Packing structure of porous asphalt mixture (PAM)

Dana Mutiara Kusumawardani

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**PACKING STRUCTURE OF POROUS ASPHALT MIXTURE
(PAM)**

**DANA MUTIARA KUSUMAWARDANI
SCHOOL OF CIVIL AND ENVIRONMENTAL
ENGINEERING**

2021

PACKING STRUCTURE OF POROUS ASPHALT MIXTURE (PAM)

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School of Civil and Environmental Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Doctor of Philosophy

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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Dana Mutiara Kusumawardani

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Authorship Attribution Statement

This thesis contains material from four papers published in the following peer-reviewed journals in which I am listed as an author.

Chapter 4 is published as Kusumawardani, D.M., and Wong, Y.D. Evaluation of aggregate gradation on aggregate packing in porous asphalt mixture (PAM) by 3D numerical modelling and laboratory measurements. *Construction and Building Materials* 246 (2020). DOI: 10.1016/j.conbuildmat.2020.118414

The contributions of the co-authors are as follows:

- Assoc. Prof Wong Yiik Diew provided the initial project direction and edited the manuscript draft.
- I prepared the manuscript draft. The manuscript was revised together with Assoc. Prof Wong Yiik Diew.
- I co-designed the study with Assoc. Prof Wong Yiik Diew and performed all the laboratory work at the School of Civil and Environmental Engineering, NTU. I also analysed the data.
- All data collection, including sample preparation and discrete element method (DEM) simulation, was conducted by me.
- Assoc. Prof Wong Yiik Diew provided guidance in the interpretation of the laboratory measurements and simulation data.

Chapter 5 is published in three manuscripts as follows:

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Kusumawardani, D.M., and Wong, Y.D. Effect of coarse aggregate surface texture on performance of porous asphalt mixture (PAM). *Under review in International Journal of Pavement Research and Technology*.

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- Assoc. Prof Wong Yiik Diew suggested the materials area and edited the manuscript drafts.
- I wrote the drafts of the manuscripts. The manuscripts were revised together with Assoc. Prof Wong Yiik Diew.
- I performed all the laboratory measurements, carried discrete element method (DEM) simulations, and conducted data evaluation and analyses.
- Assoc. Prof Wong Yiik Diew provided guidance in the interpretation of the laboratory measurements and simulation data.

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Summary

This research study evaluated the packing structure of porous asphalt mixture (PAM) and the main factors influencing it. PAM is the type of hot mix asphalt (HMA) that possesses high air voids content ($>18\%$) to allow water to permeate through the water surface. Herein, packing structure of PAM is mainly established by coarser fractions as the proportion of finer fractions is kept very low to maintain the high air voids content. The stone-on-stone interlocking in aggregate packing of PAM shall be influenced by the properties of the aggregates in the mixtures.

The primary objectives of this study are to have better understanding on the packing structure of PAM, and evaluate the influence of aggregate gradation and coarse aggregate shape properties on the packing structure and properties of PAM. A series of laboratory measurements, including permeability, Marshall stability, resilient modulus, and creep tests, were performed to evaluate the performance of PAM. Meanwhile, Particle Flow Code 3 Dimensions (PFC3D), a software based on discrete element method (DEM), was utilised to assess the packing structure of PAM. The research was classified into three phases. In the first phase, DEM model was developed to simulate PAM specimens, and model considerations and limitations were established. DEM model developed in the first phase was utilised to evaluate the packing structure of PAM in the second and third phases of study. Four packing parameters were developed from DEM model, namely porosity, coordination number, proportion of effective particles (PEP), and average contact force (ACF). The second phase was to assess the influence of aggregate gradation on the packing structure of PAM and to understand the roles of coarse and fine aggregates on the packing structure. Subsequently, the optimum gradation obtained from the second phase was utilised in the third phase. Meanwhile, the third phase evaluated the impact of coarse aggregate shape properties on the packing structure of PAM.

In packing structure of PAM, the results indicated that coarser fractions of coarse aggregates (19.0 – 6.3mm) are the primary size range to establish the main

structure of aggregate packing. Herein, coarser fractions of coarse aggregates have a function to create the main skeleton framework and carry major forces when an external loading is applied. Meanwhile, finer fractions of coarse aggregates (6.3 – 4.75mm) generally have a function to assist load transmitting throughout the packing framework. The results showed that coarse fractions of fine aggregates (4.75 – 2.36mm) is a critical size fractions, thereby the proportion of these fractions should be controlled. The excessive proportion of 4.75 – 2.36mm fractions was found to disrupt the skeleton framework of packing structure as many ineffective contacts were generated such that these ineffective particles only have a role to fill in the voids in the aggregate packing rather than contribute on load distribution. Meanwhile, insufficient proportion of 4.75 – 2.36mm fractions would result in the packing structure of PAM not having enough particle contacts to establish a stable skeleton framework.

Furthermore, aggregate shape properties showed a great influence on the aggregate packing structure and properties of PAM. Aggregate shape properties determine the degree of stone-on-stone interlocking between particles. Herein, three independent shape characteristics were considered, namely form (overall shape), angularity (roundness), and surface texture. The results indicated that cubical-shaped, angular, and/or rougher aggregates generate higher proportion of effective particles in the packing structure of PAM. As cubical-shaped, angular, and/or rougher aggregates possess a wider surface area, they are able to generate more particle contacts in aggregate packing. Moreover, the edges or corners and the irregularity in aggregate surface strengthen the particle interlocking, thereby ensuring that more effective contacts are generated. Subsequently, packing structure of PAM with cubical-shaped, angular, and/or rougher aggregates would suffer less stress and result in PAM with cubical-shaped, angular, and/or rougher aggregates having the best mechanical properties, with higher Marshall stability and lower permanent strain.

Based on the research findings, DEM simulation is deemed feasible to simulate the packing structure of PAM. The results of DEM simulation are found to be agreeable with conventional packing theory and laboratory measurements.

List of Publication

- Kusumawardani, D.M., and Lin, J.D. Evaluations of performance and thermal properties in porous asphalt concrete containing steel slag. *Advanced Materials Research* 1025-1026 (2014) 688-92. DOI: 10.4028/www.scientific.net/AMR.1025-1026.688
- Kusumawardani, D.M., and Wong, Y.D. Evaluation of aggregate gradation on aggregate packing in porous asphalt mixture (PAM) by 3D numerical modelling and laboratory measurements. *Construction and Building Materials* 246 (2020). DOI: 10.1016/j.conbuildmat.2020.118414
- Kusumawardani, D.M., and Wong, Y.D. The influence of aggregate shape properties on aggregate packing in porous asphalt mixture (PAM). *Construction and Building Materials* 255 (2020). DOI: 10.1016/j.conbuildmat.2020.119379
- Kusumawardani, D.M., and Wong, Y.D. Effect of aggregate shape properties on performance of porous asphalt mixture (PAM). *Journal of Materials in Civil Engineering* 33(8)(2021). DOI:10.1061/(ASCE)MT.1943-5533.0003801.
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List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ACF	Average contact force
AIMS	Aggregate Imaging System
AIV	Aggregate Impact Value
ASTM	American Society for Testing and Materials
BS	Breaking Sieve
CAD	Computer Aided Design
CUW	Chosen Unit Weight
DASR	Dominant Aggregate Size Range
DEM	Discrete Element Method
DOT	Departments of Transportation
FEM	Finite Element Method
FHWA	Federal Highway Administration
HMA	Hot mix asphalt
IC	Interstitial components
ITS	Indirect tensile strength
IV	Interstitial volume
LAV	Los Angeles Abrasion Value
LTA	Land Transport Authority
LUW	Loose Unit Weight
NCAT	National Center for Asphalt Technology
NPMS	Nominal Maximal Particle Size
OGFC	Open-graded friction course
PAM	Porous asphalt mixture
PEP	Proportion of effective particles
PCS	Primary control sieve
PFC3D	Particle Flow Code 3 Dimensions
PMB	Polymer-modified binders
SBS	Styrene Butadiene Styrene

SCS	Secondary control sieve
SHRP	Strategic Highway Research Program
TCS	Tertiary control sieve
TFV	Ten Percent Fines Value
TMD	Theoretical Maximum Density
VCA	Voids in coarse aggregate
VFB	Voids filled with binder
VMA	Voids in mineral aggregates
VTM	Voids in total mix

List of Symbols

A_p	Surface area of the particle
A_s	Surface area of a sphere with the same volume with the given particle
CA	Coarse aggregates ratio
C_n	Coordination number
F	Shape factor
FA_c	Coarse portion of fine aggregates
FA_f	Fine portion of fine aggregates
k^n	Normal stiffness
k^s	Shear stiffness
N	Number of particles in each size range of aggregate gradation
p	Flatness ratio
q	Elongation ratio
R_a	Mean roughness
R_z	Maximum height of profile
Ψ	Sphericity
τ	Relaxation time

List of Standards

ASTM C131, D7064	Standard Practice for Open-Graded Friction Course (OGFC) Mix Design
ASTM D6390 – 11	Standard Test Method for Determination of Drain-down Characteristics in Uncompacted Asphalt Mixtures
ASTM D6927 – 15	Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures
ASTM D2041-11	Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
AS 2891.13.1-2013	Determination of the resilient modulus of asphalt—Indirect tensile method
AS 2891.12.1 -1995	Methods of sampling and testing asphalt Determination of the permanent compressive strain characteristics of asphalt - Dynamic creep test
BS 812-105.1	Methods for determination of particle shape. Flakiness index
BS 812-105.2	Methods for determination of particle shape. Elongation index of coarse aggregate

Chapter 1 Introduction

1.1. Introduction

This Chapter introduces the broad issues of asphalt pavement, and porous asphalt mixture and its characteristics as related to the thesis research. The problem statement that motivates this research on packing structure of porous asphalt mixture is highlighted and the objectives and scope of work for this research are explained. The organisation of the report is then described.

1.2. Background

Asphalt mixtures are composite materials that are generally used as surfacing layer of flexible pavement. Asphalt mixtures are consisting mainly of two materials, namely aggregates and asphalt binder. Meanwhile, porous asphalt mixture (PAM) is the type of hot mix asphalt that has high air voids content (above 18%) for removing water from the roadway pavement to the drainage system. The application of PAM may mitigate the storm-water drainage problem on urban road pavement as the rainwater can readily permeate through the PAM layer as rainfall directly infiltrates into the high-air voids surfacing. Moreover, the application of PAM also has many advantages such as alleviation of noise pollution, mitigation of splash and spray to drivers and pedestrians, and better skid resistance (Rungruangvirojn and Kanitpong 2010; Jomoor, Fakhri, and Keymanesh 2013; Kusumawardani and Lin 2014). PAM exhibits the potential to be a cooler pavement as its surface temperature tends to be lower due to the evaporative cooling effect under wet condition, and lower thermal conductivity and heat capacity under dry condition (Li et al. 2013). The evaporative cooling mechanism in PAM is similar to the mechanism of vegetated land cover. It has also been reported that PAM possesses a lower surface temperature at night-time than dense-graded asphalt mixtures (Stempihar et al. 2012). Herein, the application of PAM in Singapore shall be very favourable as the tropical climatic conditions in Singapore result in frequent rainy weather throughout the year.

The performance of PAM is determined by several factors, namely properties of asphalt binder and the quality of the aggregate packing structure. Herein, PAM with insufficient asphalt binder and/or thinner film at the surface could accelerate aging and ravelling potential (Chen and Yang 2020). It has been reported that increasing the proportion of asphalt content by 0.6% significantly enhances the service life of open-graded asphalt mixtures (Moseley 2020). Meanwhile, the skeleton framework of aggregate packing in PAM is mainly established by the coarse aggregate fractions as PAM gradation consists of a relatively low proportion of fine aggregates in order to maintain the high air voids content. Thereby, PAM's ability to carry traffic load and withstand the deformation is greatly determined by particle-to-particle interlocking among the coarse aggregates. Previous research have reported that the properties of aggregates are significant factors that influence the packing condition of asphalt mixtures (Chen and Wong 2016a; Elkhaliq, Napiah, and Kamaruddin 2012).

The desired properties and performance of PAM can be better understood by studying the functional roles of each size-fraction of aggregates in the packing structure and shape properties of coarse aggregates. Even though PAM has a weaker strength and durability performance as compared to dense-graded mixtures, PAM possesses good functional attributes as a pavement surfacing, such as providing a relatively dry surface in rainy weather. This has motivated this research into application of PAM for an environment like Singapore, which has frequent wet weather all year round.

1.3. Problem statement

The mechanical properties of PAM are generally weaker than dense-graded asphalt mixtures as PAM possesses a lower density. The high content of air voids compromises the mixture strength and durability of PAM to some extent. Herein, PAM is more susceptible on ravelling and clogging due to its open gradation and water accessibility (Chen 2018; Garcia et. al. 2019). Various mixture designs of PAM have been introduced to optimise the performance of PAM, in terms of both mechanical and drainage performance. However, the assessment in the performance of PAM is mainly evaluated according to a series of laboratory

measurements, namely permeability test, abrasion test, Marshall test, moisture susceptibility, rutting resistance, etc. As PAM is mainly designed for low-strength application, current requirement standards for laboratory measurements of conventional asphalt mixtures may not be appropriate for PAM. Thereby, new assessment methods to determine the performance of PAM should be developed.

On the other hand, aggregate packing structure greatly influences the properties of PAM. Herein, the state of aggregate packing structure of PAM can be utilised as an indicator of the overall performance of PAM. PAM is mostly constituted of coarse gradation to maintain the high air voids content, thereby the properties of coarse aggregates shall greatly affect the packing structure of PAM. Several studies have reported that physical properties of aggregates, such as aggregate gradation and density, are significant factors that influence the packing structure of asphalt mixtures (Chen and Wong 2016a; Elkhaliq, Napiah, and Kamaruddin 2012). Meanwhile, the effect of other aggregate properties in PAM, such as aggregate morphology, has rarely been investigated. Available knowledge about the influence of aggregate morphology has been conducted based on empirical tests on PAM, rather than assessment of its aggregate packing structure. Moreover, studies about aggregate morphology have utilised various materials as aggregates, therefore the resultant performance is influenced by confounding effects (Huang et al. 2009; Kangkhatjitre and Kanitpong 2011; Bessa et al. 2015; Jaya, et al. 2014; Tarmuzi et al. 2015; Cui et al. 2018).

Though several research studies have attempted to determine the optimum mix design for asphalt mixtures according to aggregate packing structure, yet most available packing theories and research inquiries were mainly focused on dense asphalt mixtures (Vavrik, William, and Carpenter 2002; Kim et al. 2009). The available packing theories, namely Bailey method, dominant aggregate size range (DASR) model, voids in coarse aggregates (VCA) index method, assess the quality of aggregate packing based on the maximum density level of the packing. Herein, these packing theories are not suitable to assess the packing structure of PAM, in which the high voids content is deliberately designed to achieve the drainage performance. Beside density measure, the particle-to-particle interlocking and/or

the contact mechanism of aggregates should be a more direct parameter in indicating the state of aggregate packing structure.

By utilising discrete element method (DEM) simulation which entails numerical analyses based on the alternate implementation of the force-displacement law and law of motion (Newton's second law), particle-to-particle interactions between an assembly of granular materials can be assessed. In this study, Particle Flow Code in 3 Dimensions (PFC3D), an application software based on DEM theory (Itasca 2008), was utilised to evaluate the packing structure of PAM. Herein, packing parameters are established to indicate the conditions of aggregate packing structure.

1.4. Objectives

The broad objective of this research is to contribute to the understanding of the packing structure of PAM and the main factors that influence it. Fundamental characterisation of main constituent materials in the mixture, namely the aggregates, and understanding the influence of the corresponding properties on the aggregate packing structure shall provide better analysis on the resultant performance of PAM. Herein, the influence of aggregate gradation and the three characteristics of aggregate shape, namely form (overall shape), angularity, and surface texture, are closely investigated. The specific research objectives of this research are:

- To propose and develop a new method by utilising Discrete Element Method (DEM) simulation to assess the packing structure of PAM.
- To understand packing condition and stone-on-stone interlocking in PAM via laboratory measurements and DEM simulation;
- To evaluate the role of various aggregate size fractions (19.0 – 2.36mm) on the packing structure of PAM via laboratory measurements and DEM simulation; and
- To investigate the influence of the characteristics of aggregate shape, namely form, angularity, and surface texture, on the performance of PAM, and analyse the correlation between aggregate shape properties and the packing structure and properties of PAM.

1.5. Significance

This research shall provide insight on the particle-to-particle interlocking mechanism in aggregate packing structure, and the understanding on the main factors that influence it. The knowledge about the effect of aggregate shape characteristics shall be valuable to provide useful guidelines during pre-processing of industry by-products or recycled materials for value-add utilisation in the asphalt mixtures.

DEM simulation is also introduced in this research as an alternative method to evaluate the packing structure of asphalt mixtures by providing an explicit assessment on contact mechanism among aggregate particles. Therein, the understanding on aggregate packing via DEM simulation shall be a valuable guidance to determine the appropriate mixture design of asphalt pavement, besides conventional laboratory measurements.

