and express the deepest appreciation to my supervisor, Prof. Dr. Manfred N. Partl for his overall guidance and critical review of the research output at various stages. I am very grateful for his persistent advice, encouragement and support in various ways from the very beginning. His follow-up on the writing phase and careful review of the final manuscript are also highly appreciated. In addition to this, I would like to thank Dr. Denis Jelagin and Dr. Alvaro Guarin for providing valuable guidance and support throughout the research.

I would like to thank my mother, father and brother for their support and love throughout my life.

Finally, I would like to thank my wife for her understanding, endless love and encouragement when it was most required.

Stockholm, November 2015

Ehsan Ghafoori Roozbahany

List of appended papers

This licentiate thesis is based on the following papers:

1. Ghafoori Roozbahany E., Partl M. N. and Witkiewicz P. J., “Fracture testing for the evaluation of asphalt pavement joints”, *Journal of Road Materials and Pavement Design* Volume 14, Issue 4, 2013

2. Ghafoori Roozbahany E., Partl M. N. and Guarin A., “Particle Flow during Compaction of Asphalt Model Materials”, accepted for publication in the Journal of Construction and building materials.

3. Ghafoori Roozbahany E., Partl M. N., “A new test to study the flow of mixtures at early stages of compaction” accepted for publication in the Journal of Materials and Structures.

Contribution to the appended papers

Paper 1: Ghafoori R. planned and carried out the experiments, interpreted the results and wrote the manuscript, Witkiewicz carried out part of the experiments, all supervision carried out by Partl.

Paper 2: Ghafoori R. planned and carried out the experiments, interpreted the results and wrote the manuscript, all supervision carried out by Partl; Guarin helped with obtaining the X-ray images and proofreading the manuscript.

Paper 3: Ghafoori R. planned and carried out the experiments, interpreted the results and wrote the manuscript, all supervision carried out by Partl.

List of abbreviations

4PB	4 point bending
AC	Asphalt Concrete
BE	Bitumen Emulsion
CFT	Compaction Flow Test
CMA	Cold Mix Asphalt
CT	Computed Tomography
DEM	Discrete Element Model
DTT	Direct tension test
E_2	Secant Modulus
FE	Finite Element
Fp	Maximum tension loading capacity
Fr	Friction coefficient
F_T	Tension bonding capacity
IDT	Indirect tensile test
Kn	Normal Stiffness
Ks	Shear Stiffness
NMAS	Nominal Maximum Aggregate Size
SMA	Stone Matrix Asphalt
σ	Stress

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1 Introduction

Quality evaluation of asphalt pavement starts from material testing before and after the asphalt plant blending phase and continues after the mixtures are placed and compacted one the roads. In terms of aggregates and bitumen, as major components of an asphalt mixture, there are quite a lot of standards and qualifications available which help to avoid using materials with poor qualities. For the asphalt mixture design, there are two standard compaction methods, i.e. Marshall hammer [1] and the Superpave Gyratory [2], which help finding the desirable mixtures with required density and air void content in a laboratory scale.

Density and air void content are generally considered as the most decisive parameters for quality assurance of asphalt pavements. It is believed by most of road experts that optimal air void content in an asphalt layer increases the serviceability of the roads. However, density alone is not enough to characterize asphalt pavement quality. Performance-based test methods are required to provide a more complete picture of pavement quality, especially for weakest parts of the roads such as asphalt joints.

Performance-based tests reveal different mechanical properties of asphaltic structures, mostly, in a laboratory scale. Using such tests also helps to provide performance rankings among different construction techniques. Despite of many existing test methods, there is still need for new or adapted test methods for specific purposes, such as joints, where, besides density measurements, there is no standard method for evaluating them during and after the road construction.

As asphalt mixtures are very complex, it is sometimes easy to misinterpret the test results and confuse the dominating phenomena behind some of their behaviors. Therefore, enough fundamental knowledge about each phase of the road construction is required for reliable interpretations of the test results. Despite of lots of researches conducted on the compaction phase, in which some of them led to recommendations for improving asphalt mixture [3], there is still little known about the behavior of different asphalt mixtures in terms of particle rearrangements and flow during roller compaction in the field. Also, the standard laboratory scale compaction simulators have often been unsuccessful to fully reproduce the obtained field results due to their fundamental differences from the field conditions.

The objective of this research is to recommend complementary adapted test methods for evaluating the mechanical properties of asphalt construction joints and also providing a scientific basis for enhancing the understanding of asphalt particle rearrangements and flow during the compaction phase as one of the influential parameters on joint performance. In addition, this research aims to use the obtained flow results for examining the feasibility of developing a simple field evaluating method that can help to avoid poor road constructions.

The first part of this thesis focuses on introducing three adapted mechanical test methods for evaluating the quality of asphalt joints constructed with different techniques. Firstly, selected asphalt joints were produced in a laboratory scale using different construction techniques. Then, the adapted test methods were used for finding the techniques with the highest impact on the joint performance (paper I).

The second part focuses on simulating the compaction phase in a small scale with respect to the particle flow as one of the major findings of the first part. Therefore, a simple flow test was used with simple model materials as an initial step for simulating and understanding the compaction flow process. Then, the flow test was used for testing two different real mixtures and their results were compared with the ones obtained from the model material testing (paper II).

In the third part, some of the findings of the second part were used to modify the flow test for examining the feasibility of developing a simple test method for workability measurements. Hence, mixtures with different characteristics were tested with the modified flow test (compaction flow test) and the results were compared with each other (paper III).

1.1 Background

Asphalt pavement joints between two attached layers can be found on all types of roads. They have considerable impact on driving safety and comfort as well as durability of the whole road. Poorly constructed joints are one of the most vulnerable parts in an asphalt pavement. Deteriorated open joints (Figure 1) may cause serious safety problems for two-wheeled vehicles and increase the traffic noise effects. They also trigger fast loss of road functionality due to water intrusion and ice formation and also differential pavement movements from traffic and temperature cycles. Last but not least, loss of aggregates at the edge of the joints may influence surface friction and even lead to windshield damages from local raveling.

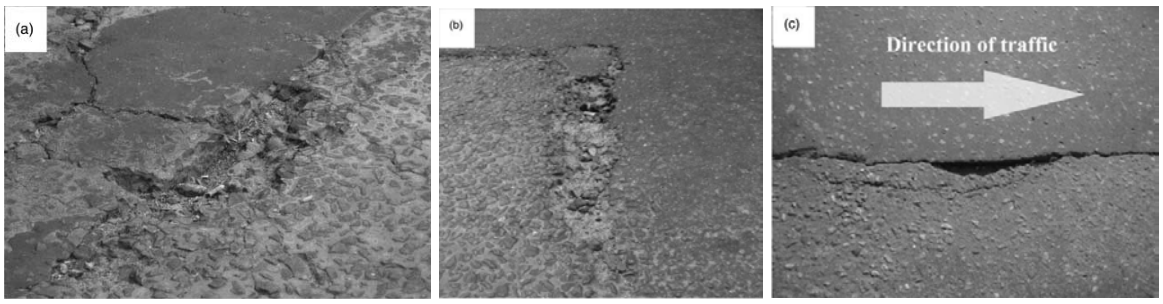

Figure 1 (a) deteriorated cold joint in an urban street in Stockholm; (b) deterioration of the joint at a local bus stop and (c) opening of the joint along the traffic direction.

Deterioration of the joints may be caused by different effects such as inadequate compaction, bad preparation of the joint surfaces, unfavorable pavement temperatures and temperature changes combined with repeated action of water and frost from top and bottom of the pavement and also traffic loading in vertical and horizontal directions.

Joints are produced during construction of new roads. Depending on the temperature of the existing pavement when placing the new mixture, construction joints are categorized as hot, warm and cold. If the temperature difference between the newly placed and the existing layers is not significant and the temperature of the colder side is still higher than 80 $^{\circ}$C, the joint is called “hot”; If the fresh mixture is placed before the temperature of the existing lane falls below 49°C, the joint is called “warm”; and finally if the temperature of the existing lane is below 49°C, a “cold” joint is formed. In case of construction joints, cold joints are formed as a result of a long delay between constructing two adjoining lanes.

Cold joints are also formed in case of repair and maintenance. Patching with narrow joints is an acceptable way of repair. However, as compared to the construction joints, more specific problems have to be considered.

The only required standard measurement for evaluating joints is density. The Swedish standard allows only 2% of difference between the densities of the main lane and the joints. Normally, coring and non-nuclear density gauges [3] are used for such measurements whereas other in-situ measurements, such as Intelligent Compaction (IC) [4], do not give reasonable results in the case of thin asphalt layers.

Based on field inspections, some recommendations for constructing asphalt joints with acceptable qualities are listed as follows.

Joint interface shape

Based on Kandhal's and Mallick's (1997) extensive investigation on different construction methods for joints in US [5] , shape of construction joints is important for the density of the joints. They proposed a notched wedge joint maker (Figure 2(a)). Fleckenstein et al. (2002) [6] suggested restraining wheels (Figure 2(b)) for constructing the first lane with a slope for providing better joint interface interaction when the second lane is laid.

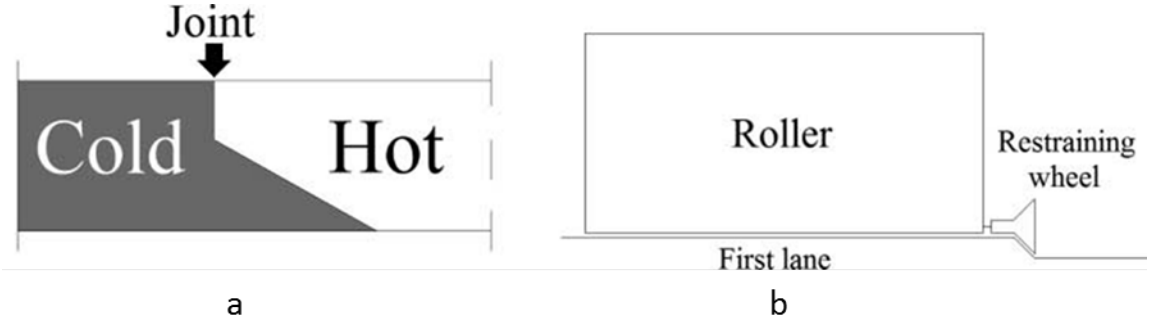

Figure 2 (a) Construction joint geometry when using the notched wedge joint maker for first lane compaction (Kandhal & Mallick, 1997) [5]; (b) using restraining wheel when compacting the first lane (Fleckenstein, Allen, & Schultz, 2002) [6]

Compaction technique

In addition to the shape of the joints, Kandhal and Mallick (1997) [5] also suggested, that the frequent compaction methods (Figure 3(a) and 3(b)), in which the compaction starts from the joint, are not as effective. Instead, they recommended that the compaction starts from the hot side and about 15 cm away and towards the joint (Figure 3(c)).

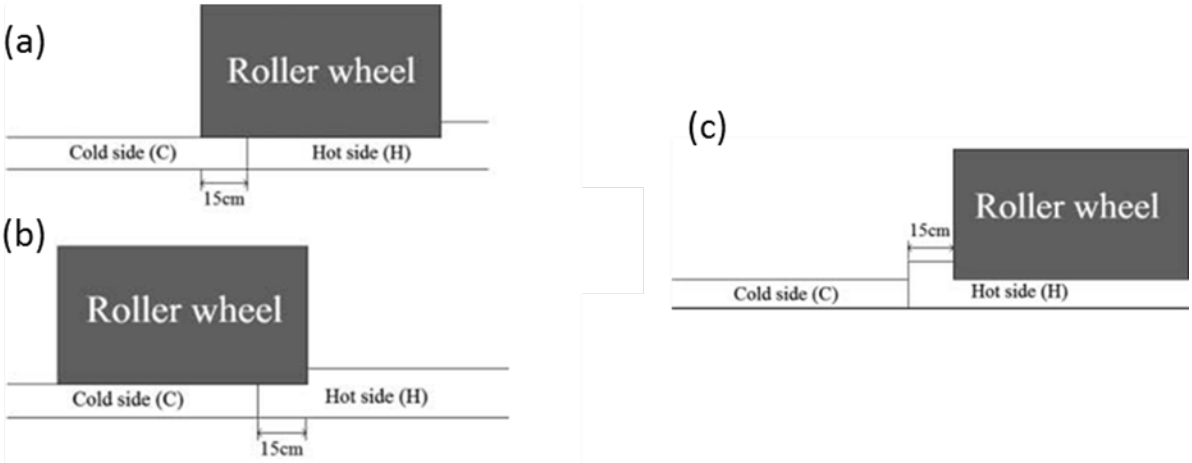

Figure 3 (a) and (b) initial rolling on the joint (frequent methods); (c) initial rolling from hot side away from the joint, recommended by Kandhal & Mallick [5].

Joint treatments

Some road construction guidelines, e.g. Swedish specifications (AMA 98, 2005) [7], contain instructions for treating the joint interface after cleaning. Since normal bitumen at high temperatures is avoided for safety reasons, it is recommended to seal and bond the joint interface with BEts (latex-modified emulsion) or other emulsions with high bitumen contents, e.g. BE65R (BE stands for bitumen emulsion with 65% bitumen and 35% water; R stands for rapid breaking emulsion). Pre-heating is also recommended as an alternative for sealing by Swedish specifications [7].

Although much attention is dedicated to the construction of the joints, reliable tools for determining their mechanical properties for the design and performance assessments are still required.

2 Summary of appended papers

2.1 Fracture testing for the evaluation of asphalt pavement joints

In this paper, some of the common and recommended techniques for constructing asphalt joints were selected and used for producing laboratory scale joints. These techniques included different joint interface treatments such as Bitumen Emulsion (BE) and pre-heating as well as different interface shapes (Figure 4) and two compaction techniques (Figure 3). Totally, 14 different techniques were used for producing joints that are summarized in Table 1.

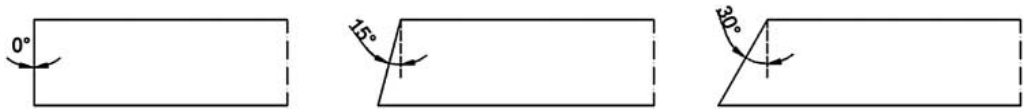

Figure 4 Three different inclination angles at the joint interface

Table 1 Selected compaction and surface treatment techniques as well as joint interface shapes used for laboratory production; note the abbreviations for each construction technique, as used in this study.

Compaction techniques		Frequent technique		First passings away from the joint
Angles:	0°	15°	30°	0°
Sealing with BEts	Seal-0	Seal-15	Seal-30	Seal-aside
Pre-heating	Heat-0	–	–	–
Untreated joint surface	Untreated-0	Untreated-15	Untreated-30	Untreated-aside
Pre-heating + Sealing with BEts	Heat + Seal − 0	Heat + Seal − 15	Heat + Seal − 30	Heat + Seal − aside
Sealing with BE65R	Seal2-0	–	–	–

Patching as one of the critical cases for joints was the main aim of this paper. In case of patching, the cold side of the joints is normally aged, therefore, is stiffer than its fresh side. Hence, in order to make the aged side of the joint, firstly, full slabs of 625 x500x56mm^3 were produced using 50/70pen Stone Mastic Asphalt (SMA) [8] mixtures which are slightly stiffer than the frequently used 70/100pen SMA mixtures. Then, depending on the intended joint interface angles each slab was cut into half. Afterwards, the aged "old" half was shortly aged and allowed to cool down to the ambient temperature before putting it back into the frame. Before placing the fresh side, the cold side of the joint interfaces, were treated by sealing, pre-heating and etc. Then, the remaining half of the slab was filled with 70/100pen SMA mixture and compacted.

For eleven cases, the whole slab was compacted at once with a steel roller representing the "frequent compaction technique". While, for the other three cases, compaction started about 75mm aside from the joint using a wooden plank for the first two passing before compacting the whole slab (Figure 5).

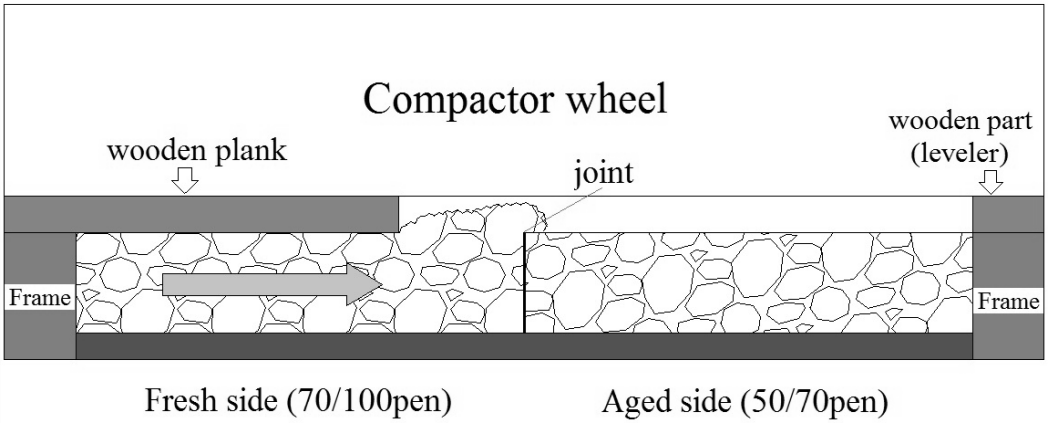

Figure 5 Pushing the fresh mixture to the vertical joint using a wooden plank for first roller passes; the arrow shows the expected transport direction of the fresh material towards the joint; example shows a vertical joint.

Three different test methods, i.e. Indirect Tensile test (IDT), for measuring joints adhesion properties, Direct Tensile Test (DTT), for measuring maximum tension loading capacity of the

joints, and 4 Point Bending (4PB), for simulating poorly supported thin layers under quasi-static vertical traffic loading, were chosen.

Because of the angularity of some of the joint interfaces (Figure 4), it was decided to use rectangular IDT specimens. It was shown by simple 2D and 3D finite element models that no significant difference of stress distributions for such geometry change could be expected at the joint locations. The schemes of the test configurations are shown in Figure 6.