1.6. Organisation of thesis

This thesis consists of six chapters, including this introduction chapter that covers the background of the research, objectives and scope of work. The subsequent chapters document different aspects of the research.

Chapter 2 reviews the literature and previous studies that are related to PAM design, such as restricted zone, aggregate gradation and morphology, etc. This Chapter also discusses the issues related to packing theories and numerical simulations, including the parameters of packing structure, implementation of the theories and current practices. It also highlights the gaps of current knowledge and research.

Chapter 3 covers the methodology that is used in this research, especially on the laboratory experimentation. In-lab experimental design for the first phase of this research (identification phase) is described in this Chapter. This Chapter also covers the development of the aggregate packing by utilising a software based on discrete element method, Particle Flow Code 3 Dimensions (PFC3D), and in-lab experiments and measurements.

The main body of this thesis is in Chapters 4 and 5, which are listed as follows:

- Chapter 4 focuses on the development of aggregate gradation of PAM by investigating the packing structure and the properties of PAM with various aggregate size distribution. The role of the coarse and fine aggregates in the aggregate packing is also explained in this Chapter.
- Chapter 5 examines the influence of aggregate shape properties, namely form, angularity, and surface texture, on the performance of PAM via laboratory measurements and DEM simulations, and evaluates the correlation between aggregate shape properties and packing parameters.

Chapter 6 summarises the findings of this study and lists recommendations for further research.

Chapter 2 Literature Review

2.1. Overview

This Chapter compiles research works related to porous asphalt mixture (PAM), including its characteristics and design. The developments of aggregate packing theories are explained, including associated benefits and limitations. In addition, aggregate packing factors are introduced, such as aggregate gradation and morphology (form, angularity and surface texture).

2.2. Porous Asphalt Mixture

Porous asphalt mixture (PAM) is a type of hot mix asphalt (HMA) that allows water to drain through the pavement surface due to its high air voids content. The high air voids in PAM can be achieved by reducing the proportion of the finer fractions of the aggregates. Generally, PAM has weaker performance in terms of durability and load bearing capacity as compared to conventional dense mix due to the high proportion of interconnected voids. Thus, current application of PAM is mainly limited to low-strength pavement, such as parking areas, pedestrian walkways, sidewalks, bicycle lanes, etc. (Chen and Wong 2016b). With proper design and installation, PAM pavements can serve as a cost-effective and environmentally friendly solution for storm-water management.

2.2.1. Advantages of PAM

The advantages of PAM can be grouped into two aspects:

- 1) Performance benefits
 - a) Traffic safety from improved skid resistance, reduced splash and spray, lesser light reflection; and
 - b) Storm-water management.
- 2) Environmental benefits, from noise reduction and cooling effect.

These advantages of PAM are described in details in the following.

- 1) Skid resistance

There are three important characteristics of the road surface that are related to wet-road skid resistance, namely adequate micro-texture of the surface, adequate drainage of the water from the surface, and good macro-texture of the surface which is needed to maintain skid resistance at higher vehicle speeds (Hosking 1992). The high proportion of coarser aggregates in PAM creates coarser surface texture of the pavement, thus improving macro-texture of pavement's surface and its skid resistance. Application of PAM as compared to hot mix asphalt can also reduce the loss of skid resistance during wet condition since the water run-off on the pavement surface can be eliminated quickly.

2) Splash and spray

Splash and spray occurs when vehicle wheels toss the water when running on a wet surface. Splash and spray can interfere with the visibility of road users and thereby results in serious problems in terms of driving safety. PAM pavement can reduce splash and spray by eliminating cumulative water on the road surface. Research has indicated that visibility loss of conventional mix is approximately 1.4 times higher than PAM during wet conditions (Rungruangvirojn and Kanitpong 2009).

3) Storm-water management

Application of PAM can improve storm-water management by allowing accumulated water to drain through interconnected voids and lengthen the distance to reach drainage systems. This phenomenon can help to slow down the time of concentration to the drainage outlet and delay peak run-off. Thus, over-flowing run-off during heavy rain in the drainage system can be reduced.

4) Noise reduction

The noise level can be lowered by around 3 dB(A) with the application of PAM, which is attributed to two aspects: (a) PAM decreases noise emerging from tyres, and (b) air voids in PAM absorb the noise that is channelled downwards (Nelson and Abbot 1990; Bendtsen and Andersen 2005). With vehicle wheels rolling, the interaction between tyres and the pavement surface generates a vibration due to air compressing and relaxing. In PAM, the air voids relieve the air compression when

tyres interact with pavement surface, thus decreasing the noise. In several countries, such as Germany, Denmark, U.K., Belgium, and, Netherlands, noise reduction is the major objective of PAM application (Nelson and Abbot 1990; Khalid and Jimenez 1995).

(5) Cooling effect

In wet condition, PAM results in a cooler pavement by evaporation of water collected inside the voids when the pavement surfacing layer is being heated up (Li et al. 2013). This mechanism is similar to evaporative cooling from vegetated land cover. Meanwhile in dry condition, the high air voids content in PAM results in greater surface area which slows the heat transmission from the lower part of surfacing layer to the upper part (Li et al. 2013). Thus, the heat that is trapped inside the pavement will be released more slowly during night time, thereby reducing the peak of the heat island effect.

2.2.2. Disadvantages of PAM

Due to higher content of air voids, mixture strength and durability of PAM are compromised to some extent. The various disadvantages associated with PAM are as follows.

(1) Ravelling

Ravelling, which refers to aggregates becoming loose, is caused by the adhesiveness and cohesiveness of asphaltic materials being weakened due to the combined effects of moisture damage and ageing. Moreover, PAM's overall strength is decreased due to ravelling, which can be reflected by lowered Marshall stability as determined in the Marshall test.

(2) Clogging

Clogging refers to porosity reduction, which is a major issue for permeable pavement. Garcia et al. (2019) indicated that the size of the air voids is the key factor influencing clogging ratio of asphalt mixtures. One of the methods to exterminate vegetation materials from clogging the voids of PAM is to use

herbicides. Herein, using herbicides may pollute the soil and the waterways. Alternative methods to manage clogging are by cleaning the permeable pavements using high-pressure water jets and vacuum suction, the process of which may itself damage the integrity of PAM.

2.1.3. PAM design

In the United States, the Federal Highway Administration (FHWA) has developed a mix design procedure for open-graded friction course (OGFC) as early back as 1974. Many departments of transportation (DOTs) adapted PAM design procedures specified in the FHWA Technical Advisory T5040.31. However, some agencies had feedback of unfavourable results that, though OGFC may have good performance, it is lacking in durability. Such experiences resulted in many DOTs to stop using OGFC. Then, a new generation of OGFC was developed by the National Center for Asphalt Technology (NCAT) that was published in 2000 which recommends more rational mix design procedures for OGFC (Mallick et al. 2000). The main parameters of this latter method establish the asphalt content limit, maximum drain-down, air voids range (17–19%), maximum abrasion loss, and minimum retained tensile strength ratio. The NCAT method recommends a minimum permeability of in-place PAM.

PAM designs in several countries, such as European, Japanese, etc. are similar to the NCAT 2000 method in many aspects though the respective procedures do vary from agency to agency (Alvarez et al. 2006). In many cases, polymer-modified binders (PMB) and fibres are utilised to minimise drain-down. However, the Netherlands and Switzerland are still utilising conventional binder, even though it has been allowed to use modified binder in Switzerland (Alvarez et al. 2006). The recommended air voids content, generally > 20%, is similar to the U.S. designs, but it is possible to go as high as 26%. The addition of fibre is commonly intended to mitigate drain-down problems during mixing, handling, and placement process. The Cantabro test is a commonly-used method to determine sufficient resistance to degradation and determine the cohesivity level of the mixtures, and thereby establishes the minimum binder content. In Europe, a minimum permeability of post-construction PAM is not specified. Yet, the minimum field permeability that

has to be measured immediately after mixture placement was established in the United Kingdom.

2.3. Restricted Zone in the aggregate gradation

2.3.1. Significance of restricted zone

The concept of restricted zone in the aggregate gradation was put forward a long time ago in that an aggregate gradation that falls within the intermediate sieve sizes is susceptible to tenderness and rut in the field. The restricted zone became formal guideline after SHRP's aggregate gradation recommendation was established in the Superpave mix design method (SHRP 1994).

After the restricted zone was included in the Superpave mix design method, asphalt pavement expertise discovered that certain HMA mixtures actually demonstrated good performance even though they did not meet the Superpave specifications. Indeed, it has been reported in some studies that there is no correlation between Superpave restricted zone and rutting or fatigue performance of asphalt mixtures (Chowdhury, Button, and Grau 2001; Kim 2006). Moreover, asphalt mixtures with gradation falling inside restricted zone possess similar or even better properties than the gradation outside restricted zone (Chowdhury, Button, and Grau 2001; Zhang, Cooley Jr, and Hurley 2003). Herein, it seems that mixtures with gradation cutting through and passing below the restricted zone can still be used for wearing courses (Mampearachchi and Fernando 2012).

Some recent studies suggested that the restricted zone does have influence on volumetric and compaction properties of asphalt mixtures. Asphalt mixtures which violate restricted zone possess higher air voids than mixtures with gradation above or below the restricted zone. The results also indicated that, in some cases, mixtures violating restricted zone had favourable traits than mixtures above and below restricted zone, such as a lower effective binder content and being easier to meet Superpave voids-in-mineral-aggregate (VMA) criteria (Al-Khateeb, Ghuzlan, and Al-Barqawi 2017).

The significance of restricted zone remains debatable due to conflicting findings that restricted zone is redundant for mixtures that meet all Superpave volumetric parameters and the required fine aggregate angularity (Kandhal 2001). Yet the results also suggested that restricted zone does influence asphalt performance to some extent. This phenomenon can be explained from packing structure perspective using Bailey method. In Bailey method, the restricted zone falls within coarse fractions of the fine aggregates zone, which is the zone that has a role to create voids that will be filled with fine portion of the fine aggregates. To achieve desired packing condition, coarse fractions of fine aggregates is controlled by a parameter called FA_C ratio with recommended value at around 0.35 – 0.5. However, the FA_C ratio value of restricted zone is 0.488 – 0.591, which falls outside the recommended bounds. This indicates that mixtures with gradation passing through the restricted zone may have excessive amount of the fine portion of the fine aggregates, and the fine aggregates would overfill the voids, thus resulting in potentially tender mixtures.

Nevertheless, it is possible for a gradation outside the restricted zone to have a higher FA_C ratio than a gradation violating restricted zone. Thus, a potentially tender mixture is not exclusively falling within the restricted zone. Herein, restricted zone should be re-evaluated by considering the proportion of finer fractions to the coarser fractions. This is because an excessive amount of fine portion in some gradations may yet be appropriate and sufficient in others, as depending on the voids established by the coarser fractions.

2.3.2. Restricted zone in PAM

Due to the requirement for a high content of coarse aggregates, PAM gradation will always straddle below the lower bound of the restricted zone in Superpave mix design. Thus, restricted zone for Superpave HMA developed by SHRP is of limited coverage in the porous asphalt. Moreover, coarser fractions have more significant influence in determining performance of PAM rather than fine fractions. Therefore, the concept of ‘restricted zone’ or ‘controlled zone’ for PAM shall be examined not only for the fine fractions but also the coarse fractions.

Although there are no regulations or guidelines explicitly discussing this matter, knowledge of the influence of coarse aggregates in PAM has actually been applied for development of PAM's gradations in different countries, as summarised in Table 2.1. It can be observed that significant difference can be discovered in the proportion of coarser aggregates, especially in the proportion passing 9.5mm, as well as proportions of finer aggregates passing 4.75mm and 2.36mm. Thus, it has been acknowledged in several countries that modifying the amount of certain size of the coarser aggregates could influence the performance of PAM to achieve the desired performance suitable for the condition and requirement of each country.

Table 2.1 Gradations of PAM used in different countries and research institutes (% passing)

sieve size (mm)	Taiwan	China	Japan	FHWA of USA	Spain	LTA-PA Singapore
25.4	100	-	-	-	-	-
19	95-98	100	100	100	100	100
13.2	-	90-100	90-100	-	-	79-89
12.5	64-74	-	-	85-100	70-100	-
9.5	44-55	60-80	-	55-75	50-80	67-77
4.75	10-21	12-30	11-35	10-25	15-30	17-26
2.36	10-15	10-22	10-20	5-10	10-22	13-23
1.18	7-13	6-18	-	-	-	-
0.6	6-11	-	-	-	-	8-18
0.3	5-9	-	-	-	-	6-12
0.15	3-7	-	-	-	-	4-10
0.075	3-5	2-6	3-7	2-4	3-6	4-8

The packing structure of PAM is mainly established by the coarse aggregates, thus finding appropriate proportion of each fraction size of coarse aggregates is important to create a functional PAM with adequate strength. Wang et al. (2018) stated that the proportions passing 2.36mm and 4.75mm sieves have negligible influence on skeleton strength, while proportion passing 9.5mm sieve has the biggest influence on skeleton strength of PAM. It was recommended that 40% and 80% as lower limit and upper limit for proportion passing 9.5mm sieve.

Meanwhile, Chen and Wong (2018) suggested that 19.0 - 6.3mm fractions have a key role to provide stone-on-stone framework and a high content of 4.75 - 2.36mm fractions may disrupt the skeleton framework created by the coarser fractions. Study by Xiao et al. (2015) supported both claims, in which mixtures with a high amount of 19.0 - 9.5mm fractions (more than 50%) have better rutting resistance, while mixtures with high amount of 4.75 - 2.36mm fractions (20-50%) perform the worst.

2.4. Aggregate shape properties

Aggregate particles significantly influence the overall mechanical properties and performance of asphalt mixtures (Yeggoni et al. 1994; Vavrik et al. 2000; Bessa et al. 2015; Hamzah et al. 2014; Jaya et al. 2014; Mahmud et al. 2014; Tarmuzi et al. 2015; NCAT 2017). As the shape properties of aggregates vary, the shape factor highly determines the characteristics of the mixtures including their behaviour and performance. The geometry of an aggregate particle can vary greatly as depending on its origin and subsequent processing. Three independent properties to characterise particle geometry are form, angularity and surface texture (Barrett 1980). Form is the overall shape of a particle. Parameters that are usually used to describe form are sphericity, shape factor, elongation and flakiness, form factor, etc. Angularity or roundness is related to variations on the particle edges or corners. Meanwhile, surface texture is the irregularity of aggregate's surface that is too small to influence its overall shape (Al Rousan 2004). A schematic of the three main characteristics of aggregate shape is presented in Figure 2.1.

Figure 2.1 Aggregate shape properties (adapted from Barrett 1980)

2.4.1. Aggregate shape characteristics

Two different methods, namely direct and indirect methods, are used to assess aggregate shape characteristics (Kandhal, Motter, and Khatri 1991). Direct methods use a direct measurement of individual particle characteristics (form, angularity, and texture) qualitatively, and possibly quantitatively. Meanwhile, indirect methods measure bulk particle shape characteristics and define them as geometric irregularities

Direct methods differ in the degree of sophistication utilised to measure aggregate shape properties. Some procedures simply depend on visual inspection of aggregates, while others use mechanical devices to classify aggregates in accordance with the proportions of aggregate dimensions. Moreover, there is an imaging system that has a mechanism for capturing images of aggregates and methods to interpret aggregate characteristics.

(1) Aggregate shape parameters

Several shape parameters have been developed to define the three independent shape characteristics. Herein, the particle form is classified by form factor (F) according to the flatness and elongation ratios of particles. Flatness ratio (p) refer to the ratio of particle thickness (the shortest length) to particle width (intermediate length), while elongation ratio (q) is the ratio of particle width (intermediate length) to particle length (the longest length) (Lees 1964). The correlation between form factor (F) with flatness and elongation ratios is expressed in Equation (2.1).

$$F = \frac{p}{q} \quad (2.1)$$

Form factor is equal to one if the particles have a shape of sphere or cube, while elongated and thin particle has a form factor less than 1, and a form factor greater than 1 is for blade shaped particle.

The other common parameter to define the form of particle is sphericity. Sphericity (Ψ) refer to the closeness of particle shape compared with the shape of a perfect

sphere. Sphericity can be calculated by utilising Equation (2.2). The sphericity ranges from near zero to 1.0, in which 1.0 is for a perfect sphere.

$$\text{Sphericity } (\Psi) = \frac{A_s}{A_p} \quad (2.2)$$

where A_s is surface area of a sphere with the same volume with the given particle, while A_p refer to the surface area of the particle (A_p),

Meanwhile, the level of aggregate angularity is defined by a roundness parameter. Roundness (R) is the ratio of the average radius of curvature of the edges of the material's silhouette to the radius of the maximum inscribed circle (Wadell 1933) as given in Equation (2.3).

$$\text{Roundness, } R = \frac{\sum r_i / N}{r_{\max-in}} \quad (2.3)$$

where r_i is radius of circle fitting each corner, $r_{\max-in}$ is radius of inscribed circle, N is number of corners. A particle of less angular shape will have a higher roundness value, and vice versa.

Lee (1964) created a diagram that combine the flatness(p) and elongation (q) ratios, the form factor (F) and the sphericity (Ψ) as shown in Figure 2.2. The aggregates are classified into four different shapes, namely disc, equidimensional, blade and rod shaped as illustrated in Figure 2.2. Equidimensional particles are either cubic or round particles.

A roughness parameter, namely mean roughness (R_a), is utilised to describe the state of aggregate surface texture. Mean roughness (R_a) refers to the arithmetic average of the roughness profile ordinates, which is expressed in Equation (2.4). Mean roughness has been widely used to measure the surface texture of object in engineering practices (Florkova and Komacka 2015; Qian and Meng 2017; Qudoos and Rehman 2018).

$$R_a = \frac{1}{l_r} \int_0^{l_r} |Z(x)| dx \quad (2.4)$$

where $Z(x)$ refers to the profile ordinates of roughness profile.

* Ψ = sphericity, F = form factor

Figure 2.2 Aggregate shape classification scheme (Lees 1964)

Another parameter to describe the surface texture of materials is maximum height of profile (R_z). Maximum height of profile refers to the absolute value of vertical distance between the maximum valley depth with the maximum profile peak height along the measurement range. Maximum height of profile is usually referred as the maximum roughness of materials.

The relationship between parameters of the three shape characteristics, namely form (shape), angularity (roundness), and surface texture, is illustrated in Figure 2.3. It can be seen that each parameter is not interchangeable to describe the state of each shape characteristic.

Figure 2.3 Relationship between parameters of the three independent shape characteristics

(2) Laboratory measurements

Several standard tests to determine aggregate shape parameters are available, namely ASTM D5821: Determining the Percentages of Fractured Particles in Coarse Aggregates, ASTM D4791: Flat and Elongated Coarse Aggregates, ASTM D4791: Flat and Elongated Coarse Aggregates, and BS 812-105: Determining Particle Shape - Flakiness and Elongation Index.

(3) Aggregate Imaging System (AIMS)

AIMS device was developed by Dr. Eyad Masad (see Figure 2.4.). Two modules of system operation are adapted in this device. The first module is to analyse fine aggregates, and the second one is to analyse coarse aggregates. A video camera and a microscope in this device have the function to capture grey images and black and white images. The fine aggregates are evaluated for form and angularity, while the coarse aggregates are investigated for form, angularity, and texture. The depth of particles is determined by utilising the video microscope, while the images of 2-D projections evaluate the other two dimensions (Masad 2003).

Figure 2.4 AIMS device (Masad et al. 2011)

2.4.2. Impact of aggregate shape properties on asphalt mixtures

Aggregate shape has been acknowledged as one of the key factors that influences asphalt mixtures' performance, thus numerous studies have been done to evaluate the impact of aggregate shape properties on asphalt mixtures' performance using various parameters (Masad et al. 2011; Hamzah et al. 2014; Jaya et al. 2014; Mahmud et al. 2014; Rose 1971; Bessa et al. 2015; Watson and Julian 2017; Vavrik et al. 2000; Kangkhatjitre and Kanitpong 2011; Yeggoni et al. 1994). In general, the research results all indicated that angular and cubical shape with rough surface is the most favourable shape properties for the aggregates. The results from various studies have indicated that by increasing the amount of cubical shaped aggregates, the mechanical properties of asphalt mixture tend to improve (Hamzah et al. 2014; Jaya et al. 2014; Mahmud et al. 2014; Watson and Julian 2017).

Flat and elongated particles are not favourable due to this type of particles resisting each other during compaction process and it is more prone to breakdown in the coarse aggregates. For hard aggregates, flat and elongated particles create more voids in the coarse aggregates structure because these particles tend to restrain against re-orientation. As for soft aggregates, the designed gradation tends to change due to increasing proportion of the coarser portion of fine aggregates after aggregate breakages (Vavrik et al. 2000). Flat and elongated aggregates may require higher asphalt binder, and it was recommended that the proportion of flat and elongated particles should be less than 20% of total weight (Watson and Julian

2017). A study using Superpave gyratory compactor (SGC) indicated that asphalt mixtures containing a large amount of flat and elongated particles are more difficult to compact, yet a larger amount of flat coarse aggregates may be easier to move and turn at certain degree of compaction energy (Gong et al. 2018). Mahmud et al. (2014) investigated the influence of flaky-shaped aggregates on asphalt mixtures by utilising three different proportions of flaky-shaped aggregates, namely 10%, 20%, and 30% by total weight. The results suggested that higher asphalt content is required for a higher proportion of flaky-shaped aggregates, while increasing the proportion of flaky -shaped aggregates also reduce the resilient modulus and increase permanent deformation of asphalt mixtures.

Bessa et al. (2015) assessed aggregates with similar properties but of three different mineralogy. The study found that using aggregates with similar shape but different mineralogy in asphalt mixtures is likely to have similar mechanical properties, thereby indicating that aggregate shape properties have greater influences on the properties of asphalt mixtures than mineralogy of aggregates. Hamzah et al. (2014) investigated the influence of geometrically cubical-shaped (GCS) aggregates on PAM by utilising five different combinations of GCS aggregates and normal-shaped aggregates. The results indicated that PAM containing 100% GCS aggregates has the best performance, and aggregate shape significantly affects both volumetric and mechanical properties of PAM, such as porosity, coefficient of permeability, and resistance on permanent deformation. Chen et al. (2013) evaluated the influence of coarse aggregate shape on the performance of stone mastic asphalt (SMA), and the results suggested that utilising cubical-shaped aggregates increases internal resistance of the mixtures on rutting. Another study compared the influence of aggregate shape by utilising two different aggregate crushers, namely compression and impact crushers, to produce two different aggregate shapes, cubical-shaped and irregular-shaped, respectively (Jaya et al. 2014). The results showed that using geometrically cubical aggregates improves the resilient and stiffness modulus of the asphalt mixtures. Aggregate shape also has a notable influence on the skid resistance of the mixtures, in which angularity, surface texture, and polished stone value (PSV) significantly affect the British pendulum number (BPN), while angularity, surface texture, and fineness modulus

influence the mean texture depth (MTD) of the mixtures (Rose 1971; Kangkhatjitre and Kanitpong 2011).

Yeggoni et al. (2014) investigated the influence of angularity and surface texture of aggregates by utilising seven aggregate blends with different proportions of crushed limestone, crushed river gravel, and uncrushed river gravel combinations. The findings showed that Marshall stability, Hveem stability, and resilient modulus increase with increasing proportions of crushed coarse aggregates. It was also indicated that fractal number of aggregates correlated with creep and deformation resistance behaviour of the asphalt mixtures. Another study that suggested similar notions as applied for PAM is that increasing the proportions of angular aggregates may improve the stability and resilient modulus of PAM (Tarmuzi et al. 2015). Huang et al. (2009) reported that coarse aggregate angularity (CAA) greatly influenced the rutting performance of asphalt mixtures when a soft binder (PG 64-22) was used, while the influence was getting less when stiffer binders (PG 76-22 and PG 82-22) were utilised. Li et al. (2019) studied the influence of aggregate geometry by utilising numerical technique and laboratory measurements, and their results indicated that angularity of aggregates has positive influence on the stability and strength of asphalt mixtures, whereas flat and elongated aggregates have negative influences.

Most studies of aggregate surface texture have mostly focused on method development to identify aggregate surface texture (Masad 2003; Al Rousan 2004; Zhang, Huang, and Zhao 2012; Florkova and Jambor 2017; Florkova and Komacka 2015). Cui et al. (2018) attempted to study the influence of aggregate surface texture by utilising three different materials as aggregates, namely basalt, limestone, and steel slag. The results indicated that aggregates with rougher surface texture improve the performance of asphalt mixtures, including Marshall and dynamic stabilities, and flexural strength. The influence of surface texture on the properties of asphalt mixture can be related to the amount of slippage when aggregates contact with each other. Thus, utilising aggregates which have rough surface texture may improve skid resistance of the asphalt mixtures (Rose 1971; Jaya, et al. 2014; Tarmuzi et al. 2015). While some studies have attempted to study

the influence of surface texture, other aggregate shape characteristics and aggregate materials were hardly controlled, resulting in confounding influence from other variation factors (Huang et al. 2009; Kangkhatjitre and Kanitpong 2011; Bessa et al. 2015; Jaya, et al. 2014; Tarmuzi et al. 2015; Cui et al. 2018).

The appropriate method on quantifying the shape properties is also one of the challenges on the study of aggregate shape properties, with most traditional testing methods being time-consuming and greatly relying on subjective judgement of the operator (Mahmoud et al. 2010; Wang et al. 2015). Moreover, many studies on the influence of aggregate shape properties assessed the results mainly based on the practical performance of asphalt performance, while the internal packing structure of asphalt mixtures has not been well elaborated.

2.5. Aggregate packing theories

The packing structure of an asphalt mixture is a prominent factor that determines its durability and performance in the field. Packing structure is dependent on various components, namely aggregate size distribution, aggregate properties (morphology, strength, unit weight, etc.), compaction process, and asphalt binder. Herein, aggregate gradation exhibits the distribution of aggregate particles with different sizes in which their amounts are proportionated by weight in the aggregate blends. In HMA, gradation is an important characteristic that establishes almost every property, such as stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and moisture susceptibility.

Most packing theories are based on dense-graded asphalt mixtures that use volumetric properties to indicate the quality of aggregate packing. High strength structure can be obtained if sufficient amount of fine aggregates and asphalt mastic fill the voids in between coarse aggregates (Vavrik, William, and Carpenter 2002). In PAM, porosity has to be maintained at 15-20% to attain sufficient permeability. Herein, suitable methods to evaluate the packing condition of PAM need to be developed, as differentiated from those used in characterising dense-graded asphalt mixtures.

2.5.1. Bailey Method

Mr. Robert Bailey from the Illinois Department of Transportation developed a method to establish asphalt mixture gradation that possesses strong rutting resistance while maintaining other appropriate durability characteristics. This method is known as Bailey method (Vavrik et al. 2002). A design criterion in the Bailey Method to provide a rut-resistant mixture is aggregate interlock. In asphalt mixtures, a strong skeleton is needed for high stability, and an adequate voids-in-mineral aggregates (VMA) is required for good durability. Therein, packing of the coarse and fine aggregates is modified to ensure that the mixture contains adequate asphalt binder.

The key focus in Bailey method is to select the breaking sieve (BS) size to divide the coarse and fine aggregates in the aggregate gradation. Conventional definition of coarse aggregates is particles retained by the 4.75mm sieve. Fine aggregates are those that pass the 4.75mm sieve (sand, silt, and clay size materials). In Bailey method, breaking sieve is selected by analysing 2-D aggregate packing (Figure 2.5), as the one closest to $0.22 \times \text{NMPS}$ (Nominal Maximal Particle Size).

Figure 2.5 2-dimensional aggregate packing model (Chen 2016)

An index by way of Chosen Unit Weight (CUW) is set to promote interlock between coarse aggregates. Rodded Unit Weight (RUW) refers to the unit weights of coarse aggregates with compaction. Meanwhile, Loose Unit Weight (LUW) is the unit weights of coarse aggregates without compaction. These two parameters, RUW and CUW, are utilised as reference to determine CUW. Herein, RUW and LUW are related to the upper and lower limits to establish packing structure, as shown in Figure 2.6. Three additional Bailey ratios, namely coarse aggregates (CA) ratio, coarse portion of fine aggregates (FA_c) ratio, and fine portion of fine aggregates (FA_f) ratio, are established to generate and assess a trial blend. To divide aggregate size in the aggregate blends, three parameters are introduced, namely primary control sieve (PCS), secondary control sieve (SCS) and tertiary control sieve (TCS).

Herein, optimum aggregate packing structure in Bailey method is aimed at designing well-packed asphalt mixtures. However, the quality of aggregate packing is not only determined by the density level, but also the contact mechanism among aggregates. The unit weight or density of the coarse aggregates does not fully indicate the state of particle-to-particle interlocking of the coarse aggregates. The proportion of aggregates in each size may also influence the quality of interlocking between coarse particles. Therefore, the selected CUW may not result in the desired packing structure of the asphalt mixtures.

Figure 2.6 Rodded Unit Weight (RUW), Chosen Unit Weight (CUW) and Loose Unit Weight (LUW) (Vavrik, William, and Carpenter 2002)

2.5.2. Dominant Aggregate Size Range (DASR) model

DASR model is a method to assess coarse aggregate packing structure by assessing the interaction between aggregate interlocking and mixture porosity (Kim et al. 2009). Two parameters namely, interstitial components (IC), and interstitial volume (IV) are applied to indicate the components and volume within the interstices of dominant aggregate size range, as shown in Figure 2.7. Interstitial volume (IV) is the total volume of materials (asphalt binder, aggregates, air voids) that occupy the interstices of dominant aggregates, while interstitial components (IC) refer to the materials within this volume. DASR porosity is described as the resultant porosity established by finer aggregates retained on next size sieve of the dominant aggregates. The interaction between aggregates within adjacent size ranges is evaluated by calculating the resultant porosity. To obtain quality performance of mixtures, it has been recommended that DASR porosity should be lower than 50%, meanwhile the proportion of aggregates retained on adjacent sieves is recommended to be 70-30% (Kim et al. 2009).

DASR model estimates aggregate gradation according to engineering experiences, thereby theoretical explanation of DASR model is still lacking. Moreover, the key principle of DASR model is limited to porosity and there is no consideration on distribution of load mechanism.

Figure 2.7 Dominant aggregate size range (Kim et al. 2009)

2.5.3. Voids in Coarse Aggregates (VCA) index method

A parameter called voids in coarse aggregate (VCA) index method was developed to determine a pass/fail standard based on VCA index (Kandhal 2002). Two VCA indices of asphalt mixtures are calculated, namely VCA of a compacted asphalt mixture (VCA_{mix}), and VCA of coarse aggregate blend under dry-rodded condition (VCA_{DRC}). Herein, the ratio of VCA_{mix}/VCA_{DRC} is suggested to be less than 1.0 to achieve a stable aggregate skeleton framework. This method is very straightforward to define the state of packing structure in the coarse section of aggregate gradation. Nevertheless, research indicated that there is no clear correlation between VCA_{mix}/VCA_{DRC} ratio and the properties of asphalt mixture (Alvarez et al. 2010).

2.5.4. Gradation-based framework

The gradation-based framework was developed by Lira et al. (2013) to establish packing parameters to identify what gradations are favourable on the performance of asphalt mixtures. Several studies have attempted to achieve ideal gradations by focusing on the densest possible packing. Fuller and Thompson (1907) investigated different sets of stones and sands for Portland cement concrete mixtures to find an optimum combination to improve the quality of the mixtures. The results showed that the largest diameter of sand should not transcend one-tenth of the larger diameter of the stone. Research by Talbot and Richart (1923) suggested that the maximum density of assemblage of spheres was achieved when a straight line in percent passing a sieve versus the particle size plot (a semi log scale) had a slope of 0.5. Another study indicated that the densest packing can be obtained by a straight line in the percent passing a sieve size versus the size of the sieve plot (a semi log scale) with a slope of 0.45 (Nijboer 1948). Goode and Lufsey (1962) validated Nijboer's notion and established the procedure for a semi-power chart of gradations resulting in the "0.45 power" chart.

However, packing density is not the only parameter to indicate the quality of asphalt mixtures, especially in PAM where high air voids is deliberately designed to achieve drainage performance. Some studies have shown that main load carrying

structure and stress transmitting paths have remarkable influence on the performance of asphalt mixtures (Jaeger 1992; Santamarina and Klein 2001). Gradation-based framework has established a method to identify the main structure of the mixtures that carries the load and relate it to the performance of the mixtures.

The gradation-based framework divides the aggregates into three different groups: the Primary Structure, the Secondary Structure and Other material. The Primary Structure (PS) refers to interactive size ranges in the gradation that establish the main network for load bearing. The more connections there are in PS, the stronger the main network is. The Secondary Structure (SS) is the aggregates in smaller size ranges than the PS. The SS has a function to fill the voids created by the PS particles. Meanwhile, other particles refer to aggregates that float in the matrix even though they may have size larger than the PS. To determine PS, the interaction between particles retained on two contiguous sieves is calculated by Equation (2.5).

$$0.311\overline{D_n} + 0.689\overline{D_{n+1}} \leq D_{avg} \leq 0.703\overline{D_n} + 0.297\overline{D_{n+1}} \quad (2.5)$$

where D_{avg} is the weighted average size within two contiguous sieve sizes, D_n is the mean size of retained aggregates in larger sieve, and D_{n+1} is the mean size of retained aggregates in smaller sieve.

The mean size of retained aggregates in each sieve size can be determined by Equation (2.6).

$$\overline{D_n} = B(D_{min} + D_{max}) \quad (2.6)$$

where B represents the mean value of distribution (between 0 and 1), D_{min} is the opening size of the observed sieve, and D_{max} is the opening size of the previous sieve.