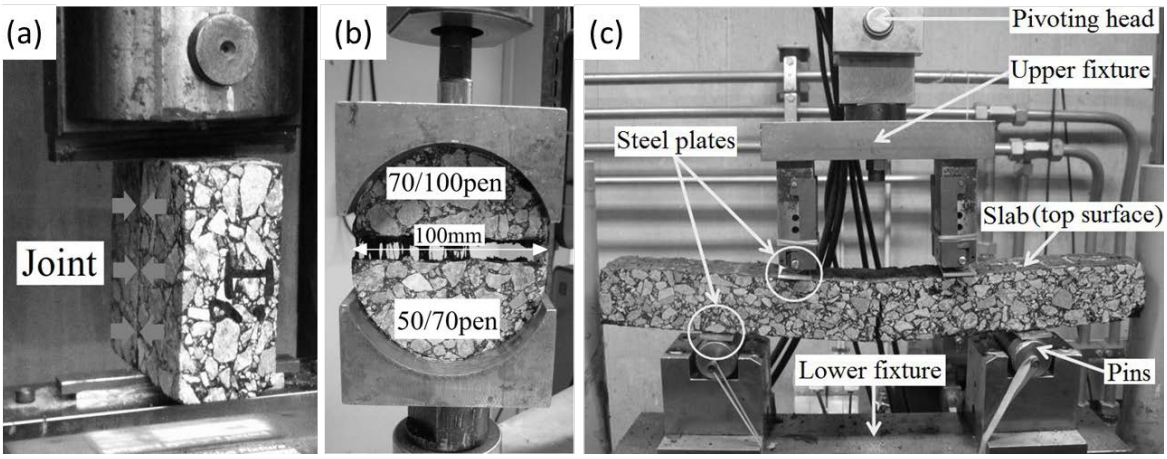

Figure 6 Test configurations; (a) IDT, (b) DTT, (c) 4PB

From each test, the required fracture load and its relative displacement were recorded for each specimen. Then, simple homogeneous models were generated for obtaining the stress distributions as well as secant modulus at each joint interface; the mean values of the results for each joint type were calculated and used as parameters for comparing different joint construction techniques. Examples of the generated models for the three tests are shown in Figure 7.

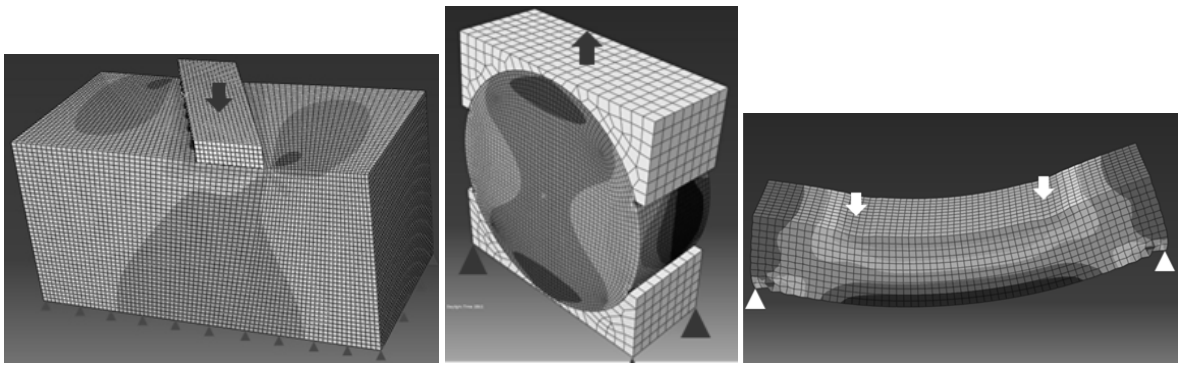

Figure 7 Schemes of IDT (left); DTT (middle); and 4PB (right) generated finite element models

The summary of the mean values obtained from the results for all chosen techniques are shown in Figures 8 and 9.

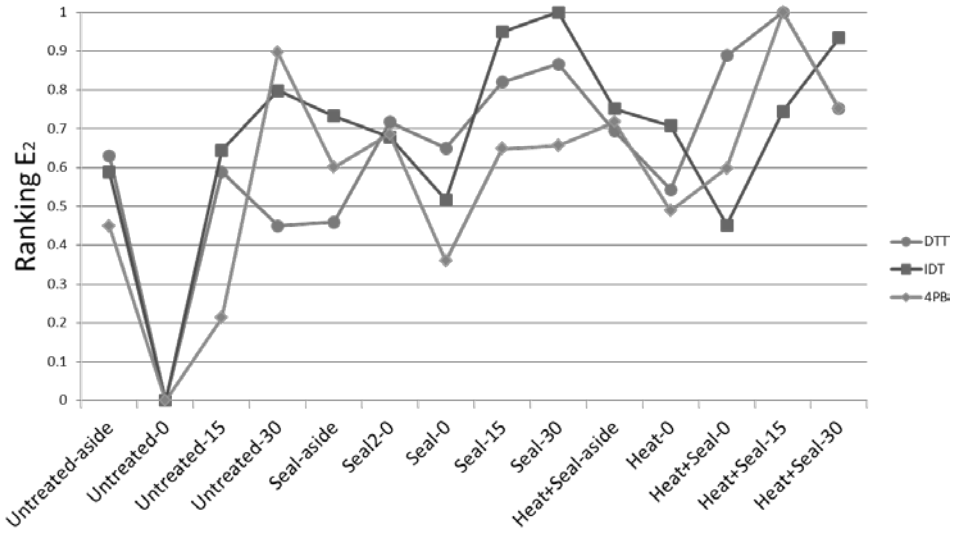

Figure 8 Comparison of relative ranking of secant moduli between DTT, IDT and 4PB

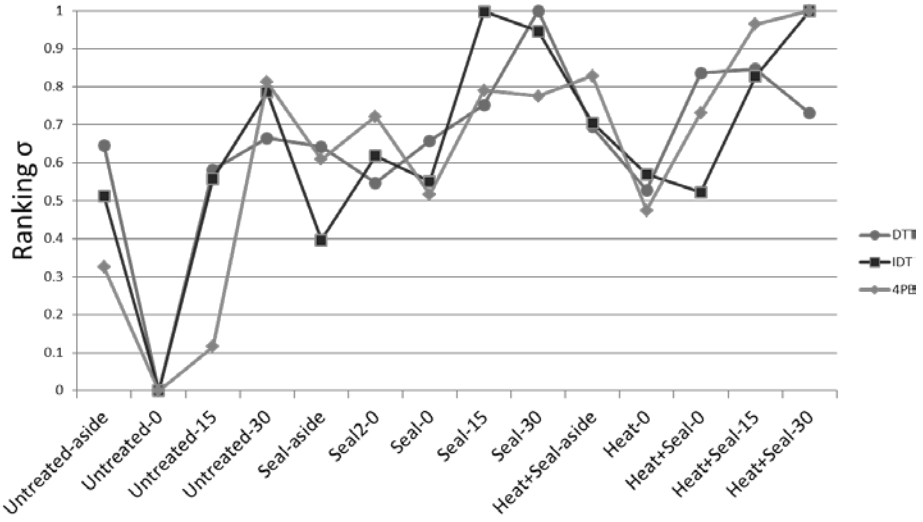

Figure 9 Comparison of relative ranking of stresses between DTT, IDT and 4PB

Obviously, not all test methods resulted in exactly the same ranking among different construction techniques since each test method enlightened different mechanical properties of the tested joints. However, it was obvious in most cases that the angular joints have improved the joint properties. In addition, the results suggested that changing compaction technique for increasing the flow of mixture towards asphalt joints resulted in improvement of mechanical properties of the joints.

Despite of its importance, the knowledge about the material flow during the compaction phase is very little. In addition, the confined configurations of the laboratory compaction methods do not allow large particle flow as it happens during initial stages of the field compaction. Therefore, in the second paper, asphalt compaction with respect to the particle flow was studied.

2.2 Particle Flow during Compaction of Asphalt Model Materials

In order to simulate the flow and densification of an asphalt layer during compaction a Flow Test device (FT), was designed. The FT device consisted of a simple container filled with

an asphalt mixture and loaded from one side. Hence, there would be a load-free area for the material to flow and create a material uplift due to the compaction pressure. Such a configuration was intended to roughly simulate the settlement of the roller compactor wheel on the loose mixture as shown in the Figure 10.

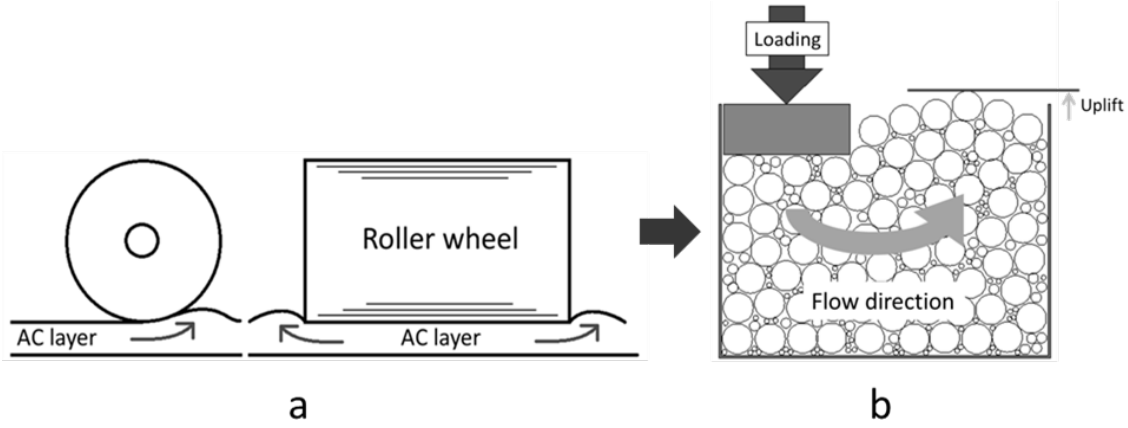

Figure 10 (a) directions of the material flow during field compaction; (b) side view of the schema of the flow test configuration

In order to understand the particle flow behavior, the idea was to lower the amount of mixture flow disturbances as much as possible. Therefore, after some trial tests, a square prism mold was chosen.