Meanwhile, the weighted average size is computed by Equation (2.7).

$$D_{avg} = \frac{\theta_n \overline{D_n} + \theta_{n+1} \overline{D_{n+1}}}{\theta_n + \theta_{n+1}} \quad (2.7)$$

where θ_n and θ_{n+1} are the concentrations of two contiguous sieves, respectively.

The interaction formula (Equation (2.5)) was established by taking four assumptions, as follows: particles are assumed as spheres; the particles within a sieve follows a uniform distribution ($B=0.5$); the maximum density for spheres of two contiguous sizes is equal to packing structure of rhombohedral; and all particles are uniformly distributed in the total volume. The interaction between particles should be conducted in a systematic way for all sieve sizes, and size range with the highest concentration is selected as PS. The PS range is recommended to have a minimum concentration of 45%. Lira et al. (2013) denoted that the 2.36 – 1.18mm size range serves as cut-off size range as the asphalt mortar starts to lose its flow ability when filler size is 1.18mm or above. Herein, the smallest particles of PS are the particles with size range of 2.36 – 1.18mm.

In summary, most existing aggregate gradations and aggregate packing methods are based on volumetric properties due to their feasibility to be evaluated using laboratory measurements. Volumetric based theories may not be appropriate to evaluate the packing condition of PAM, since the high porosity in PAM is deliberately achieved to allow water drainage through the surfacing layer. Herein, the packing condition of asphalt mixtures is evaluated according to relevant criteria that have been developed according to engineering experiences of dense-graded mixtures. Therefore, the explanation of packing mechanism in PAM using existing theories (basically developed for HMA) is less than satisfactory. Indeed, complementary explanations can be advanced using parameters such as contact force and contact points which can give much better understanding on the behaviour of asphalt mixture under applied loading/deformation. Herein, both volumetric and mechanical parameters need to be included in aggregate gradation design and in evaluating packing condition of an asphalt mixture, which is a key approach being undertaken in this research.

2.6. Numerical simulation of asphalt mixture

Application of numerical analysis is increasingly favourable in civil engineering design by eliminating the excessive and tedious trial-and-error laboratory works

involving conventional methods. Moreover, numerical simulation has an ability to analyse mechanical details of the materials, including stress/strain distribution, contact forces, etc. Two types of numerical simulation methods that are commonly used in modelling asphalt mixtures are Discrete Element Method (DEM), and Finite Element Method (FEM). Herein, FEM is a numerical analysis based on continuum theory that will be more appropriate to analyse relatively homogenous materials. Meanwhile, DEM simulate materials as an assemblage of discrete elements, thereby this method is suitable for granular materials, and is well fitting for modelling PAM.

2.6.1. Finite Element Method (FEM).

FEM simulation generally models the deformation and stress of solid bodies in structural mechanics. The key principle of FEM simulation is to solve the integral equations and Partial Differential Equations (PDE) and find the approximate solution.

In pavement engineering, FEM has been used to study creep behaviour of materials, viscoelasticity behaviour of asphalt mixtures and the effect of viscoelasticity on cracking, stress analysis, etc. (Cheung and Cebon 1997; Lawrence et al. 2012; Kim, Roque, and Byron 2009). The results from these studies indicated that FEM is a reliable method to evaluate asphalt pavement behaviour under different loading. However, not many studies have been performed to simulate the micro-mechanical behaviour of PAM by utilising FEM, because of its inability to consider the aggregate slippage in aggregate packing. Furthermore, it is generally very hard to model the particle-to-particle interlocking of compacted granular materials by utilising FEM.

2.6.2. Discrete Element Method (DEM)

DEM simulates a group of discrete particles, in which the movements and interactions among individual particles can be calculated by alternately applying law of motion and force-displacement law (Newton's second law) (Itasca 2008). DEM was generally applied to solve problems in rock and soil engineering, and the corresponding research have testified that DEM simulation is well-fitting for

evaluation of assemblage of discrete particles, especially in packing of granular particles (Cundall and Strack 1988). Research has shown that DEM is reliable to estimate the Young's modulus and unconfined strength of assembly of rock-like materials, and evaluate spalling in rock engineering (Holt et al. 2005; Cho et al. 2010).

PAM, which mainly consists of coarse aggregates, acts more closely like an assembly of granular materials than homogenous materials, thereby it is more appropriate to simulate the stress/strain behaviour of PAM by DEM technique instead of FEM model. In recent years, Particle Flow Code (PFC), a program based on DEM, has been utilised in pavement engineering to evaluate the asphalt mixture behaviour in terms of micro-mechanism and establish the correlation between micro-mechanism and macro-behaviour (Abbas et al. 2005; Shen and Yu 2010; Micaelo et al. 2011).

For the packing of aggregates in an asphalt mixture, previous research studies have simulated static compaction procedure of asphalt mixtures via PFC2D, and the results indicated that simulation results are in line with corresponding laboratory tests (Micaelo et al. 2011). Other studies have developed PFC3D models to define the aggregate gradation of asphalt mixtures, in which the functions of fine and coarse aggregates were evaluated according to the influence of the corresponding size fractions on the volumetric properties (Shen and Yu 2010). Another study evaluated the behaviour of asphalt mastic in terms of its dynamic mechanical properties via PFC2D, and the results revealed that there are close correlation between volumetric proportion of mineral fillers with the stiffening effect (Abbas et al. 2005).

A recent research investigated the mechanical response of asphalt mixtures by utilising PFC3D, and the results showed that such virtual test has capability to predict permanent deformation of asphalt mixtures including the mechanical response, such as the translation and rotation movements of aggregates (Xue et al. 2020). PFC3D was also utilised to study the fracture behaviour of asphalt mixtures, and the results indicated that the crack propagation paths are greatly influenced by NMAS, temperature, and aggregate strength (Xue et al. 2020). Several studies

evaluated the micro-mechanical performance of high modulus asphalt concrete (HMAC) as compared with conventional asphalt mixtures, and the results showed that PFC3D can simulate the stress behaviour of asphalt mixtures under uniaxial loading (Si et al. 2019). Li et al. (2019) simulated asphalt mixtures with parameterised aggregate shape and size gradation, and the results showed that DEM model has good agreement with laboratory measurements in simulating uniaxial test. The force evolution and the effect of flat and elongated aggregates on the compaction process of aggregate blends were investigated via PFC3D, and simulation results showed capability to predict the force evolution trends and it was found that flat and elongated particles have remarkable influence on contact force increment (Wang et al. 2020).

In essence, DEM simulation has capability of facilitating extensive insights into micro-mechanism of an assembly of granular materials and to simulate interactions among particles. The stone-on-stone framework created in PAM is more appropriate to be regarded as discrete objects. Hence, DEM is well suited for evaluating the packing condition of PAM, and is useful in calibrating the parameters to describe aggregate interlocking mechanism.

2.7. Summary

PAM has been applied worldwide for its benefit to mitigate run-off water and increase driving safety, such as decrease splash and spray, alleviate noise reduction, increase skid resistance, etc. Clogging and ravelling are two major issues for PAM, and these problems can be mitigated with correct treatments and design. Asphalt mixture design varies in different countries according to their own specific conditions with performance-based design.

Several studies indicated that aggregate morphology, such as size, form, angularity, and surface textures, have major influences on the properties of asphalt mixtures. In terms of size and gradation, some relevant industries or organisations have continued to utilise restriction zone to indicate crucial fraction size that needs to be maintained in dense-graded asphalt mixture. However, the significance of this restriction zone is debatable and should be re-evaluated when applied on PAM. Meanwhile, three individual shape characteristics of aggregates (form, angularity,

surface texture) determine the quality of aggregates interlocking in asphalt mixtures.

The existing packing theories for asphalt mixtures, namely Bailey method, DASR model, VCA index method, are mainly based on volumetric properties. PAM packing structure is greatly established by coarse aggregates to maintain high air voids, thus volumetric based theories are not sufficient to analyse the condition of packing structure of PAM. On the contrary, DEM method is able to give thorough insights of micro-mechanism for an assembly of granular materials. The aggregate packing structure established in asphalt mixtures is more suitable to be viewed as discrete objects. Thereby, it is suitable to assess the packing structure of PAM by utilising DEM software program, PFC3D, in this research.

Chapter 3 Research Methodology

3.1. Overview

This research consists of three main phases, as illustrated in Figure 3.1. The development of PAM's modelling by Particle Flow Code 3 Dimensions (PFC3D), a software based on discrete element method (DEM), was conducted in the first phase, and the resulting PAM model is described in this Chapter. PAM model developed in the first phase of this research was utilised to evaluate the packing structure of PAM in the second and third phases. Meanwhile, the detailed description of second and third phases of this research is explained in Chapters 4 and 5, respectively.

Figure 3.1 Scope of work

In this research, the data collections are obtained by both in-lab experiments and numerical simulations. Materials selection and fabrication method for PAM are

described in this Chapter. Laboratory measurements to evaluate volumetric and mechanical properties of PAM are explained, and the numerical simulation in PFC3D is introduced.

3.2. PAM specimens

3.2.1. Materials selection

Several materials, namely granite, steel slag, and Jurong sedimentary rocks, were utilised as aggregates in this study. The mechanical properties of aggregates are summarised in Table 3.1. All the values in the mechanical properties of sedimentary rock and steel slag were notably higher than granite, which indicates that sedimentary rock and steel slag have better properties at load bearing. In fact, granite's mechanical properties failed to satisfy the LTA requirements. Nevertheless, relatively weak aggregates can be utilised in this research due to the application focus of this research being on low-strength pavements. It has been reported that aggregate mineralogy and mechanical properties may not significantly influence the mechanical properties of asphalt mixtures (Kangkhatjitre and Kanitpong 2011; FHWA 1994; Bessa et al. 2014). Thereof, utilising weak aggregates should not be an issue for PAM.

On the other hand, sedimentary rock has a greater amount of flaky and elongated particles compared to granite and steel slag, as indicated by higher flakiness and elongation indices. All in all, sedimentary rock, steel slag and granite are suitable material to be used in this research to evaluate the impact of shape properties in PAM.

In general, mechanical strength and durability of PAM are not as strong as conventional dense asphalt mixture. Thus, asphalt binder of performance grade 76 (PG-76) was utilised to enhance PAM's overall properties. The existence of Styrene Butadiene Styrene (SBS) in PG-76 asphalt binder increases stiffness and improves temperature susceptibility of PAM. Moreover, PG-76 binder also has a higher viscosity, which improves bonding between the aggregates and binder. The PG-76 binder used was obtained from Shell Bitumen Singapore and has the properties as listed in Table 3.2. It has been reported that utilising polymer-

modified asphalt binder improves the mechanical properties of asphalt mixtures (Sirin et al. 2008; Chen et al. 2015).

Table 3.1 Properties of mineral aggregates

Property	Sedimentary Rock	Granite	Steel slag	*LTA Requirements
Average Bulk Specific Gravity of Coarse Aggregate (Mg/m^3)	2.71	2.60	3.1	-
Average Water Absorption of Coarse Aggregate (%)	0.477	0.61	1.21	< 1
Average Bulk Specific Gravity of Fine Aggregate (Mg/m^3)	2.78	2.60	-	-
Aggregate Impact Value (AIV) (%)	13.6	29.4	14.4	< 25
Los Angeles Value (LAV) (%)	25.1	36.0	22.0	< 20
Elongation Index (%)	25.0	20.1	-	< 30
Flakiness Index (%)	33.4	12.3	8.3	< 25
Ten Percent Fines Value (TFV) (kN)	280	111	-	> 130

*LTA: Land Transport Authority (of Singapore)

Table 3.2 Specification of PG-76 Binder

Property	Value
Specific Gravity at 25 °C	1.02
Viscosity at 135 °C ($\text{Pa}\cdot\text{s}$)	1.377
Penetration at 25 °C, 100g (0.1mm)	57
Penetration of Residue at 25 °C	91
Softening Point, Ring and Ball (°C)	82
Loss on Heating (% wt)	0.1
Flash Point, Cleveland Open Cup (°C)	285
Mixing temperature (°C)	165-175
Compacting temperature (°C)	155-165

Apart from the type of binder used, the amount of binder used in the mixture is also crucial in determining the performance of PAM. Optimum binder content ensures adequate coating and protection of the aggregates and better adhesiveness between the binder and aggregates. Optimum binder content for each mix design requires the correct amount of binder added and not being excessive or insufficient. Excessive binder can cause drain-down and weakening of the asphalt mixture whereas insufficient binder can lead to loss of durability, ravelling, and premature failure of the mixture.

Meanwhile, hydrated lime was utilised as filler for all the PAM designs in this research. Hydrated lime has been widely known as an anti-stripping agent in asphalt mixtures. The presence of hydrated lime in asphalt mixtures improves the durability of asphalt mixtures by generating higher stiffening effect, increasing the moisture durability, and mitigating rutting and stripping (Lesueur et al. 2013). It has been reported that the presence of filler is associated with lowered optimum asphalt content (Kandhal et al. 1998; Al-Suhaibani et al. 1992), thereby utilising filler in asphalt mixtures may also be beneficial in terms of reducing material usage.

3.2.2. Compaction method

Gyratory compaction machine, as shown in Figure 3.2., was selected for fabrication of cylindrical specimen instead of conventional Marshall compaction machine. Gyratory compaction machine has a better ability to re-orient aggregate particles while minimising aggregate breakage as compared with conventional Marshall hammer. Moreover, compaction method by a gyratory compactor simulates compaction process under in-field condition better than Marshall method (Hainin et al. 2013). A standard configuration of gyration level by Superpave design method with compaction pressure of 600 kPa, 50 gyration counts, gyration rate of 30 rpm, and gyration angle of 1.25° was adopted in this study. However, the compaction pressure was decreased to 100 kPa for the design mixture of the second independent shape characteristic: angularity (see later at Sections 5.2.2. and 5.3.1). Herein, the specimens of dimensions at about 100 mm in diameter and 55–65 mm in height were produced. The varying height of specimens was mainly due to the

different materials of aggregates used in the mixture design. The fabricated Gyratory specimens in this research generally possessed similar dimension with Marshall specimens. As Gyratory compactor setup is easier to control, the specimens for the same mixture design tend to have uniform height.

3.2.3. PAM gradations

In this research, a total of twenty gradations were designed to facilitate the study on the packing structure of PAM. In the second phase of this research, two different studies, namely Study A and Study B, were conducted to analyse the influence of aggregate gradations on the packing structure of PAM. Herein, each study utilised different set of aggregate gradations, in which each set of aggregate gradations consisted of ten gradations. The details of gradations used in Study A and Study B are elaborated in Sections “4.2. STUDY A: Influence of aggregate proportions on the packing structure” and “4.3. STUDY B: In-depth study on the influence of fine fractions on the packing structure”, respectively.

Figure 3.2 Gyratory compactor (blue unit)

3.3. Volumetric Properties

In PAM, packing structure of aggregates is mainly created by coarse aggregates' stone-on-stone framework. Voids content is the common parameter utilised to describe the packing level in a compacted aggregate blends or asphalt mixture.

The voids-in-total mix (VTM) content can be calculated by Equation (3.1). The theoretical maximum specific gravity of asphalt mixture, G_{mm} , was obtained according to ASTM D2041-11.

$$VTM = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100\% \quad (3.1)$$

where G_{mb} refers to the bulk specific gravity of asphalt mixtures.

3.4. Performance tests

Several laboratory measurements were performed to evaluate the performance of PAM, including Drain-down, Cantabro Abrasion, Marshall Stability and Flow test, Permeability test, Indirect Tensile Stiffness Modulus test, and Creep test. For each laboratory test, three specimens with diameter of 100mm and of similar height were fabricated for each mixture design.

3.4.1. Drain-down test

Asphalt mixtures with a high proportion of coarse aggregates, such as stone mastic asphalt (SMA) and PAM, usually suffer a phenomenon in which some parts of asphalt mastic seeps out of the asphalt mixtures during mixing, transporting, and compacting process. This phenomenon is called drain-down. Drain-down is also closely correlated with a high binder content and/or lack of fine aggregates and fillers to establish stiff asphalt mastic. Under high temperature and heavy loading, drain-down may cause rutting and ravelling in the fields. Drain-down test in the laboratory is performed on loose asphalt mixtures using ASTM D 6390-11 (2017) procedures. The assembly of drain-down apparatus is shown in Figure 3.3. The drain-down proportion can be expressed by Equation (3.2). The upper limit of drain-down proportion is recommended to be 0.3% by mass (Rajib et al. 2000).

$$\text{Drain - down (\%)} = \frac{(D - C)}{(B - A)} \times 100\% (<0.3\%) \quad (3.2)$$

where: A = Mass of empty wire basket (g)

B = Mass of wire basket + specimen(g)

C = Mass of empty catch plate (g)

D = Mass of catch plate + drained material (g)

Figure 3.3 Drain-down Assembly

3.4.2. Cantabro abrasion test

Cantabro test was developed in Spain in the 1980s. This test is generally utilised to determine the minimum binder content for open-graded friction course (OGFC), while drain-down test is used to select the maximum binder content. Cantabro test has been recommended by several studies to evaluate the durability of the mixtures and also serves as an indicator of durability performance during in-service life (Alvarez et al. 2010; Arambula-Mercado et al. 2016). The procedures of Cantabro test are quite similar with Los Angeles (LA) abrasion test of aggregates, except no ball bearing is used in the Cantabro test. In this study, Cantabro test was performed according to ASTM D7064-08-App X2 in which compacted PAM samples undergo 300 revolutions at 30–33 rpm at a temperature of 25°C in LA abrasion machine (Figure 3.4.). The Cantabro loss value is calculated by Equation (3.3). The upper limit of Cantabro loss is recommended to be 20% (Rajib et al. 2000).

$$P = \frac{P_1 - P_2}{P_1} \times 100\% \quad (<20\%) \quad (3.3)$$

where: P = Cantabro abrasion loss

P_1 = Initial weight of specimen (g)

P_2 = Final weight of specimen (g)

Figure 3.4 Los Angeles Abrasion Machine

3.4.3. Marshall stability

Marshall stability test is performed to evaluate the strength of asphalt mixtures by utilising Marshall Compression Machine (Figure 3.5.). There are two types of Marshall specimens, namely un-conditioned and moisture-conditioned. The un-conditioned Marshall test was performed according to ASTM D6927 – 15. Before loading, PAM specimens are to be submerged in the water bath at 60 ± 1 °C for 30 to 40 minutes. Marshall stability is the maximum load carried by the specimens, while flow value is the deformation during loading up to the peak load.

Moisture-conditioned Marshall test is performed to evaluate the susceptibility to the damage of moisture on the performance of asphalt mixtures. The procedures of moisture-conditioned are similar to un-conditioned Marshall test, with the difference in the specimens being soaked in water bath at 60 ± 1 °C for 24 hours in moisture-conditioned Marshall test. The Retained Marshall Stability (RMS) is the ratio of the average conditioned Marshall Stability value (S_c) against the average unconditioned Marshall Stability value (S_u), as expressed in Equation (3.4).

$$\text{RMS(\%)} = \frac{S_c}{S_u} \times 100\% \quad (3.4)$$

Figure 3.5 Marshall Compression Machine

3.4.4. Permeability test

Permeability is the ability of porous material to allow liquids to flow through it, thereby it is an important characteristic in PAM in terms of its drainage function, such as reducing splash and spray, minimising aquaplaning, and overall providing a safer condition for driving in wet weather. The falling head apparatus is recommended by many researchers for permeability test due to its accuracy and convenience (Noramuela-Contreras et al. 2014; Charbeneau et al. 2011). In this study, permeability apparatus setup developed by Florida Department of Transportation [Florida DOT] (2004) (as shown in Figure 3.6) was utilised. The coefficient of permeability is calculated by Equation (3.5).

$$k = \left(\frac{aL}{At} \right) \times \ln \frac{h_1}{h_2} \times t_c \quad (3.5)$$

where, k = coefficient of permeability (cm/s)

a = inside cross-sectional area of the burette (cm²)

L = average thickness of the test specimen (cm)

A = average cross-sectional area of the test specimen (cm²)

t = elapsed time between h₁ and h (s)

h₁ = initial head across the test specimen (cm)

h₂ = final head across the test specimen (cm)

t_c = temperature correction for viscosity of water

Figure 3.6 Permeability testing apparatus

3.4.5. Resilient modulus test

Indirect tensile stiffness modulus (ITSM) test is performed to measure the resilient modulus of asphalt mixtures. The test was conducted by utilising Universal Testing Machine (UTM) with the apparatus assembly shown in Figure 3.7. Resilient modulus refers to the stiffness of asphalt mixture under cyclic loading. There are several factors that influence resilient modulus, namely temperature, frequency of the loading, and the properties of materials. The test was done by following the Australian Standard Method 13.1 (Australian Standard [AS] 1995). The input parameters of the test are summarised in Table 3.3., while the test setup is presented in Figure 3.6. Resilient modulus (M_R) can be expressed in Equation (3.6).

$$M_R = \frac{P(v+0.2734)}{\delta t} \quad (3.6)$$

where, P refers to the magnitude of dynamic load, v refers to Poisson's ratio, δ is the total recoverable deformation, and t is the thickness of PAM's specimen.

As PAM possesses many craters on the surface of specimens, the transducers of ITSM test may fall into the craters and results in erratic measurements. Thereof, it is important to ensure that the transducers lay on flat surfaces. Furthermore, the position of transducers shall be set up to some positive value so the transducers will be in zero position after conditioning pulses applied.

Figure 3.7 Apparatus for ITSM test

Table 3.3 ITSM test parameters

Parameter	Value
Specimen orientation	0° and 90°
Loading waveshape	Haversine
Target peak strain ($\mu\epsilon$)	50 ± 20
Loading pulse width (ms)	100
Pulse repetition period, 10% to 90% (ms)	3000 ± 5 seconds
Test temperature (°c)	25 ± 0.5

3.4.6. Dynamic creep test

Creep test is utilised to analyse the sensitivity of an asphalt mixture to the immediate recoverable and non-recoverable strain and permanent deformation or rutting under applied loading. Creep test is an important test to evaluate the quality of aggregates and asphalt binder in asphalt mixtures and to determine the permanent deformation resistance of asphalt mixtures (Lau, 2012). This test is convenient to perform and has been widely utilised by many researchers to evaluate the behaviour of asphalt mixtures on permanent deformation (Uzan 2003; Delgadillo 2008; Huang et al. 2009; Zulkati 2012). The dynamic creep test was conducted according to AS 2891.12.1 – 1995 procedure, and the input parameters are summarised in Table 3.4. The setup of creep test is shown in Figure 3.8. The

cumulative permanent strain of the asphalt specimen is recorded throughout the test.

Table 3.4 Creep Test Parameters

Parameter	Value
Compressive Stress	$200 \pm 0.5 \text{ kPa}$
Loading Period	$0.5 \pm 0.05 \text{ seconds}$
Pulse Repetition Period	$2.0 \pm 0.05 \text{ seconds}$
Test Temperature	$50 \pm 0.5 \text{ }^{\circ}\text{C}$
Pre-conditioning	$50 \pm 0.5^{\circ}\text{C}$ 2 hours
Termination of Test	5% termination strain OR 40,000 pulse counts

Figure 3.8 Creep Test setup

3.5. DEM simulation

In this study, a software package called Particle Flow Code 3-Dimensions (PFC3D) was utilised to evaluate the packing condition of compacted aggregate blends. This software is based on DEM theory, and the basic procedures of the simulation by PFC3D are as follows:

- a) generate particles in accordance with the size distribution and apply physical and mechanical properties to represent designed aggregate gradation and the type of material used;

- b) select simulation parameters (namely porosity and coordination number) to represent the level of the contacting mechanism among particles;
- c) simulate the compacting process of particle assembly via a servo-mechanism process; and
- d) conduct analysis based on the simulation parameters.

Meanwhile, laboratory measurements shall be conducted as verification values for air voids obtained from PFC3D simulations.

3.5.1. Particle and boundary generation

In simulation model generation, two main objects are ‘wall’ and ‘ball’. Wall is constructed as boundary of the position and movement of the balls. Aggregates are simulated by balls or clumps with various sizes and proportion following the designed aggregate gradation. The physical and mechanical properties of the walls and balls in a model can be input via the stipulated parameters used in PFC3D. Meanwhile, the interaction parameter between two objects (i.e. ball-to-wall or ball-to-ball) is determined based on the contact model. The details of model consideration applied in this study are as follows:

- (a) Number of particles within the corresponding size range was estimated by using volumetric Equation (3.7).

$$N = \frac{3PV(p_{n+1}-p_n)}{4\pi\left(\frac{r_{n+1}+r_n}{2}\right)^3} \quad (3.7)$$

where,

N = number of particles in each size range;

P = volume proportion of aggregate particles in the mixture;

V = total volume of the asphalt mixture;

p_n, p_{n+1} = percentage passing (by volume) of the aggregate through sieve size $2r_n$ and $2r_{n+1}$, respectively; and

r_n, r_{n+1} = lower and upper limits of balls’ radii in each size range.

- (b) Due to DEM limitation to compute very large number of particles, it is broadly acceptable to determine lower limit of aggregate size for particle generation. Lower limits of aggregate size that have been utilised in past research were 1.18 mm, 2.0 mm, or 2.36 mm (Yu 2012, Si et al. 2019, Liu, et al. 2009, Cai et al. 2013). In this study, aggregate size 1.6mm was chosen as a lower limit of aggregates size. Fine aggregate (2.36 - 0.075mm) was thus modelled as balls with diameter 1.6mm. Meanwhile, filler has a major function to produce a stiffening effect on the asphalt binder and interact with asphalt binder to form a viscous-liquid phase in the asphalt mastic. The interaction between asphalt mastic and filler consists of three aspects, namely volume-filling, physico-chemical, and particle-interaction reinforcements (Zulkati, 2013). Herein, asphalt mastic is more appropriate to be simulated as a contact model (see later) rather than granular particles in PFC3D.
- (c) The surface texture effect of coarse aggregate for DEM model was simulated by adjusting the coefficient of friction in aggregate contact model. Herein, the coefficient of friction for each material was obtained from the literature as reference values. Then, these values were adjusted to obtain the DEM model that possessed the closest creep behaviour and density level with the laboratory-casted specimens. This method has been widely adapted in several research studies to obtain the correct texture effect of aggregates in DEM model (Ding et. al. 2018; Xue et al. 2020).
- (d) Three walls were utilised to simulate the shape of PAM specimen. One cylindrical wall with diameter 100mm and height 60mm was utilised, and two plate walls were placed at the top and the bottom of the cylinder, respectively.

3.5.2. Clumps

PFC3D provides a function to generate a designed particle shape to simulate the actual shape of granular particles; this function is called clump. A clump logic was done by solidly attaching a set of spheres to create a new-shape particle. Clump was utilised to represent the realistic shape of aggregates; however, it should be noted that it will not be possible to replicate all of the aggregate shapes in the mixtures due to the large number of particles. Herein, clump templates were

created based on the average measurements of the aggregates. The procedure to create clump template is explained in the following.

(a) Create geometry files using 3D CAD software

First, the shape of the clump was drawn in 3D CAD software before it was imported into PFC3D. In this study, AutoCAD 3D was utilised to create the surface of the clumps. The geometry files were saved as STL format, then the STL file was imported to PFC3D software by using geometry import command. Example of clump surface is presented in Figure 3.9.

Figure 3.9 STL surface of clump

(b) Create clumps with bubble pack feature

Clump template can be created automatically by utilising bubble pack feature. By activating this feature, the pebbles will automatically fill the specified STL surface. The number of pebbles can be adjusted to achieve the smoothness of the surface representation by specifying two template parameters, namely distance and ratio. The two template parameters have great influence on the final product of aggregate model as these two parameters determine the number of pebbles on the clumps. While aggregate shape can be represented accurately by adjusting the values of the appropriate parameters, the efficiency of computational calculation will be significantly compromised due to the high number of pebbles (Liu et al. 2017). In this study, the template parameters of distance and ratio were chosen as 150 and 0.2, respectively, as these values were deemed appropriate to balance the efficiency and accuracy of PFC calculation (Liu et al. 2017). An example of clump template is shown in Figure 3.10.

Figure 3.10 Clump template of aggregate model

3.5.3. Contact model

To simulate the constitutive behaviour of a material in PFC3D, contact model is assigned for each contact. Several research studies have been done to simulate the elastic behaviour of asphalt mixtures by using linear parallel bond model (Yao et al. 2012; Cai et al. 2014; Liu et al. 2018; Si et al. 2019). In linear parallel bond model, a linear model serves simultaneously with a parallel bond. Parallel bond simulates an elastic interaction and this bond works in parallel with either slip or linear model. For two contacting entities, a parallel bond consists of two elastic springs working in parallel with the springs that are utilised to simulate the particle stiffness at a point. However, parallel bond is only suitable to simulate asphalt mixture behaviour in its elastic condition, thus limiting the utilisation.

Another model that has been widely used to model the behaviour of bituminous materials is Burger's model (Liu et al. 2009; Adhikari and You 2010; Zelelew and Papagiannakis 2010; Yao et al. 2012; Cai et al. 2012; Dondis et al. 2013; Vignali et al. 2014; Feng et al. 2015; Papagiannakis et al. 2018; Li et al. 2019; Xue et al. 2020). This model describes elastic, viscoelastic, and viscous components of the materials. The mechanical entities of Burger's model consist of a set of Kelvin model and Maxwell model acting in series for both normal and shear directions, as illustrated in Figure 3.11. Maxwell and Kelvin models are two-element models, and these two models are usually used to define the viscoelasticity of materials. The combination of Maxwell and Kelvin models into more complicated arrangements is generated to achieve better accuracy on the simulation of creep and relaxation behaviour of viscoelastic materials (Sperling 1992; Roylance 2001). The normal stiffness of Burger's model is presented in Equation (3.8).

$$K_n = \left[\frac{1}{K_m} + \frac{t}{C_m} + \frac{1}{K_k} (1 - e^{-t/\tau}) \right]^{-1} \quad (3.8)$$

where K_m and K_k represent the stiffness of Maxwell and Kelvin sections, respectively, C_m and C_k refer to the viscosity of Maxwell and Kelvin sections, respectively, t is the loading time, while relaxation time, τ , is expressed by Equation (3.9).

$$\tau = \frac{C_k}{K_k} \quad (3.9)$$

When a quick loading is applied ($t \approx 0$), asphalt mixture will act as an elastic material ($C \approx 0$). In elastic condition, the normal stiffness of Burger's model is simplified as shown in Equation (3.10).

$$K_n = \left[\frac{1}{K_m} + \frac{1}{K_k} \right] \quad (3.10)$$

Equation (3.10) expresses the stiffness of two springs that act in parallel, this being similar with the normal stiffness of parallel bond. Thus, Burger's model was selected in this study because it has an ability to simulate asphalt mixture behaviour in various conditions.

Figure 3.11 Rheological components of Burger's model (Itasca, 2008)

Liu and You (2012) developed iterative procedures to predict the parameters of Burger's model according to creep behaviour of asphalt mastic and/or asphalt mixtures. The procedures are as follows:

1. Initialisation of the viscous strain at $t = t_1, \varepsilon_v(t_1)$

As the time increases, viscous strain is recovered which can be completely recovered when the time is infinite. Herein, viscous strain can be expressed in Equation (3.11). In laboratory test, the time cannot be assumed as infinite, therefore initialised viscous strain is the minimum strain of recovery data.

$$\varepsilon_v(t_1) = \lim_{t \rightarrow \infty} \varepsilon(t) \quad (3.11)$$

2. Determination of constant c in the linear equation at recovery section ($t > t_1$)

Linear equation of recovery section can be expressed in Equation (3.12).

$$y = cx \quad (t \geq t_1) \quad (3.12)$$

where, c , x , y can be calculated by Equations (3.13). From initialised viscous strain and creep-recovery data, the variables x and y can be calculated.

$$x = t - t_1, \quad y = \ln\left(\frac{\varepsilon - \varepsilon_v(t_1)}{\varepsilon(t_1) - \varepsilon_v(t_1)}\right), \quad c = -\frac{C_K}{K_K} \quad (3.13)$$

3. Determination of Kelvin section's parameters (K_K and C_K)

Using the test data at $t=t_1$ and constant c , K_K can be determined by Equation (3.14). Then, parameter C_K can be calculated by submitting the values of K_K and c in Equation (3.13).

$$\frac{\sigma_0}{K_K} (1 - e^{-ct_1}) = \varepsilon(t_1) - \varepsilon_v(t_1) \quad (3.14)$$

4. Determination of the constants in linear equation of creep section ($t < t_1$)

With calculated K_K and C_K , the linear strain (ε_l) can be determined by Equation (3.15). Then, the two constants (a and b) of linear equation of creep section can be calculated by fitting $\varepsilon_l(t)$ and t in Equation (3.16).

$$\varepsilon_1 = \varepsilon(t_1) - \frac{\sigma_0}{K_K} \left(1 - e^{-\frac{K_K}{C_K}t}\right) \quad (3.15)$$

$$\varepsilon(t_1) = a + bt \quad (t < t_1) \quad (3.16)$$

5. Determination of Maxwell parameters (K_M and C_M)

The two parameters can be determined by the following equations:

$$a = \frac{\sigma_0}{K_M} \quad \text{and} \quad b = \frac{\sigma_0}{C_M}$$

6. Average absolute errors (AAE)

The AAE of creep data can be expressed in Equation (3.17), where N is the total test data.

$$AAE = \frac{1}{N} \sum_i^N \frac{\varepsilon_{predicted}(t_1) - \varepsilon_{measured}(t_1)}{\varepsilon_{measured}(t_1)} \quad (3.17)$$

7. Finalisation of Burger's parameters

The six steps are done repeatedly to obtain the minimum AAE value, in which the final Burger's parameters are selected. The Burger's model parameters utilised in this study are presented in Table 3.5.