Besides, X-ray Computed Tomography (CT) was used for tracking the flow patterns. Such a study has been previously carried out where some embedded particles were tracked in asphalt specimens during repeated heating, compacting and cooling before each scan [9]. However, the intention of this study was to observe the flow during the test without the effect of temperature change. Therefore, spherical glass beads with similar density to the real aggregates were chosen to represent the structural part of the asphalt mixture; also, bitumen was replaced with a motor oil (15w-50) that its viscosity at 20°C was similar to the viscosity of the 70-100pen bitumen at the compaction temperature (140°C). A mold of 130x80x100mm^3 was used for the tests (Figure 11).

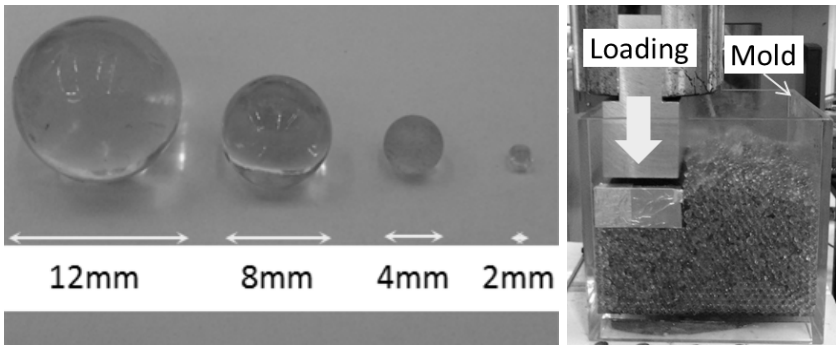

Figure 11 Left: Glass bead sizes; Right: New test configuration used for glass bead specimens

In order to have repeatable test results, it was decided to use the densest possible glass bead size combinations at loose assemblies. Hence, a literature review [10-15] was conducted for finding such combinations for two binary (12&2 and 8&2) and one ternary

(8&4&2) combinations. Table 2 shows the volumetric fraction of each size for both binary and ternary combinations.

Table 2 The volumetric fractions for binary (left) and ternary (right) sphere size combinations used in this study

Binary combinations				
Bead sizes:	8mm	2mm	12mm	2mm
Chosen combinations	72%	28%	75%	25%

Ternary combination			
Bead sizes:	8mm	4mm	2mm
Chosen combination	33.3%	33.3%	33.3%

Each combination was tested in both dry and lubricated conditions; dry combinations were considered to represent asphalt mixtures with low binder content because the spherical shape still let the particles flow under loading without crushing. In addition, lubricated combinations were meant to represent the mixtures with higher binder contents.

For simultaneously recording the required force and tracking the particles inside the specimens, a servo-hydraulic load frame was placed in between of the x-ray Computed Tomography (CT) source and its detector (Figure 12).

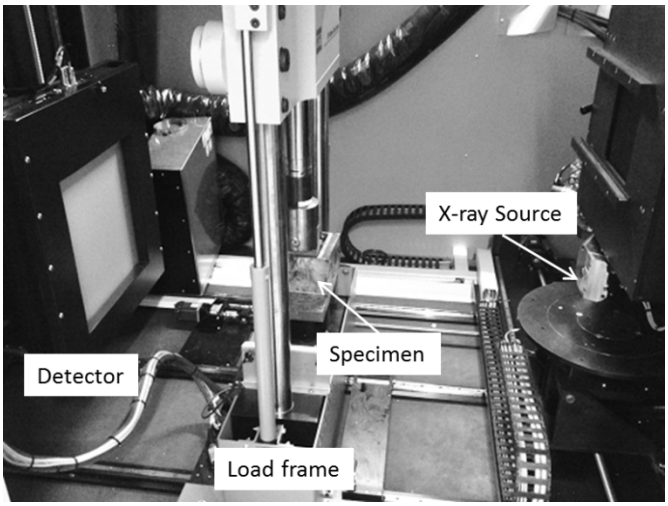

Figure 12 The particle tracking system for obtaining 2D CT images

Because of the fixed X-ray source, 2D CT was conducted for each test. For obtaining a clear picture of the overall internal flow in a XZ plane for each specimen, it was decided to place steel pins inside a few hollow glass beads and place them in specific regions (Figure 13) of each specimen.

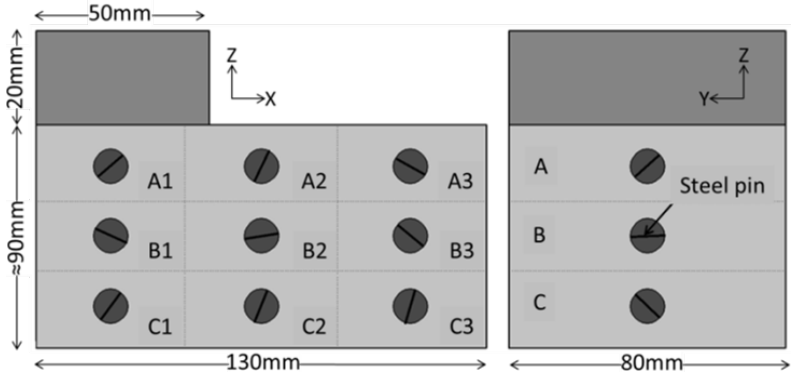

Figure 13 Left: locations of the glass beads with steel pins inside of each specimen; Right: the tracking system

In addition to the pins for internal investigations, 3 more beads with pins were placed on the surface of each specimen for studying the surface changes (see pins 1, 2 and 3 in Figure 14). The required load for imposing 20mm of displacement as well as maximum XZ movement of each pin for each condition and combination were recorded and then compared with each other.

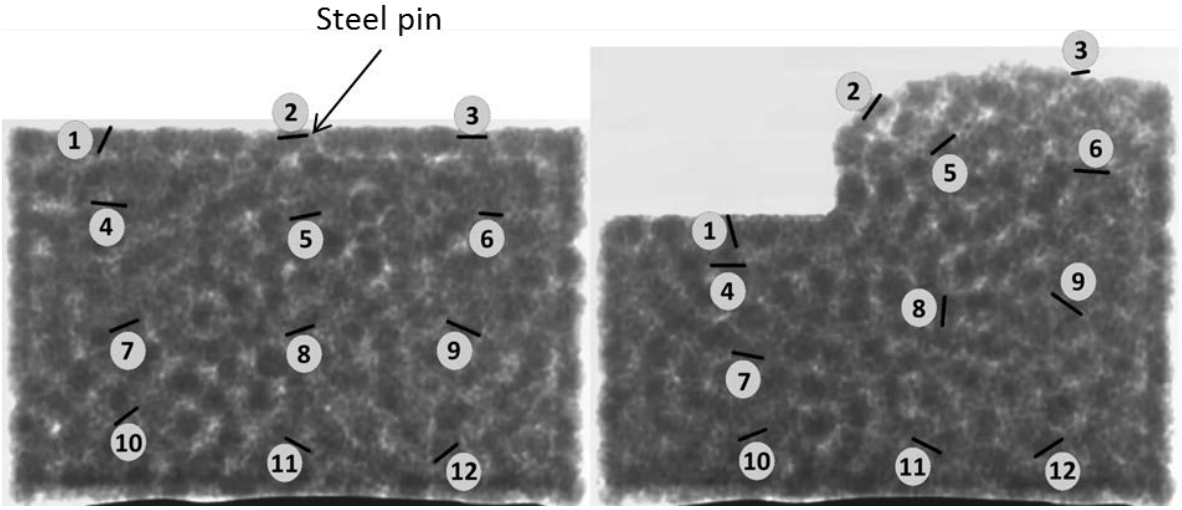

Figure 14 One example of analyzed X-ray CT images (8&2-lubricated specimen); black lines show the XZ position of the pins

The results of the FT on model materials are shown in Figures 15 and 16. In terms of load-displacement, the ternary combination 8&4&2 required higher force than the binary ones which were comparable for most of the test. On the other hand, extensive drainage of the lubricant in the 12&2 lubricated combination, due to its relatively low total surface area, resulted in higher forces throughout the test as compared with the other two lubricated combinations with comparable results.

As expected, the required overall forces for the dry condition specimens at different displacements were mostly higher, especially for the 8&2 and 8&4&2 combinations. This indicated that more energy was consumed for stiffer specimens to reach the same level of imposed displacement. Similar results were also expected when comparing real mixtures with low and high binder contents.

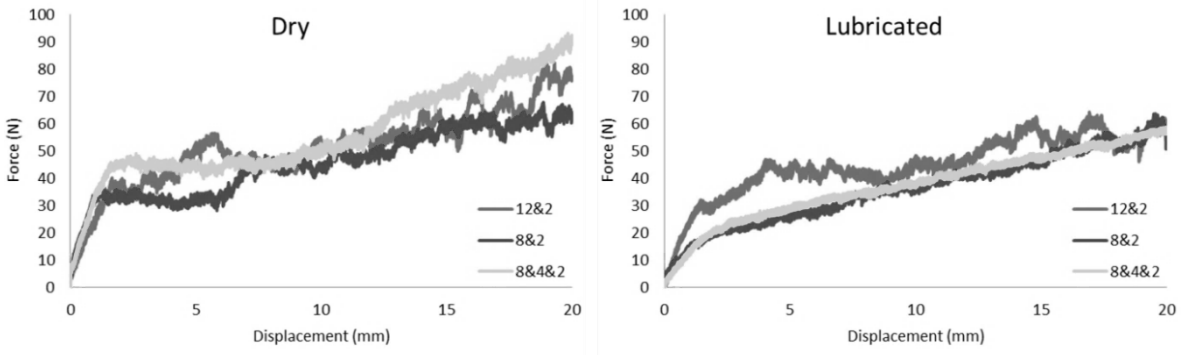

Figure 15 Mean force vs. displacement curves of the combinations for dry (left) and lubricated (right) specimens

Investigating the overall movements at each specimen height level for the three combinations indicated that the lubrication had increased the depth where particle flow occurs in the specimens (Figure 16). This shows the impact of the lubrication on expanding the shear planes in lubricated specimens as compared with the dry ones. In addition, investigating the surface pins 1, 2 and 3, indicated that by measuring the surface uplift one can clearly see the difference between the dry and lubricated specimens.

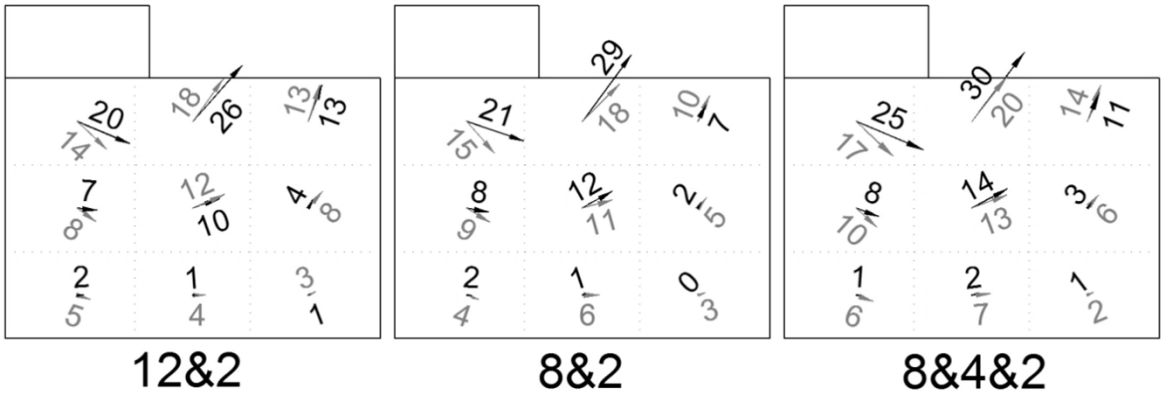

Figure 16 Average of maximum XZ movements of the pins at different regions of each combination for dry (black arrows) and lubricated (grey arrows) specimens (results are in millimeter)

In order to understand observations from the tests, it was decided to generate simple models that could explain the test results. Since the 8&4&2 combination was the most relevant and closest to an asphalt concrete gradation, this combination was used for a relative comparison between the dry and lubricated conditions.

Two simple descriptive models were generated for explaining the FT particle flow as well as the force-displacement results. Since the movements out of the XZ plane as well as rotations were neglected during the CT X-ray imaging, a 2D commercially available discrete element software PFC was used. For simplifications, the contact model among the elements (balls) was assumed to be linear. In addition to the number of the balls and their density, the inputs for the model consisted of normal (Kn) and shear (Ks) stiffness as well as the friction coefficient (Fr). No additional bonding was introduced to the generated models. The sizes of the container and the loading strip were 130mm x 90mm and 50mm respectively. All parameters for the dry and lubricated cases were assumed the same and only the friction coefficient was varied.

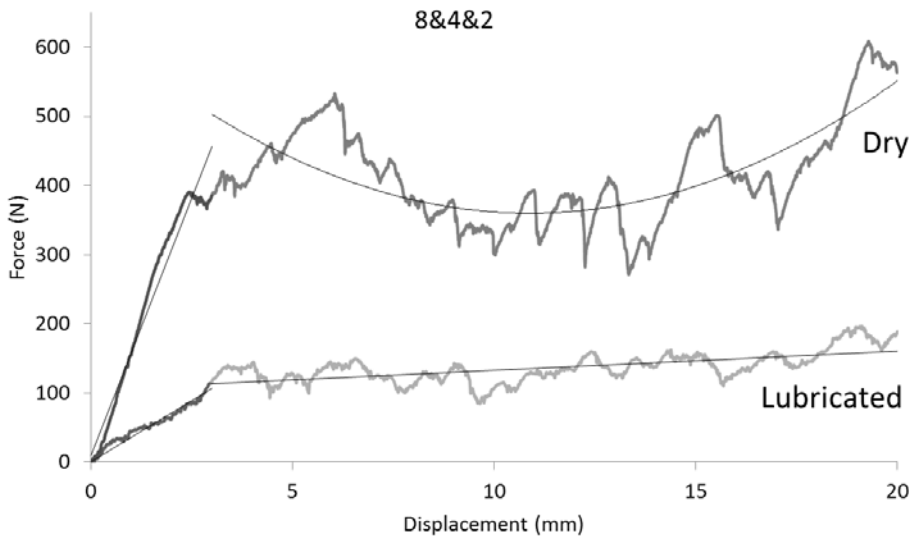

Figure 17 Load vs. displacement curves obtained from the modeling of dry and lubricated 8&4&2 combination

Despite of simplicity, the generated models were able to reasonably produce similar load-displacement trends and particle flow patterns to the FT results (Figures 17 and 18). Hence, with these models it was easier to understand the load changes at different stages of imposed displacement and also the rearrangements of the particles in a comprehensive way.

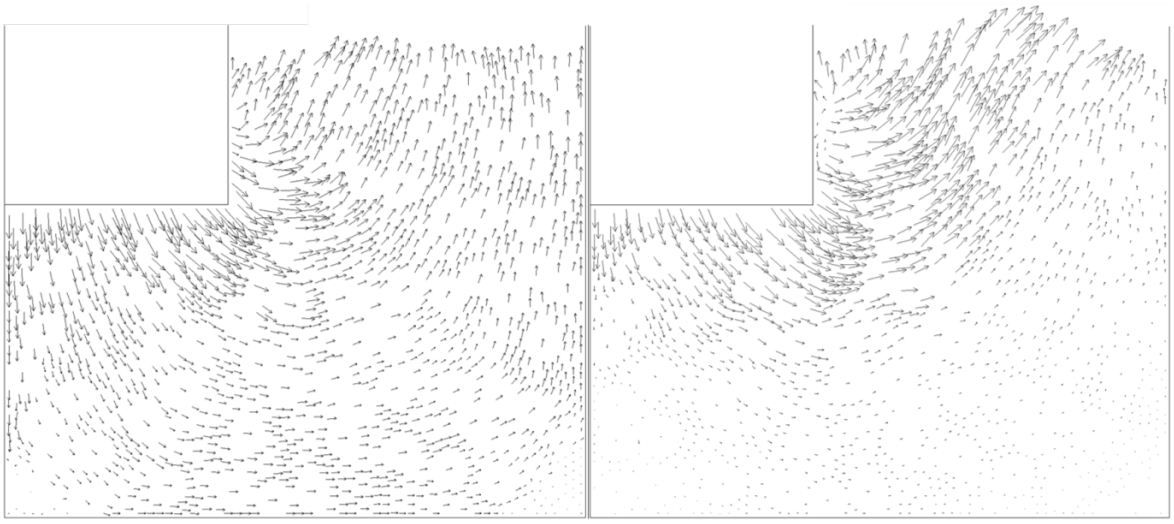

Figure 18 flow patterns of the particles obtained from the modeling: (left) lubricated; (right) dry for the 8&4&2 combination

As the results of the FT on the model materials appeared to be promising, it seemed logical to examine the applicability of such a test method on real asphalt mixtures.

Application for real mixtures

Reference asphalt mixture

In order to apply the FT on real mixtures, three reference mixtures with real crushed aggregates of 8&4&2 were prepared. Then, one combination was left dry and the other two were mixed with 70/100pen bitumen, one with 3% and another one with 6% of their total

mixture weights. The mold used for the glass beads was substituted by a metal container of 150x100x100mm^3 for withstanding the mixtures at high temperatures. A loading strip of 50mmx100mm was used to leave enough free space for the mixture to flow.

For tracking purposes and in order to achieve more visibility in the CT images, totally 9 thick screws were placed at the surface, middle and lower height levels of each specimen (Figure 19). Then, the FT was conducted at 140°C and simultaneously CT images were obtained from each mixture.