Table 3.5. Burger's model parameters

Parameters	Value
K_m (kPa)	87.64
C_m (kPa.sec)	8.12
K_k (kPa)	10.31
C_k (kPa.sec)	3.42

3.5.4. Compacting process in PFC3D

In PFC3D, moving wall with specified velocity was applied to simulate the compressive load given by gyratory compactor. To maintain constant loading during compacting process, the servo-control mechanism was performed in PFC3D. Servo-control mechanism preserves a constant stress, including axial and confining stresses, throughout the simulation. In every calculation cycle, servo-control mechanism is called to calculate the current wall stresses and minimise the deviation of measured stress and required stress by adjusting the wall velocities. The servo-control algorithm is expressed in Equation (3.18):

$$\dot{u}^{(w)} = G(\sigma^{measured} - \sigma^{required}) = G\Delta\sigma \quad (3.18)$$

where G is the 'gain' parameter calculated using the following steps. The maximum addition in wall force due to the wall movement in one cycle is given by:

$$\Delta F^{(w)} = k_n^{(w)} N_c \dot{u}^{(w)} \Delta t \quad (3.19)$$

where, N_c is the number of contacts on the wall and k_n is the average stiffness of these contacts. Thus, the shift in mean wall stress is calculated by:

$$\Delta\sigma^{(w)} = \frac{k_n^{(w)} N_c \dot{u}^{(w)} \Delta t}{A} \quad (3.20)$$

where A is the wall area. To achieve the stability requirement, the deviation between the measured and required wall stress should be more than the shift in wall stress. Herein, a relaxation factor α is calculated as:

$$|\Delta\sigma^{(w)}| < \alpha |\Delta\sigma| \quad (3.21)$$

Combining Equations (3.19) and (3.20) into Equation (3.21) gives:

$$\frac{k_n^{(w)} N_c G |\Delta\sigma| \Delta t}{A} < \alpha |\Delta\sigma| \quad (3.22)$$

$$G = \frac{\alpha A}{k_n^{(w)} N_c \Delta t} \quad (3.23)$$

where G is the ‘gain’ parameter to be substituted into Equation (3.18) to obtain the required wall stress.

3.5.5. Simulation parameters

In this study, four simulation parameters were generated to evaluate the packing condition of PAM model, namely voids content, coordination number, proportion of effective particles (PEP), and average contact force (ACF).

(a) Porosity

Porosity (n) refers to the ratio of voids volume in a measurement sphere of DEM model, which can be expressed by Equation (3.24).

$$n = \frac{V_{void}}{V_{mea}} = 1 - \frac{V_{mat}}{V_{mea}} \quad (3.24)$$

V_{void} = volume of the voids in the region of measurement sphere;

V_{mat} = volume of the materials in the region of measurement sphere; and

V_{mea} = volume of the measurement sphere.

(b) Coordination number

Coordination number (C_n) is the mean number of contacts for each particle in the mixtures, and the relevant calculation is given in Equation (3.25).

$$C_n = \frac{1}{N_p} \left(\sum_{N_p} n_c^{(p)} \right) \quad (3.25)$$

N_p = number of particles with the centroids within the region of measurement sphere; and

$n_c^{(p)}$ = number of contacts around each particle.

(c) Proportion of effective particles (PEP)

The number of effective particles that participate on load distribution in the mixture are obtained from normal contact force distribution. Then, the proportion of effective particles (PEP) of the mixture can be calculated by Equation (3.26). A higher PEP value is desirable as it indicates more effective particles present in the aggregate skeleton framework, thereby the packing structure of PFC3D model generates extensive load distribution throughout the aggregate skeleton upon receiving an external loading.

$$\text{PEP} = \frac{\text{number of contributing particles in load distribution } (N_{ef})}{\text{total number of particles } (N)} \quad (3.26)$$

(d) Average contact force of particles (ACF)

The average contact force (ACF) of PFC3D for each observed size range can be calculated from contact force distribution by utilising Equation (3.27). Average contact force (ACF) of the mixtures can be utilised to indicate the durability and stability of aggregate skeleton framework upon carrying an external loading. A higher ACF value denotes that the PFC3D model experiences higher level of stress compared with the one which has a lower ACF value. Herein, aggregate packing structure that has a lower ACF value shall have better durability and stronger skeleton framework.

$$ACF_s = \frac{\sum_{i=1}^{j_{ef}} F_i}{j_{ef}} \quad (3.27)$$

where F_i is the contact force at the i^{th} contact point of particles in the observed size range, and j_{ef} represents the total number of effective particles of the observed size range, while s represents the observed size range.

Chapter 4 Influence of aggregate size and gradation on PAM's packing structure

4.1. Overview

The performance of PAM is reliant on many factors, including materials' properties, aggregate gradation, and compaction method, etc. Therefore, the influence of these factors in asphalt mix design should be evaluated to achieve desired performance of PAM for specific applications. In this Chapter, the impact of aggregate size and gradation on PAM is analysed as based on laboratory measurements and DEM simulation results. This Chapter presents the results of two studies. In the first study (Study A), the influence of aggregate proportions (fine fractions, coarse fractions) on the packing structure of PAM is investigated. This is followed in the second study (Study B) that delves into in-depth analysis of the roles of fine fractions in the packing framework of PAM.

4.2. STUDY A: Influence of aggregate proportions on the packing structure

4.2.1. PAM Mixture Design

Gradation is one of crucial factors that determine the permeability and strength of PAM. Aggregates in the gradation are classified into two broad fractions, namely coarse and fine aggregates. In this study, 4.75mm was chosen as a breaking sieve between coarse and fine aggregates. Coarse aggregates have the function to establish the skeleton framework to bear the applied load, while fines mainly have a function to fill the space in between the coarse aggregates. The voids content of PAM is generally above 18% to allow recipient water to soak through the PAM layer on the pavement surface. To achieve this, a small proportion of fine aggregates is utilised, thereby creating a higher voids content in the asphalt mixture. The high amount of air voids, however, compromises the mixture strength. Hence, a proper gradation design is necessary.

In this research, nine gradations (designated G1-G9) were established by varying the proportions of 9.5 - 6.3mm (finer portion of coarse aggregates) and 4.75 - 2.36mm fractions (coarser portion of fine aggregates) as the literature indicated that

these two fractions have critical influence on the establishment of aggregate packing. Herein, the nine designed gradations are shown in Table 4.1 and Figure 4.1. Three different proportions of 9.5 - 6.3mm fractions, namely 2%, 32% and 42%, were chosen. Three proportions of the 4.75 - 2.36mm fractions, at 5%, 12%, and 25%, were utilised. To complete the gradation, 8% of 2.36 – 0.075mm fractions and 5% hydrated lime as fillers were utilised in all nine gradations.

Figure 4.1. Selected aggregate gradation design

4.2.2. Laboratory measurements

A series of laboratory measurements were conducted to evaluate the properties of PAM with various gradations. The selected binder content for each gradation satisfied the requirements of Cantabro and drain-down tests (see Table A.1 in Appendix A). Herein, the volumetric and mechanical properties of PAM were measured, and the results presented.

Table 4.1 Selected aggregate gradation design

Sieve Size (mm)	Passing by mass (%)								
	G1	G2	G3	G4	G5	G6	G7	G8	G9
19.0	100	100	100	100	100	100	100	100	100
13.2	85	85	85	85	85	85	85	85	85
9.5	70	70	70	80	80	80	40	40	40
6.3	38	38	38	38	38	38	38	38	38
4.75	25	38	18	25	38	18	25	38	18
2.36	13	13	13	13	13	13	13	13	13
1.18	10	10	10	10	10	10	10	10	10
0.6	8	8	8	8	8	8	8	8	8
0.3	7	7	7	7	7	7	7	7	7
0.15	6	6	6	6	6	6	6	6	6
0.0075	5	5	5	5	5	5	5	5	5

Volumetric properties

The volumetric properties of the nine PAM blends are given in Table 4.2. The Theoretical Maximum Density (TMD) values were similar for the nine gradation designs. Gradations (G2, G5, G8) with higher proportion of fine fractions (4.75 - 2.36mm) aggregates notably had lower voids content as denoted in the VTM values. The results showed that G3 possessed the highest VTM, even though G9 possessed higher proportions of 19.0 – 9.5mm fractions. Herein, G3 consisted of 30% of 19.0 – 9.5mm fractions and 32% of 9.5 – 6.3mm fractions. As the proportions of two coarse fractions were similar, both particles of 19.0 – 9.5mm and 9.5 – 6.3mm fractions were dominant particles in the packing structure of PAM. The voids generated by 19.0 – 9.5mm fractions may not be big enough to be filled by the many particles of 9.5 – 6.3mm fractions. As the particles try to fill into the smaller voids, they end up pushing the other particles and re-arranging the aggregate packing. Thereof, more voids were generated in aggregate packing of G3.

Meanwhile, the coarser fractions of coarse aggregates in G9 consisted of 60% of 19.0 – 9.5mm fractions and 2% of 9.5 – 6.3mm fractions. Herein, 19.0 – 9.5mm fractions were the dominant particles to establish the aggregate packing. The large proportion of 19.0 – 9.5mm fractions generated voids that are big enough to be filled by the smaller particles. Thereby, G9 established denser packing as many voids generated by larger particles were filled by smaller fractions.

Table 4.2 Volumetric properties of PAM

Gradation	TMD (g/cm ³)	VTM (%)	Standard Error (%)
G1	2.45	17.25	0.23
G2	2.45	15.04	0.31
G3	2.45	18.86	0.12
G4	2.45	18.12	0.18
G5	2.45	15.41	0.25
G6	2.45	18.27	0.29
G7	2.45	17.23	0.27
G8	2.45	16.78	0.17
G9	2.45	17.07	0.21

*n = three specimens for each mix design

Permeability test

The coefficient of permeability is a more direct indicator than voids content to determine the quality of PAM in terms of its drainage function. In this study, coefficient of permeability was measured by utilising the falling head apparatus. The results for this test are summarised in Figure 4.2. A higher coefficient of permeability value implies that the specimen has more voids spread across the mixture. Coefficient of permeability for G5 was notably much lower compared with other blends. G5 blend consisted of a low proportion of coarse fractions (80% passing 9.5mm) and a high proportion of 2.36 – 4.75mm fractions (25%), thus resulting in the G5 blend being more densely packed.

*n = three specimens for each mix design

Figure 4.2. Coefficient of permeability for PAM (average $\pm$ standard error)

Marshall stability test

Marshall stability test was performed to measure the maximum load that a specimen can carry under loading rate of 50.8 mm/minute. Marshall test represents rupture behaviour of PAM, thereby denser mixtures tend to have higher resistance against fracture. The Marshall stability values are shown in Figure 4.3. The results showed higher Marshall stability for gradations with higher proportion of fine aggregates (4.75 - 2.36mm) (and hence lower VTM's) (see blue blocks within each diagram), and lower proportion of coarse aggregates (9.5 - 6.3mm, equivalent to higher proportion of >9.5mm aggregates)(see corresponding blocks across the three diagrams).

Creep test

Total permanent strain of each gradation after under-going 40,000 cycles of repeated load was obtained from creep test. The results are presented in Figure 4.4. A higher value of total permanent strain indicates that the specimens suffered higher permanent deformation. The general observation from the laboratory measurements was lesser permanent deformation for higher proportion of fine aggregates and very coarse (>9.5mm) aggregates.

(a)

(b)

*n = three specimens for each mix design

(c)

Figure 4.3 Marshall stability of PAM for: (a) 2% of 9.5 - 6.5mm fractions; (b) 32% of 9.5 - 6.5mm fractions; (c) 42% of 9.5 - 6.5mm fractions (average $\pm$ standard error)

(a)

(b)

*n = three specimens for each mix design

loading period : 0.5 ± 0.05 seconds;

pulse repetition period: 2.0 ± 0.05 seconds

(c)

Figure 4.4 Permanent strain of PAM for: (a) 2% of 9.5 - 6.5mm fractions; (b) 32% of 9.5 - 6.5mm fractions; (c) 42% of 9.5 - 6.5mm fractions (average $\pm$ standard error)

4.2.3. DEM simulation

For numerical simulation in PFC3D, the procedures of generating objects (i.e. walls and balls), setting the objects' properties, selecting contact model, and compacting assembly of balls have been described in Chapter 3. Four stipulated parameters, namely (1) porosity, (2) coordination number, (3) proportion of effective particles (PEP), and (4) average contact force (ACF) were computed based on Newton's second law and force-displacement law. The simulation results are evaluated in this section.

4.2.3.1. Clumps

Clump templates were created to represent the actual aggregate shape. Fifty pieces of granite were selected as the measurement's samples and the average of shape properties was calculated as indicated in Table 4.3. Two clump templates that have similar aggregate shape properties with granite were generated as shown in Figure 4.5. The shape properties of the clump templates are summarised in Table 4.4. Clump-1 was utilised to simulate aggregates size 19.0 – 9.5mm, while clump-2 was used to model aggregate size 9.5 – 2.36mm. Herein, balls with diameter 1.6mm were generated to model the finer fraction of fine (2.36 - 0.075mm) aggregates, as explained in Section 3.4.1. The properties of clump templates were assigned according to the properties of granite, in which elastic modulus of 40 GPa, coefficient of friction of 0.43, and Poisson ratio of 0.2.

Table 4.3 Average shape characteristics of granite

No	Aggregate size	Form Factor (F)	Sphericity (Ψ)	Roundness (R)
1	19.0 – 9.5mm	0.839	0.735	0.412
2	9.5 – 4.75mm	0.925	0.842	0.422

Figure 4.5 Designed clumps: (a) clump-1, and (b) clump-2

Table 4.4. Shape characteristics of clumps

No	Clump templates	Form Factor (F)	Sphericity (Ψ)	Roundness (R)
1	Clump - 1	0.842	0.777	0.432
2	Clump - 2	0.918	0.823	0.415

4.2.3.2. Simulation results for DEM model

Validation of DEM model

The DEM simulation results were validated by analysing the correlation between laboratory measurement and DEM simulation on two aspects: (a) voids content, and (b) strain curve. The analysis was performed to ensure DEM models are reliable to simulate the packing structures of PAM.

Voids content is a direct parameter to indicate the packing condition of granular materials. Aggregate packing with fewer voids possesses a more dense-packed structure. However, PAM has a primary functional role to drain surface water, and its packing structure is inherently less dense. Herein, voids content serves as a design parameter in developing the aggregate packing structure for PAM that will have adequate drainage function without compromising too much on strength. As mentioned in Section 3.5.1., asphalt mastic was simulated as a contact model rather than balls or clumps. Thereby, asphalt mastic does not fill the voids or space in DEM model. Herein, the voids in total mastic (VTM) of DEM model was predicted by utilising Equation (4.1). The voids occupied by asphalt mastic were estimated to make the volumetric properties of DEM models comparable with laboratory measurements. The results showed that the average difference between predicted-

VTM of DEM model and measured-VTM was $\pm 1\%$ error value, as shown in Figure 4.6. Thereby, the packing structure of DEM model was on similar density level with PAM specimens and can be utilised to assess the packing condition of PAM.

$$\text{Predicted VTM} = n - \frac{\text{volume of asphalt mastic}}{\text{total volume}} \quad (4.1)$$

where, n refers to the porosity obtained from DEM model.

Figure 4.6 Correlation of air voids content from DEM simulation and laboratory measurements

Total permanent strains of PAM from creep test and DEM simulations were compared and the results shown in Figure 4.7. The results from DEM simulations and laboratory measurements showed a good agreement with average difference within $\pm 5\%$ error value. Based on the results, the simplification of fine aggregates as balls with a constant diameter of 1.6mm is acceptable and did not notably degrade the quality of PAM model. Herein, DEM model is deemed feasible to simulate the behaviour of PAM under external loading.

*(S) represents the results were obtained from DEM simulation

Figure 4.7 Total permanent strain of DEM model and PAM specimens

Packing structure of PAM

Three packing parameters, namely coordination number, proportion of effective particles (PEP), and average contact force of particles (ACF) were utilised to assess the quality of packing structure of PAM. Coordination number and PEP for each gradation were calculated and the results are presented in Figure 4.8. Packing structure with higher coordination number and PEP is more desirable as those values indicate that the aggregate packing generates more particle contacts and a higher proportion of particles contribute to load bearing. As shown in Figure 4.8., increasing the proportion of coarser particles of fine (4.75 - 2.36mm) aggregates increases the coordination number of PAM, regardless the composition of the coarse aggregates. Meanwhile, the PEP values of PAM had apparently quadratic relationship with the proportion of 4.75 - 2.36mm fractions.

Figure 4.8 Packing parameters of PAM for: (a) 2% of 9.5 - 6.5mm fractions; (b) 32% of 9.5 - 6.5mm fractions; (c) 42% of 9.5 - 6.5mm fractions

The distribution of normal contact force for each PAM model was obtained and the results are shown in Figure 4.9. The contact force distribution illustrates the load transmission chain between aggregate particles in the mixtures. A thicker line indicates that the particle transmits a greater magnitude of the normal force. Herein, gradations with a lower proportion of coarser particles of fine (4.75 - 2.36mm) aggregates, namely G3, G5, G9, possessed notably fewer thinner lines as lower forces are usually carried by the finer particles.