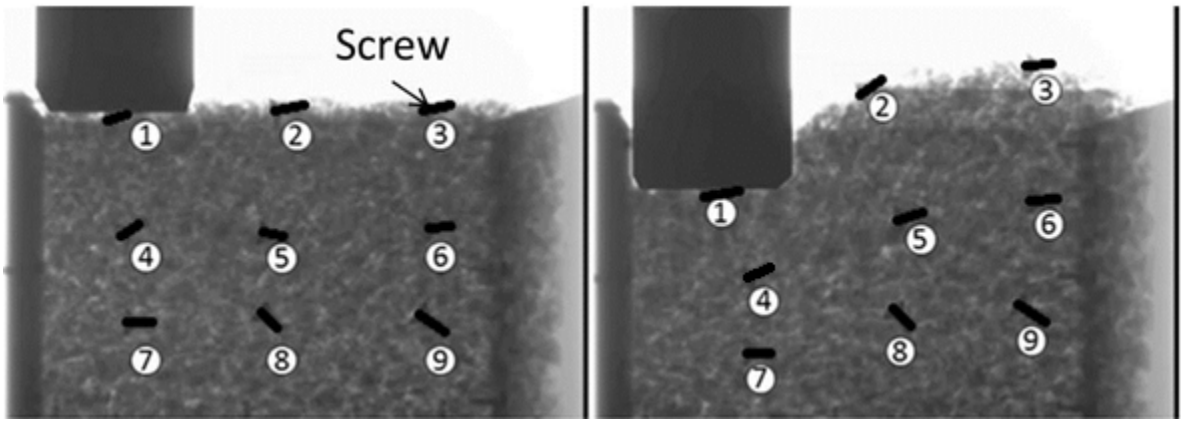

Figure 19 Locations of the screws before and after FT (8&4&2 real aggregates with 3% binder content)

The results of the comparison between the three mixtures are presented in Figure 20. Because of the absence of binder in the dry specimen and large movements at its surface near the loading, the middle screw (no. 2) fell down from an opening between two large aggregates after some upward movements; therefore its final location did not reflect its total flow. However, the other screw at its free surface (no. 3) showed larger movements than the mixtures with 3% and 6% binder contents. The overall results of uplift were in agreement with most of the glass bead results. At low height levels of the specimens, the dry aggregate combination still demonstrated large XZ movements as compared with the other two mixtures. The extremely high load difference between the dry and the other two mixtures (3% and 6%) justifies such movements.

When comparing the two wet mixtures at mid-height and bottom of the specimens, the directions of the movements under the loading were more horizontal for the 3% and more vertical for the 6% mixture which was also similar to the observations from the glass bead results. The vertical movements of the screws away from the loading strip were more upward for the 3% mixture which also indicated similarities to the glass beads FT results. Such internal differences were clearly observed on the surface of the specimens where mixtures with the higher binder content can be easily distinguished from the ones with lower binder content.

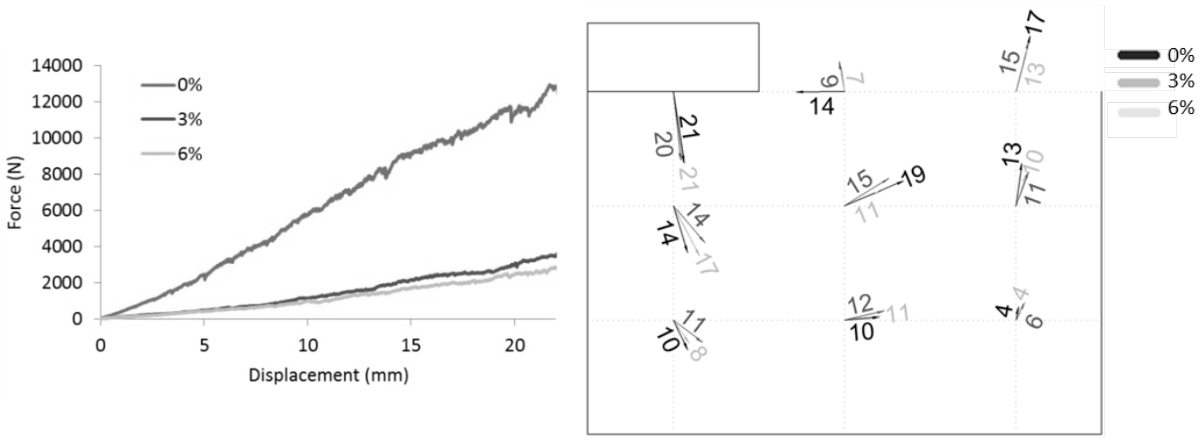

Figure 20 FT results for 8&4&2 aggregates; Left: load vs. displacement results; Right: XZ movements of the embedded screws in the specimens

After studying the mixture with similar gradation to the ternary glass bead combination, two Stone Matrix Asphalt (SMA) mixtures with the same gradation and the NMAS of 11.2mm [16] were prepared to examine if the flow behaviors from the previous specimens could also be observed in real mixtures. Hence, two mixtures with the binder contents of 4% and 6% of their total mixture weights were prepared and tested with the FT. The same test settings and temperature as for the reference mixtures were also used for these tests.

As presented in Figure 21, the test results showed that besides of a clear load difference between these two mixtures, the amount of uplift was also higher for the mixture with the lower binder content, especially at the surface and next to the loading strip. Since both mixtures contained bitumen which made them similar to the lubricated glass bead combinations, the flow reached to their lower height levels.

The lower amount of aggregate coating for the 4% mixture increases the friction among the particles. Such a friction along with angularity of the aggregates decreases the chance of the particles to rearrange; this leads to a larger flow towards the free side of the specimen. Therefore, the amount of flow at different heights of the specimens was mostly higher for the dryer specimen. Therefore, it was clearly possible to distinguish the 4% mixtures from the 6% one only by comparing their force-displacement curves as well as their overall surface uplifts.

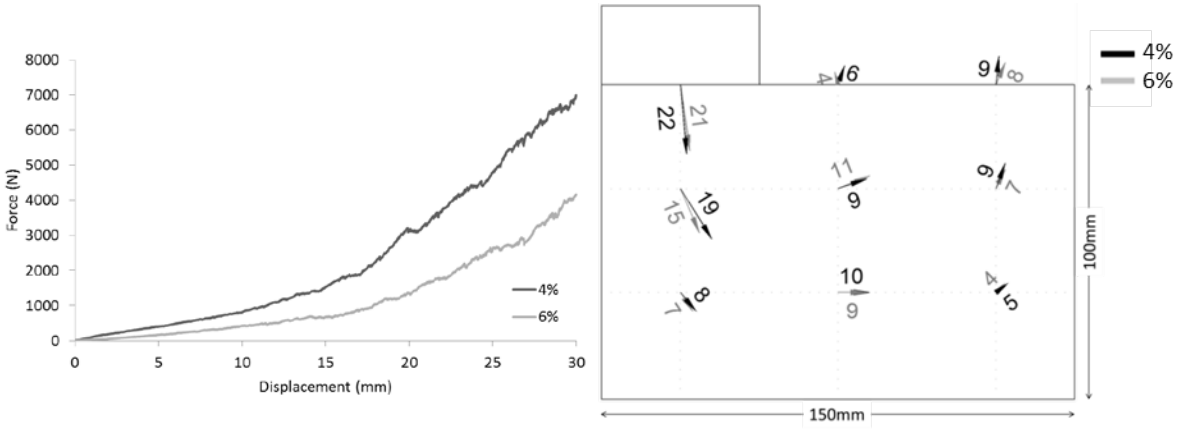

Figure 21 FT results for SMA mixtures; Left: load vs. displacement results; Right: XZ movements of the embedded screws in the specimens (all displacements are in mm)

In addition, the observed flow patterns of the SMA mixture supported the claim of the previous study on joints [17] about the occurrence of such a flow during the compaction of joints with the recommended compaction technique. Such information not only can be used for improving the joint compactions but also can help to improve of the pavement qualities in general.

Moreover, since the uplift results clearly reflect the internal rearrangement patterns of asphalt layers during compaction, this information can be used as a basis for developing a tool for an in site workability evaluation of the mixtures in a more realistic way than the existing ones [18-22]. Therefore, it was decided to complete the FT configuration to study the flow behaviors of asphalt mixtures with different characteristics on the in a more systematic way.

2.3 A new test to study the flow of mixtures at early stages of compaction

In this paper, similar to the FT setting, a uniaxial servo-hydraulic testing machine with 100kN capacity was used for loading the specimen in a displacement control mode for determining the required forces for each mixture to generate the vertical displacement of 40mm. In addition, the uplift (Figure 22) on the free side of the specimen was measured by means of an ultrasonic sensor to study the relation between the properties of the mixtures and their flow behaviors under the compaction loading. The ultrasonic sensor measured the average of the surface contour at every second of compaction. The results of the uplift were obtained in terms of voltage that can easily be converted to millimeter. The described test configuration was called the Compaction Flow Test (CFT) as shown in Figure 22.

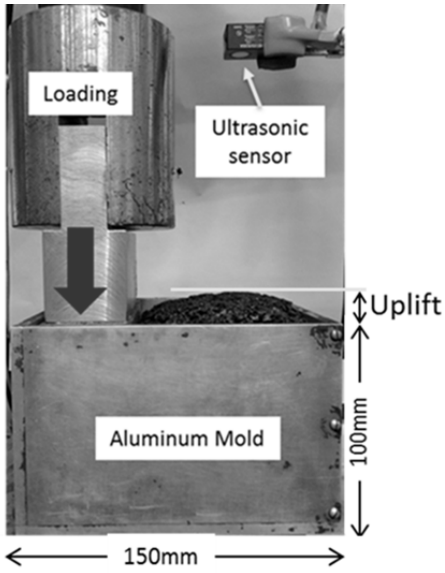

Figure 22 The Compaction Flow Test (CFT) setup

In order to investigate the influence of different mixture properties on CFT, the following five most influential workability parameters were investigated, leading to the mixture variations in Table 3.

Gradation types

The impact of gradation types was studied using two different gradations, i.e. Stone Matrix Asphalt (SMA), and Asphalt Concrete (AC) both with the Nominal Maximum Aggregate Size (NMAS) of 8mm and from the same aggregate type. SMA8 was chosen as a

coarse structured mixture used for surface courses with high traffic load capacity; while AC8 was selected as a fine structured mixture used for local roads with low traffic volumes. Normally, NMAS is 11 to 16mm for the local roads and highways. However, in this study, due to the limited size of the mold NMAS of 8mm was chosen.