Figure 4.9 Distribution of normal contact force for each selected gradation

The average contact force (ACF) for each gradation was calculated according to the distribution of contact forces and the results are summarised in Table 4.5. The ACF value for each corresponding size range was observed, and the results showed that ACF value decreased when finer aggregates were considered in the mixtures ($ACF_{19.0 - 6.3 \text{ mm}} > ACF_{19.0 - 4.75 \text{ mm}} > ACF_{19.0 - 2.36 \text{ mm}}$). The existence of finer aggregates generates more particle contacts to create the packing structure, thereby decreasing the ACF value. A higher ACF value of the mixtures indicates that PAM model experiences higher stress when the external loading is applied.

Table 4.5 Average contact force for each selected gradation

Gradation	Proportion of 9.5 – 6.3mm (%)	Proportion of 4.75 - 2.36mm (%)	Average contact force (ACF) [N]		
			19.0 - 6.3mm	19.0 - 4.75mm	19.0 - 2.36mm
G9	2	5	203.57	138.65	100.64
G7		12	203.57	157.81	82.58
G8		25	203.57	186.87	89.54
G3	32	5	198.45	116.84	91.45
G1		12	198.45	138.24	73.76
G2		25	198.45	198.45	85.54
G6	42	5	186.87	119.56	95.21
G4		12	186.87	141.45	79.64
G5		25	186.87	203.57	88.42

4.2.4. Discussions

In this section, further discussions about the influence of aggregate size and gradation on the properties of PAM are presented. The relationship and verification between laboratory measurements and DEM simulations are also explained.

Statistical Analysis

Based on the results of laboratory measurements and DEM simulations, the aggregate size distribution has notable effect on the resultant properties of PAM. To statistically assess the influence of aggregate size distribution on the performance of PAM, two-way analysis of variance (ANOVA) with significance level of 0.05 ($\alpha = 0.05$) was applied. Herein, the interaction of two main factors, namely the proportion of coarse aggregates and proportion of fine aggregates were evaluated, and the linear model is given in Equation (4.2).

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \quad (4.2)$$

y_{ijk} = k^{th} observation of response variable;

μ = mean value of responses;

α_i = main effect of i^{th} α ;

β_j = main effect of j^{th} β ;

$(\alpha\beta)_{ij}$ = variations caused by interactions between α and β ;

ε_{ijk} = error term.

Herein, the null hypothesis (H_0) was that the mean value of the response variable (i.e. VTM, coefficient of permeability, Marshall stability, coordination number, PEP) remained the same despite the specific combination of two factors (i.e. proportion of coarse and fine aggregates). The confidence level of 95% was selected. Herein, H_0 should be accepted if resultant F -statistic (F) value was no greater than a threshold value of F -critical (F_c), which is corresponding to a P value at 0.05. In this research, the Levene's and Shapiro-Wilk tests were conducted before performing ANOVA to ensure the homogeneity and normality of variance of the data. As the p -values of observed Levene's and Shapiro-Wilk statistics were more than 0.05, the null hypothesis was rejected as there was no significant difference and the data were deemed to satisfy the homogeneity and normality requirements.

The results of statistical analysis are presented in Table 4.6. The results indicated that the size distribution of coarse aggregates did not have significant influence on the resultant properties of PAM at 0.05 significance. Meanwhile, the size distribution of fine aggregates showed great influence on the properties of PAM and the interaction between the two main factors concerning the proportions of fine and coarse aggregates can significantly influence the performance of PAM. Herein, adjusting the size distribution of fine aggregates would be more efficient to achieve the desired corresponding properties of PAM.

Table 4.6 .ANOVA results for laboratory measurements

Source of variation		df	F	P
VTM				
main factor	coarse aggregates (9.5-6.36mm)	2	1.65	0.982
	fine aggregates (4.75-2.36mm)	2	7.12	0.023
two-factor interaction	coarse & fine aggregates	4	25.1	0.006
error (MS)	0.43			
Coefficient of permeability				
main factor	coarse aggregates (9.5-6.36mm)	2	2.43	0.188
	fine aggregates (4.75-2.36mm)	2	6.31	0.031
two-factor interaction	coarse & fine aggregates	4	28.9	0.008
error (MS)	0.32			
Marshall stability				
main factor	coarse aggregates (9.5-6.36mm)	2	2.31	0.182
	fine aggregates (4.75-2.36mm)	2	4.65	0.092
two-factor interaction	coarse & fine aggregates	4	50.12	0.002
error (MS)	0.34			
Total permanent strain				
main factor	coarse aggregates (9.5-6.36mm)	2	1.88	0.611
	fine aggregates (4.75-2.36mm)	2	46.82	0.004
two-factor interaction	coarse & fine aggregates	4	22.13	0.011
error (MS)	0.45			
coordination number				
main factor	coarse aggregates (9.5-6.36mm)	2	1.69	0.782
	fine aggregates (4.75-2.36mm)	2	50.43	0.003
two-factor interaction	coarse & fine aggregates	4	44.56	0.005
error (MS)	0.37			

*df=degree of freedom, F = F -static value, and MS=mean square

Influence of aggregate size distribution on the properties of PAM

The influence of aggregate size distribution was analysed in this section. From DEM model, three packing parameters, namely coordination number, proportion of effective particles (PEP), and average contact force of particles (ACF) were obtained. The results showed that the proportion of fine aggregates had significant influence on the packing structure of PAM, but not the composition of coarse aggregates, as shown in Figure 4.8. Herein, increasing the proportion of fine (4.75 – 2.36mm) fractions in the gradation increased the coordination number and decreased the PEP value of aggregate packing. These results indicated that many ineffective contacts were generated in the mixture when a higher proportion of fine fractions was introduced into the mixtures, thereby the packing possessed lower PEP value despite having more contacts. In essence, there exists a higher proportion of particles that only have a function as space filler in the packing structure of PAM. Moreover, the ACF value of the mixtures ($ACF_{19.0 - 2.36 \text{ mm}}$) had quadratic correlation with the proportion of fine (4.75 – 2.36mm) fractions, as shown in Figure 4.10. The $ACF_{19.0 - 2.36 \text{ mm}}$ initially decreased when more fine particles were introduced into the mixtures then increased when too many fine particles were present in the mixtures. These results indicated that higher proportion of fine fractions has potential to disrupt the skeleton framework of aggregate packing, as a higher proportion of the finer aggregates acts mainly as space filler.

The packing structure of PAM with various aggregate gradations was also assessed according to conventional packing theories, namely gradation-based framework. For gradation-based framework, primary structure (PS) is selected according to which aggregate size range has the highest proportion in the aggregate gradation, and it is recommended that PS should have minimum proportion of 45% (Lira et al. 2013). PS refers to the size fraction that contributes to the establishment of the main packing structure. Herein, the weighted average diameter of gradation was calculated according to the Equation (2.7). Gradation-based framework suggested that the weighted average diameter of gradation (D_{average}) shall fall within the range values between D_{min} and D_{max} , as stated in the Equation (2.5), to obtain optimum

aggregate contacts in the packing structure. Herein, the values of weighted average diameter of PS for each gradation are summarised in Table 4.7.

Figure 4.10 Correlation between the proportion of 4.75 – 2.36mm fractions and ACF of PAM for: (a) 2% of 9.5 - 6.5mm fractions; (b) 32% of 9.5 - 6.5 mm fractions; (c) 42% of 9.5 - 6.5mm fractions

Table 4.7 Weighted average diameter of PS for the selected gradations

Gradation	Primary structure (PS)		D _{min} (mm)	D _{average} (mm)	D _{max} (mm)
	Size fraction (mm)	Proportion (%)			
G1	13.2 - 6.3	47	8.97	9.00	10.33
G2	13.2 - 6.3	47	8.97	9.00	10.33
G3	9.5 - 4.75	52	6.26	6.99	7.19
G4	9.5 - 4.75	55	6.26	7.34	7.19
G5	13.2 - 6.3	47	8.97	8.27	10.33
G6	9.5 - 4.75	62	6.26	7.13	7.19
G7	19.0 - 9.5	60	12.83	12.54	14.69
G8	19.0 - 9.5	60	12.83	12.54	14.69
G9	19.0 - 9.5	60	8.97	12.54	14.69

As shown in Table 4.7., the primary structure (PS) in aggregate packing is dominated by the coarser fraction of coarse (19.0 – 6.3mm) aggregates. Herein, coarser fraction of coarse aggregates has a major role to create the main structure of aggregate packing for load bearing. The dominant size range within coarser fraction of coarse aggregates is determined by the proportion in aggregate gradation. The results of the weighted average diameter of gradation (D_{average}) showed that only four gradations, namely G1, G2, G3, G6 satisfied the requirement of two contiguous sieve sizes. Herein, G1, G2, G3, and G6 possessed an optimum particle interaction within their main packing structure, and resulted in more stable aggregate packing structure.

Next, the weighted average diameter of gradation (D_{average}) for size range 6.3 - 2.36mm was calculated to evaluate the particle interaction in the secondary structure (SS). The finer fraction of coarse (6.3 - 2.36mm) aggregates, as secondary structure (SS), has a major function to fill the space within the primary structure (PS). The values of the weighted average diameter of SS for each gradation are presented in Table 4.8. The results indicated that only gradations containing 12% of 4.75 – 2.36mm, namely G1, G4, G7, met the requirement of gradation-based method even though all nine gradations possessed the same proportion of 6.3 -

2.36mm fractions. Herein, the proportion of finer fractions in SS had significant influence on the particle interaction within the aggregate packing. Moreover, proportion of 4.75 – 2.36mm fractions also possessed notable influence on the volumetric properties of aggregate packing, in which increasing proportion of 4.75 – 2.36mm decreased the VTM of PAM, as shown in Table 4.2. According to gradation-based framework, G1 possessed the most desirable results, in which the gradation generated sufficient particle interaction in both primary and secondary structures.

Generally, both the results of DEM model and gradation-based framework suggested that higher proportion of fine aggregates in PAM mixtures may reduce the stability of the overall packing structure of PAM. The results of DEM model are in line with gradation-based framework, in which G1 exerted the most desirable packing properties. DEM results showed that G1 generated packing structure with the highest PEP value and lowest ACF value. DEM simulation possesses better abilities to evaluate the packing structure of PAM by demonstrating an explicit assessment on contact mechanism and load distribution among aggregate particles, while gradation-based framework analysis the state of packing structure only based on the interaction between particles in two contiguous sieves.

Table 4.8 Weighted average diameter of SS for the selected gradations

Gradation	size range 6.3 - 2.36 mm		
	D _{min} (mm)	D _{average} (mm)	D _{max} (mm)
G1	4.17	4.58	4.94
G2	4.17	3.56	4.94
G3	4.17	5.13	4.94
G4	4.17	4.58	4.94
G5	4.17	3.56	4.94
G6	4.17	5.13	4.94
G7	4.17	4.58	4.94
G8	4.17	3.56	4.94
G9	4.17	5.13	4.94

As the aggregate size distribution has direct influence on the aggregate packing structure, aggregate size distribution may affect the resultant properties of corresponding PAM. For the Marshall stability, the results exhibited that increasing the proportion of finer fractions increase the Marshall stability of PAM (Figure 4.3). As the proportion of finer fractions increases, the VTM of the mixtures decreases. Therein, gradation that generates more well-packed structure tends to have greater durability to withstanding external load, and results in a higher maximum load to reach fracture state.

Meanwhile, the results of creep test indicated that aggregate size distribution affect the total permanent strain of the mixtures, in which increasing the proportion of finer fractions generally decreases the permanent strain (Figure 4.4.). However, the total permanent strain increased when high proportion of finer aggregates was present in the mixtures, as shown in some cases, e.g. G2, G5, and G8, which possessed 25% of 4.75 – 2.36 mm fractions. These results indicated that tightly packed structure is not a guarantee for PAM to have better resistance on permanent deformation. As explained before, packing structure of PAM with high proportion of fine aggregates is established by higher proportion of ineffective particles and results in the aggregate packing experiencing higher stresses. The packing condition of PAM with high proportion of fine aggregates is reflected in its mechanical properties, thereby PAM with high proportion of fine aggregates suffers higher permanent deformation when external loading is applied.

Herein, aggregate size distribution greatly influences the aggregate configuration of the main skeleton framework. The aggregate configuration determines the stability of packing structures and the resultant properties of PAM. Load distribution and contacting mechanism of the aggregate packing are better indicators to describe the stability of packing structure than density level and/or voids content. Next up, the following Study B shall delve into the roles of fine fractions in the packing framework of PAM.

4.3. **STUDY B:** In-depth study on the influence of fine fractions on the packing structure

As the results of study A indicated that higher proportion of fine aggregates disrupts the stability of aggregate packing, more in-depth study on the influence of fine (< 4.75mm) aggregates were conducted. Herein, the proportion of aggregate size fraction less than 2.36mm was generally kept to a low proportion (< 10%) to maintain the high air voids content in PAM. Therein, aggregate size < 2.36mm is not a concern in PAM. In this study, the influence of aggregate size 4.75 - 2.36mm on the packing structure of PAM was assessed by utilising ten gradations with varying proportions of 4.75 - 2.36mm fractions, as shown in Figure 4.11 and Table 4.9.

Figure 4.11 Selected gradation of PAM

Table 4.9 Selected aggregate gradation design

Sieve Size (mm)	Passing by mass (%)									
	Ga	Gb	Gc	Gd	Ge	Gf	Gg	Gh	Gi	Gj
19	100	100	100	100	100	100	100	100	100	100
13.2	85	85	85	85	85	85	85	85	85	85
9.5	70	70	70	70	70	70	70	70	70	70
6.3	37	37	37	37	37	37	37	37	37	37
4.75	7	12	17	19	22	27	29	32	35	37
2.36	7	7	7	7	7	7	7	7	7	7
1.18	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
0.6	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
0.3	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
0.15	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
0.075	5	5	5	5	5	5	5	5	5	5

4.3.1. Laboratory measurements

A series of laboratory measurements were performed to evaluate the volumetric and mechanical properties of PAM, and the results are presented in this section. Meanwhile, the selected binder content for each gradation satisfied the requirements of Cantabro and drain-down tests (see Table A.2 in Appendix A).

Volumetric properties

The volumetric properties of PAM specimens for each gradation were measured, and the results are summarised in Table 4.10. The results exhibited that VTM of PAM generally decreased when higher proportion of finer fractions was introduced in the mixtures.

Coefficient of permeability

Coefficient of permeability for each gradation was measured by utilising falling head apparatus, and the results are illustrated in Figure 4.12. The results indicated that PAM with higher proportions of fine aggregates generally possessed lower coefficient of permeability. As more fine particles exist in the mixtures to fill the voids, PAM's ability to permeate water also decreases.

Table 4.10 Summary of average-VTM of PAM for each selected gradation

Gradation	Proportion of 4.75 - 2.36 mm (%)	VTM (%)	Standard Error (%)
Ga	0	19.89	0.24
Gb	5	19.75	0.35
Gc	10	19.81	0.21
Gd	12	19.46	0.23
Ge	15	19.13	0.27
Gf	20	18.76	0.17
Gg	22	18.84	0.21
Gh	25	18.54	0.15
Gi	28	18.40	0.16
Gj	30	17.65	0.24

*n = three specimens for each mix design

Figure 4.12 Coefficient of permeability for each selected gradation (average $\pm$ standard error)

Marshall stability

Marshall stability values of PAM with varying aggregate size distribution were measured, and the results are summarised in Figure 4.13. Marshall stability of PAM increased when the proportion of fine aggregates was increased; however Marshall stability decreased when proportion of 4.75- 2.36mm fractions was more than 22%.

*n = three specimens for each mix design

Figure 4.13 Marshall stability of PAM for each selected gradation (average $\pm$ standard error)

Creep test

The results of total permanent strain for each gradation are presented in Figure 4.14. It can be seen that total permanent strain of PAM decreased with additional proportion of fine aggregates. However, the total permanent strain increased when high proportion of 4.75- 2.36mm fractions (>20%) was introduced into the mixtures.

*n = three specimens for each mix design

loading period : 0.5 ± 0.05 seconds;

pulse repetition period: 2.0 ± 0.05 seconds Figure 4.14 Total permanent strain of PAM with varying aggregate gradation (average $\pm$ standard error)

4.3.2. Simulation results for DEM model

Validation of DEM model

The results of DEM simulations and laboratory measurements were compared to validate the feasibility of DEM model. Two aspects, namely voids content and strain, were analysed. As similar to Study A, the average differences between predicted-VTM of DEM model and measured-VTM were within the same bandwidth of $\pm 1\%$ error value (see Figure B1.1 in Appendix B1), thereby DEM model had similar density level with corresponding PAM specimens. Similarly, for permanent strain curve, the average differences between DEM model and laboratory measurements were within the same bandwidth of $\pm 5\%$ of error value (see Figure B1.2 in Appendix B1). Thereof, DEM model is deemed feasible to simulate visco-elastic behaviour of PAM under external loading despite the limitations of the model.