Binder Type

The impact of binder type at the early stages of compaction was studied using two different binder types; bitumen 70/100pen, which is normally used for roads exposed to long winter times and large temperature changes, and a softer bitumen 160/220pen that might be used for roads in special cold climate conditions.

Binder content (B.C.)

Different binder contents were used for investigating the influence of the amount of aggregate coating on the flow. Three binder contents were used for AC, i.e. 6.4% (Swedish standard requirements [16]) and two lower binder contents of 5.8% and 4%. Since SMA is a coarser mixture, the 6.4% binder content resulted in large binder drainage. Hence, only the other two, 5.8% and 4% were used for preparing SMA mixtures.

Conditioning

All mixtures were produced within the same temperature range (155°C-160°C) as required by the Swedish standard [16].Two different temperatures, i.e. 160°C and 120°C, were chosen for examining the role of the temperature during densification at early stages of compaction.

Table 3 Mixture variations as well as the abbreviations used for each one in this study

Mixture type	Temp.(℃)	Binder type (pen)	Binder content (%)	Abbreviations
AC	160	70-100	6.4	T-H-7-6.4
AC	160	70-100	5.8	T-H-7-5.8
AC	160	70-100	4	T-H-7-4
AC	160	160-220	6.4	T-H-16-6.4
AC	160	160-220	5.8	T-H-16-5.8
AC	160	160-220	4	T-H-16-4
AC	120	70-100	6.4	T-W-7-6.4
AC	120	70-100	5.8	T-W-7-5.8
AC	120	70-100	4	T-W-7-4
AC	120	160-220	5.8	T-W-16-5.8
SMA	160	70-100	5.8	S-H-7-5.8
SMA	160	70-100	4	S-H-7-4
SMA	160	160-220	5.8	S-H-16-5.8
SMA	160	160-220	4	S-H-16-4
SMA	120	70-100	4	S-W-7-4
SMA	120	160-220	5.8	S-W-16-5.8
SMA	120	160-220	4	S-W-16-4

After preparing each mixture and before filling the mold with each one, all internal mold walls were lubricated with oil for minimizing the wall effects. Then, the preheated mold was filled to approximately the same mixture weight, and then the surface was gently flattened to the top edges of the mold to make sure that the same amount of material filled the same volume. Then, for conditioning, the specimen was placed in the oven for 1.5 hours before testing. After conditioning, the specimen was placed under the loading and the results of load-displacement (Figure 23a) together with the ultrasonic measurements (Figure 23b) were obtained.

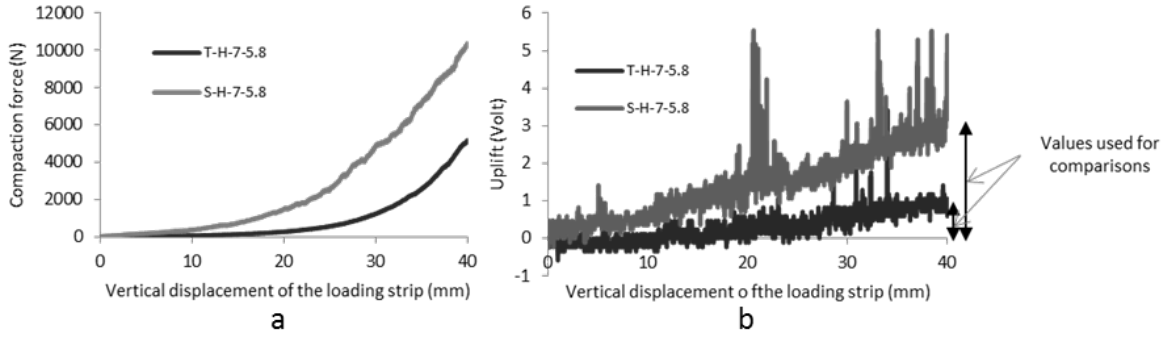

Figure 23 Raw test results obtained from individual specimens; a) loading results; b) ultrasonic results

Three replicates were used for testing each mixture variation. The results of the maximum compacting forces and the uplifts for all mixture variations are shown in Figures 24 and 25.

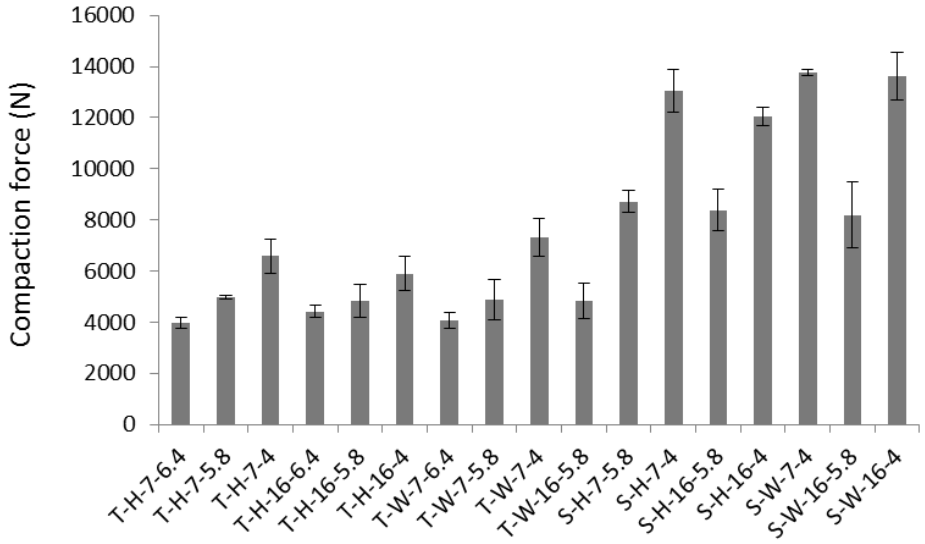

Figure 24 mean values of compaction forces for each mixture type and their standard deviations obtained from 3 tests

Based on the results, the most influential parameter on the flow appeared to be the gradation. Obviously, the required forces as well as uplift values for compacting the SMA mixtures were significantly higher than for the AC ones.

Comparing the force results also indicated that the difference between mixtures compacted at 160℃ and 120℃ were not very significant for the AC mixtures. However, almost all 120℃ SMA mixtures required higher compaction forces than the 160℃ ones. The

same conclusion applied for the uplift results. From this observation, it appeared that the temperature difference between 160℃ and 120℃ did not significantly influence the flow at early stage of compaction. However, decreasing temperature was found to affect the capability of mixtures to gain their desirable densities.

The binder type did not clearly show any influence on the compaction at high temperatures. Based on these results, it could be concluded that the differences of the binder stiffness at 160℃ and 120℃ may not be very decisive on the required load and the flow. However, further investigations are needed to support this finding.

The second most influential parameter on both the force and uplift appeared to be the binder content. As shown in the Figures 24 and 25, in most cases, the mixtures with low binder content are subjected to a higher forces and consequently to higher uplifts. This is probably due to the thinner binder film which allows direct corn to corn contact under the loading.

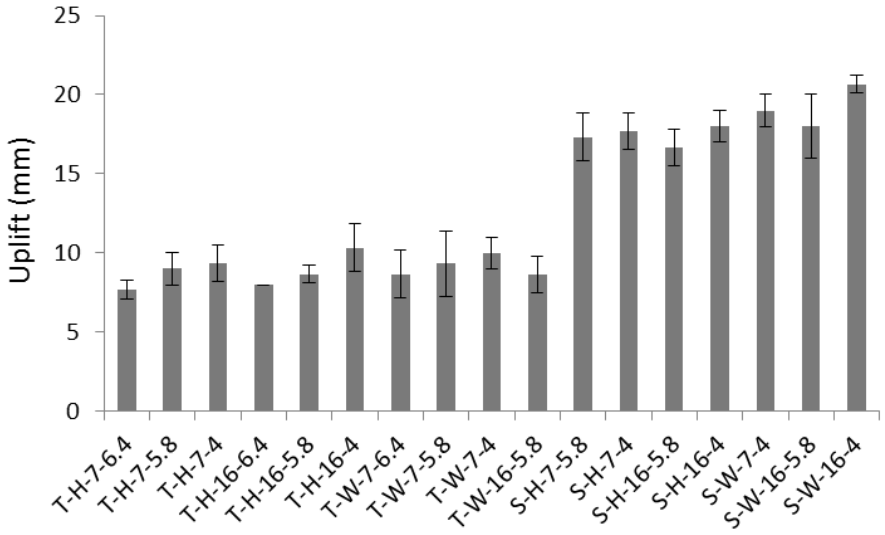

Figure 25 mean values of measured uplift at 40mm compaction displacement for each mixture type and their standard deviations obtained from 3 tests

Simple Discrete Element Models (DEM) were generated for qualitatively explaining the influence of gradation as the most effective parameter on the CFT results. Three spherical sizes were used to represent coarse, medium and small aggregates in an asphalt mixture. The coarse particle size d=10mm was chosen to form the main structure of the DEM models and the other two sizes were chosen as filling particles. Hence, based on the packing theory for filling the gaps of a single size assembly with different arrangements [23], 0.414·d=4.14mm, and 0.225·d=2.25mm, were chosen as medium and small sizes respectively. These particle sizes were used for generating four mixture models with the same total volume but different combinations. Based on the number of the 10mm particles used in each mixture, they were classified as relatively coarse (A), medium (B), fine (C) and finest (D). Combination of particle sizes for each mixture is shown in Table 4. In order to reduce the computational time, a mold of 150x75x100mm^3 was generated. The stiffness and friction coefficient for mold walls was assumed to be 10E20 and 0.6 respectively.

Table 4 Input data for the modeling

Sizes (mm)	Kn=Ks (N/m)	f_r	A (%)	No.	f_r	B (%)	No.	f_r	C (%)	No.	f_r	D (%)	No.
10	1E+08	0.452	80	1014	0.526	70	887	0.6	60	761	0.674	0.5	634
4.14	1E+05		10	1787		15	2680		20	3573		0.25	4466
2.25	1E+03		10	11129		15	16694		20	22258		0.25	27823

All samples were loaded to the same deformation level as in the CFT settings, i.e. 40mm. The results of the overall flow under the loading are shown in Figure 26.

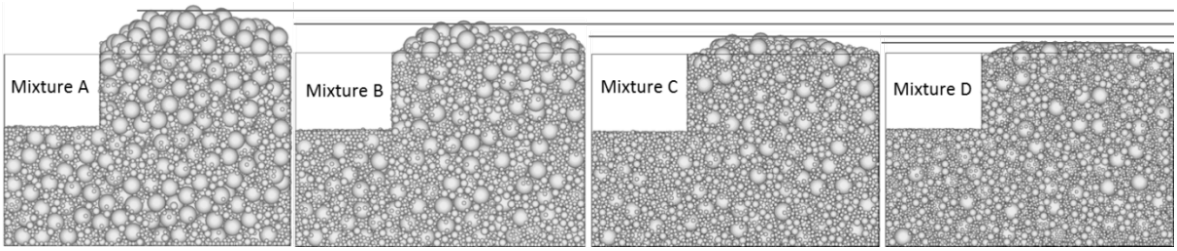

Figure 26 the uplift for different model mixtures at the end of the simulated tests, the lines show the overall maximum uplift for each model mixture

Based on Figure 27, the compaction force trends for the generated mixture models especially for the mixtures B, C and D are similar to the test results shown in Figure 23, thus qualitatively confirming the experimental findings. The fluctuation of the results for mixture A is because of lacking smaller particle fractions for a smoother load progression as for the other three mixture models.

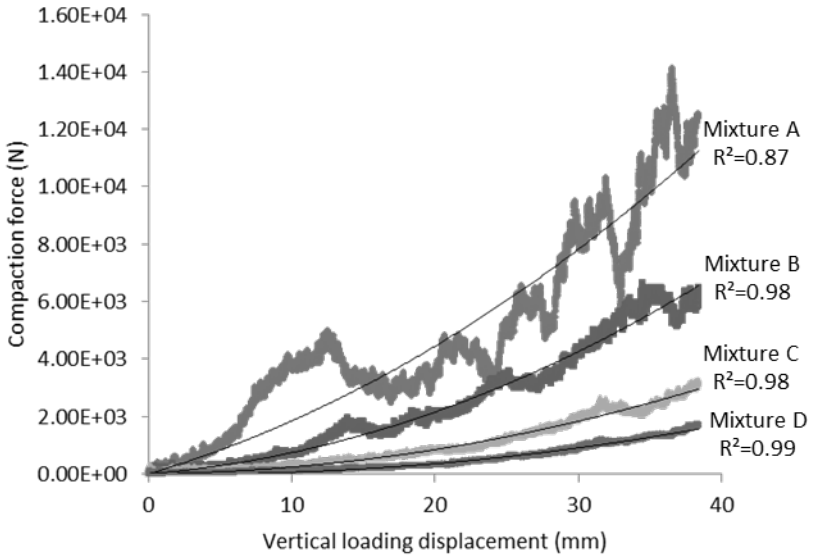

Figure 27 Force-displacement curves obtained from the discrete element models

Comparing the flow traces of the aggregates and binder remained on the walls of the testing mold after the CFT (Figures 28a and 29a) with the model particle displacement results (Figure 28b and 29b) indicated that the simplified models successfully produced displacement patterns similar to the tests; i.e. more concentrated and shorter flow lines for the finer mixtures and fewer and longer flow lines for the coarser mixtures.

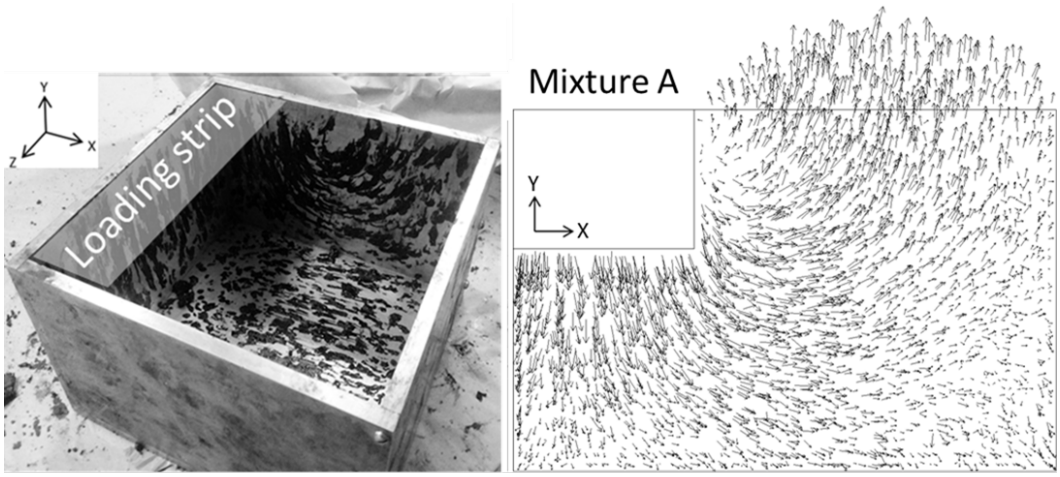

Figure 28 an example of stone flow traces remaining on the CFT mold walls; Left: SMA mixture; Right: coarsest model mixture (mixture A)

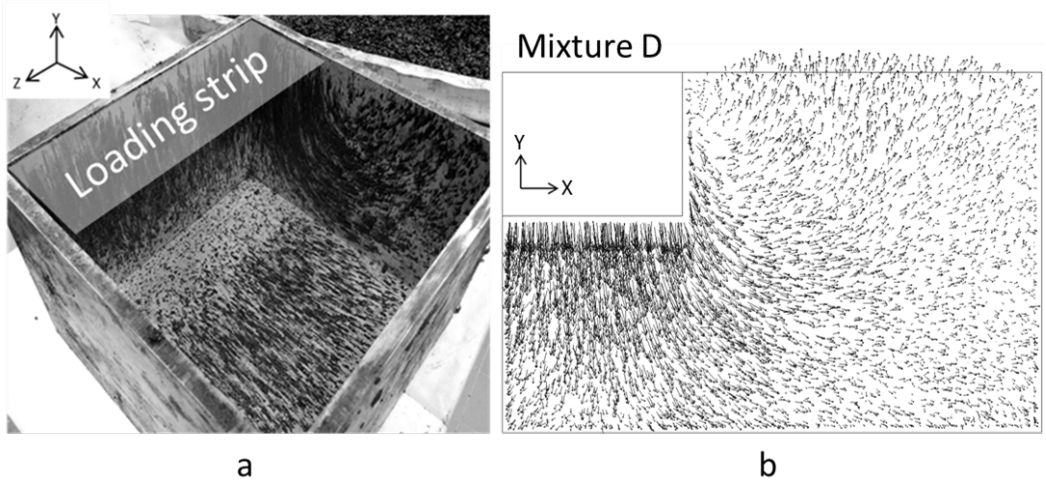

Figure 29 an example of stone flow traces remaining on the CFT mold walls; Left: AC mixture; Right: finest model mixture (mixture D)

3 Conclusions

- Results of performance-based test methods used for evaluating different asphalt construction joints indicated that the joint interface treatments, shapes and also the compaction patterns influence the quality of the joints. The differences among the test methods, when ranking joints construction techniques, demonstrated the capability of the test methods for capturing different aspects of the joints properties.
- Among different construction methods and techniques, changing the compaction pattern appeared to have a considerable impact on the quality of the joints. It highlighted the need for further complementary studies for understanding the compaction phase not only for the sake of joints but also for improving roads qualities in general.
- A Flow Test (FT) was proposed and used along with CT imaging to study the particles flows of different combinations subjected to compacting forces. The results of the initial

tests on model materials clearly demonstrated differences between combinations with different properties. The test also demonstrated its capability of reflecting the internal rearrangements on the free surface of the specimens. The results of the FT on real mixtures also confirmed the findings from the model materials testing.

- A more complete FT, i.e. Compaction Flow Test (CFT), was developed and proven to be capable of conducting evaluative measurements, showing clear differences among asphalt mixtures with different properties.
- Based on the CFT results, mixtures with coarse structures and/or the ones with low binder content required higher compaction forces and consequently demonstrating higher uplifts for reaching the same level of compaction.
- By operating a loading device inside the CT, it was successfully demonstrated that the ultrasonic sensor measurements effectively reflected the internal structural rearrangements during the CFT. In addition, the remaining flow traces on the walls of the mold used as a reliable indicator to justify the CFT results.
- The main conclusion drawn based on the findings of this work is that it was possible to propose a simple experimental method for evaluating the flow of aggregate particles during compaction of asphalt mixtures; this methodology appears a promising tool for predicting the required compaction energy and the flow of particles during the compaction process in the field. In this sense, it may contribute to optimizing the compaction of asphalt pavements in order to increase quality and produce more economical and more environmentally friendly roads.

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