Aggregate packing structure

Three packing parameters, namely coordination number, proportion of effective particles (PEP), and average contact force (ACF) were utilised to define the packing condition of DEM model. The results of coordination number and PEP for each gradation are summarised in Figure 4.15. The results showed that both coordination number and PEP had quadratic relationship with the proportion of 4.75 – 2.36mm fractions. Herein, coordination number and PEP increase with the increasing the proportion of 4.75 – 2.36mm fractions until they reaches the peak value and later starts to decrease. The results showed that packing structure of PAM reaches the optimum coordination number when the proportion of 4.75 – 2.36mm fractions is 22%. Meanwhile, packing structure of PAM was established by the optimum PEP when the proportion of 4.75 – 2.36mm fractions was 15%.

Figure 4.15 Packing parameters of PAM with varying gradations

The distribution of normal contact force for each gradation is shown in Figure 4.16. It can be seen that gradation with higher proportion of fine aggregates possessed denser force chain with more thin lines. Herein, thinner lines indicate lower magnitude forces that are usually carried by finer fractions. From distribution of

normal contact force, average normal force (ACF) of each gradation was calculated and the results are summarised in Table 4.11.

Figure 4.16 Distribution of normal contact force for each selected gradation

The ACF value decreased significantly when 4.75 – 2.36mm fractions was considered in the mixtures, indicating that 4.75 – 2.36mm fractions not only occupied space in aggregate packing but also contributed on load transmission. Herein, ACF value of the mixture ($ACF_{19.0-2.36mm}$) had quadratic correlation with

the proportion of 4.75 – 2.36mm fractions, in which $ACF_{19.0-2.36mm}$ decreased with increasing proportion of 4.75 – 2.36mm fractions but at some points started to increase.

Table 4.11 Average contact force (ACF) for each gradation

Gradation	Proportion of 2.36 – 4.75mm fractions (%)	ACF [N]	
		19.0 – 4.75 mm	19.0 – 2.36 mm
Ga	0	84.2	84.2
Gb	5	84.9	80.1
Gc	10	86.2	77.4
Gd	12	86.5	75.7
Ge	15	88.3	72.3
Gf	20	91.6	67.1
Gg	22	92.1	68.6
Gh	25	92.8	76.3
Gi	27	94.3	77.8
Gj	30	95.1	80.7

4.3.3. Discussion

In this section, further discussions about the influence of aggregate shape properties are presented. The relationship between laboratory measurements and DEM simulations are also explained.

Influence of fine aggregates on packing structure

The results of packing parameters obtained from DEM model were examined to analyse the influence of the proportion of fine aggregates in PAM. As shown in Figure 4.15, coordination number and PEP had quadratic relationship with the proportion of 4.75 – 2.36mm fractions. PEP of the mixtures drastically dropped when the proportion of 4.75 – 2.36mm fractions was more than 22%, even though the coordination number was still quite high. These results indicated that there were many ineffective contacts generated within the packing structure of PAM with more than 22% of 4.75 – 2.36mm fractions. By increasing proportion of 4.75 –

2.36 mm fractions, the coarser fractions will have to re-orient and be pushed apart from each other. Thereof, the skeleton framework is mainly established by stone-on-stone interlocking between coarse-to-fine particles instead of coarse-to-coarse particles when higher proportion of finer fractions is introduced into the mixtures, as illustrated in Figure 4.17. As an excessive proportion of 4.75 – 2.36 mm fractions generate many inefficient contacts, many particles only have a function as voids filler rather than contributing on load transmission (Figure 4.17b). Herein, the fine particles that only have a role as voids filler become “redundant” particles as PAM requires high air voids to obtain sufficient drainage performance.

*red arrows indicate effective contacts

(a)

(b)

Figure 4.17 Aggregate skeleton framework; (a) sufficient proportion of fine fractions; (b) excessive proportion of fine fractions

The decrease on PEP value for PAM with more than 22% of 4.75 – 2.36mm fractions resulted in the increase of ACF value of the mixtures (Table 4.10). As more particles in the mixtures do not participate in load bearing (as illustrated in Figure 4.17b), existing effective particles have to carry higher force and results in the mixtures suffering higher stress when external loading is applied. The results of DEM simulation indicated that high proportion of fine aggregates has a potential to disrupt the packing structure of PAM, as many ineffective particles are generated in the skeleton framework of PAM with high proportion of fine aggregates. Herein, it is recommended to utilise PAM gradation with 10 – 22% of 4.75 – 2.36mm

fractions to generate sufficient skeleton strength. PAM gradation with less than 10% of 4.75 – 2.36mm fractions is not recommended because mixtures with coordination number below four is considered not stable in carrying load (Rothenburg et al. 1992). Thereof, packing structure of PAM with lack proportion of 4.75 – 2.36mm fractions generates unstable packing structure that easier to be squashed when loading is applied, as illustrated in Figure 4.18. Meanwhile, 15 % of 4.75 – 2.36mm fractions is selected as an optimum proportion to obtain the most favourable packing structure, in terms of mechanical and drainage properties.

*red arrows indicate effective contacts

Figure 4.18 Aggregate skeleton framework for PAM with lack proportion of fine fractions

Gradation-based framework was applied to further evaluate the packing structure of PAM with varying proportions of fine aggregates. The weighted average diameters (D_{average}) of primary structure (PS) and secondary structure (SS) were calculated according to the Equation (2.7), and the results are summarised in Tables 4.12. and 4.13., respectively. The D_{average} results of PS met with the requirement of interaction between particles in the Equation (2.5). These results indicated that the size distribution in coarse aggregates generated optimum particle contacts to establish the skeleton framework. Meanwhile, the particles interaction in secondary structure (SS) was evaluated, and the results suggested that PAMs with 10 – 20 % of 4.75 – 2.36mm fractions ($G_c - G_f$) generate sufficient particle contacts within the corresponding two contiguous sieves.

Table 4.12 Weighted average diameter of PS for the selected gradations

Gradation	Primary structure (PS)		D _{min} (mm)	D _{average} (mm)	D _{max} (mm)
	Size fraction(mm)	Proportion (%)			
Ga	9.5 - 4.75	63	5.53	6.77	7.90
Gb	9.5 - 4.75	58	5.53	6.88	7.90
Gc	9.5 - 4.75	53	5.53	7.00	7.90
Gd	9.5 - 4.75	51	5.53	7.06	7.90
Ge	9.5 - 4.75	48	5.53	7.16	7.90
Gf	13.2 - 6.3	48	7.90	8.98	11.35
Gg	13.2 - 6.3	48	7.90	8.98	11.35
Gh	13.2 - 6.3	48	7.90	8.98	11.35
Gi	13.2 - 6.3	48	7.90	8.98	11.35
Gj	13.2 - 6.3	48	7.90	8.98	11.35

Table 4.13 Weighted average diameter of SS for the selected gradations

Gradation	Proportion of 4.75 - 2.36 mm (%)	Size range 6.3 - 2.36 mm		
		D _{min} (mm)	D _{avg} (mm)	D _{max} (mm)
Ga	0	4.17	5.53	4.94
Gb	5	4.17	5.20	4.94
Gc	10	4.17	4.87	4.94
Gd	12	4.17	4.74	4.94
Ge	15	4.17	4.54	4.94
Gf	20	4.17	4.21	4.94
Gg	22	4.17	4.08	4.94
Gh	25	4.17	3.88	4.94
Gi	28	4.17	3.69	4.94
Gj	30	4.17	3.56	4.94

To conclude, both conventional theory and numerical simulation suggested that the proportion of fine aggregates influence the interaction between particles, and the configuration of aggregate packing. The proportion of 4.75 – 2.36mm fractions in PAM should be controlled to achieve the optimum condition of packing structure. DEM simulation is a thorough method to analyse the packing structure of asphalt mixtures, as it considers the contact mechanism and load distribution of the packing. Herein, the proportion of 4.75 – 2.36mm fractions is recommended to be 10 – 22% according to packing parameters or 10 – 20% according to gradation-based framework to achieve a stable packing structure.

Influence of fine aggregates on mechanical properties of PAM

The influence of fine aggregates on mechanical properties of PAM was observed according to the results of Marshall stability and creep tests. As the proportion of fine aggregates has significant influence on determining the quality of aggregate packing, it shall have notable effect on the resultant properties of PAM. Regression analysis was done to evaluate the correlation between ACF value of the mixtures with the mechanical properties of PAM, and the results are illustrated in Figure 4.17. Both Marshall stability and total permanent strain had polynomial relationship with ACF value. When packing structure of PAM suffered less stress (low ACF), PAM had higher Marshall stability and better resistance on permanent strain. Therein, the proportion of fine fractions should be controlled to obtain an optimum packing structure and mechanical properties. As shown in Figures 4.13. and 4.14., utilising gradation with high proportion of 4.76 – 2.36mm fractions has potential to impair the mechanical properties.

Figure 4.19 Correlation between ACF value and mechanical properties of PAM

4.7. Summary

The influence of aggregate size distribution was investigated in this study. In the first study, nine gradations (G1 – G9) with varying proportions of 9.5 - 6.3mm and 4.75 – 2.36mm fractions were fabricated to evaluate the influence of the proportion of coarse and fine aggregates on the properties of PAM. DEM simulations and laboratory measurements were performed. The results indicated that the proportion of coarse aggregates do not impose substantive influence on the properties of PAM at 0.05 significance, while the proportion of fine aggregates and the interaction between the proportion of coarse-fine aggregates possess significant influence on the performance of PAM.

The proportion of fine aggregates has the greatest influence on the deformation resistance of the mixtures, while the interaction between the proportion of coarse-fine aggregates impose the biggest influence on the Marshall stability of the mixtures. For packing parameters, ACF value of the mixtures is greatly influenced by the proportion of fine aggregates and PEP value is mainly affected by the interaction between the proportion of coarse-fine aggregates. The results of this study also suggested that high proportion of fine aggregates may have potential to disrupt the packing structure of PAM.

To have better understanding on the influence of fine fractions on aggregate packing, ten gradations (Ga – Gj) with varying proportions of 4.75 – 2.36mm fractions were designed. The results suggested that utilising high proportion of 4.75 – 2.36mm fractions in the mixtures generate higher proportion of ineffective particles in packing structure of PAM, thereby the aggregate packing possesses lower PEP and higher ACF values. The skeleton framework of PAM with high proportion of 4.75 – 2.36mm fractions as established by mainly coarse-fine particles interaction rather than coarse-coarse particles interaction results in weakening the skeleton strength. The proportion of 4.75 – 2.36mm fractions is recommended to be 10 – 22% according to packing parameters of DEM simulations. Herein, the proportion of fine aggregates is important to be controlled to achieve the optimum performance of PAM.

Chapter 5 Impact of aggregate shape properties on PAM's packing structure

5.1. Overview

PAM is an open-graded type of pavement, in which only a small portion of fine particles is allowed in order to achieve desirable permeability. Thus, the packing structure in PAM is principally established by coarse aggregates, and the proportion and shape properties of coarse aggregates will determine the level of particle-to-particle interlocking. Thereby, the properties of coarse aggregates are major factors that influence resultant performance of PAM.

Three independent shape characteristics of aggregates, namely form (overall shape), angularity (roundness), and surface texture, were considered in this research, while leveraging on feasible aggregate materials for experimentation. A series of mixture designs was carefully planned for each independent shape characteristic to mitigate the confounding effect on the corresponding resultant properties of PAM. Three studies were performed to analyse the influence of the three independent shape characteristics, as illustrated in Figure 5.1. The principal objective of these studies is to gain fundamental understanding on the effect of coarse aggregate shape properties on the performance of PAM. As coarse aggregates are major elements that determine the quality of aggregate packing structure, differences in coarse aggregate properties may result in different properties of PAM.

Laboratory measurements and numerical simulation, as described in Chapter 3, were performed to assess the properties of PAM with varying aggregate shape properties. This Chapter presents the analysis on the results obtained from DEM simulations and laboratory measurements. Specified materials and methods are described in more detail.

Figure 5.1 Overview of designed shape properties for each study

5.2. Mixture design

Three studies were conducted separately to investigate the influence of aggregate form (overall shape), angularity (roundness), and surface texture, respectively. A series of mixture designs were fabricated for each aggregate shape properties to facilitate the assessment of the influence of each independent shape characteristic. Herein, other factors, e.g. gradation, asphalt binder type, compacting method, other shape characteristics, etc., were controlled to alleviate the confounding influence on the resultant performance of PAM. Gradation G_f (Figure 5.2) was utilised as this gradation generated satisfactory results in both volumetric and mechanical properties, as investigated in Chapter 4. PG-76 was selected as asphalt binder, while hydrated lime was utilised as filler. Gyratory compacted method was applied for all laboratory specimens. In this section, the details of each series of mixture designs are explained.

Figure 5.2 Aggregate gradation of PAM (G_f)

5.2.1. First independent shape characteristic: form (overall shape)

In the first study, Jurong sedimentary rock was selected instead of the usual granite as crushed sedimentary rocks possess more variation on shape compared with granite. Two shape properties were used to characterise the aggregate form, namely form factor (F), and sphericity (Ψ). Meanwhile, the aggregate angularity was defined by roundness (R). The shape of Jurong sedimentary rocks were classified into three different forms (shapes) of cubical, blade, and disk by utilising flakiness sieve and elongation gauge that satisfy BS 812-105.1 and BS 812-105.2. The three different forms of aggregates are shown in Figure 5.2. The fourth form, rod ($p > 0.6$ and $q < 0.556$), could not be obtained from sedimentary rocks. The classification of aggregate form was performed on aggregate size 19.0 – 4.75mm (i.e. coarse aggregates). The average of aggregate shape properties was estimated by measuring the aggregate dimensions on 50 pieces of crushed sedimentary rocks, and the measurement results are summarised in Table 5.3. Generally, the aggregates with three varying forms possessed similar state of angularity (roundness) and surface texture.

Figure 5.3 Three different forms of the aggregates

Table 5.1. Average of aggregate form properties

No	Aggregate shape	Form Factor (F)	Sphericity (Ψ)	Roundness (R)
1	F-Cubical	0.944	0.805	0.270
2	F-Blade	1.038	0.548	0.238
3	F-Disk	0.803	0.707	0.247

In laboratory measurements, PG-76 binder was selected with 5% asphalt binder as it satisfied the requirements of drain-down and Cantabro tests. The results of drain-down and Cantabro tests for the three mixture designs with varying aggregate forms, namely F-Cubical, F-Blade, and F-Disk are shown in Tables 5.2 and 5.3, respectively. Gyratory compactor with compaction pressure of 600 kPa, gyration rate of 30 rpm, gyration count of 50, and gyration angle of 1.25° was utilised to compact the PAM specimens following the Superpave standard.

Table 5.2 Drain-down test results at 5% binder content

Specimen	*Drain-down (%)	Specification (%)
F-Cubical	0.18	< 0.30
F-Blade	0.24	
F-Disk	0.16	

*average values were computed for 3 specimens

Table 5.3. Cantabro abrasion test results at 5% binder content

Specimens	*Abrasion Loss (%)	Specification (%)
F-Cubical	11.6	< 20
F-Blade	10.1	
F-Disk	6.9	

*average values were computed for 3 specimens

5.2.2. Second independent shape characteristic: angularity (roundness)

In the second study, rigid shape-controlled aggregates were designed to have the same form and surface texture, with varying state of angularity. Form factor equal to one ($F=1$) was selected as cubical-shaped aggregates ($F \approx 1$) have been commonly utilised in asphalt mixtures in many research studies (Masad et al. 2011; Kangkhatjitre and Kanitpong 2011; Hamzah et al. 2014; Jaya et al. 2014; Bessa et al. 2015; Tarmuzi et al. 2015; NCAT (Wilson) 2017). Three different rigid, shape-controlled aggregates were fabricated, namely cube, cylinder, and sphere. The shape properties of rigid, shape-controlled aggregates are summarised in Table 5.4. For materials with the same form factor (F), sphericity (Ψ) has a positive correlation with roundness (R). This phenomenon indicated that sphericity can be utilised to define the angularity state of materials with similar form factor (F), in which the closer sphericity value is to one the less angular and more rounded are the materials.

Table 5.4 Form properties of the designed aggregates

No	Shape	Form factor (F)	Sphericity (Ψ)	Roundness (R)
1	A-Cube	1.0	0.806	0.524
2	A-Cylinder	1.0	0.874	0.667
3	A-Sphere	1.0	1.0	1.0

Cube-shaped and cylinder-shaped aggregates were fabricated by metal-stamping aluminium plates/rods (AL 6061-t6511), while spherical-shaped aggregates were obtained by utilising off-the-shelf ball bearings (303 SST). The shape-controlled aggregates are shown in Figure 5.4. In this study, shape-controlled aggregates were fabricated in various sizes to be utilised as coarse aggregates (19.0 – 4.75mm). Meanwhile, the fine aggregates (4.75 – 0.075mm) in the PAM were granite. As shape-controlled coarse aggregates will not be damage and/or fracture during the laboratory evaluation tests, these metallic aggregates can be recovered to produce further PAM specimens.

Figure 5.4 Shape-controlled aggregates with shape: (a) cube; (b) cylinder; (c) sphere

PAM gradation G_f with 5% asphalt binder of PG-76 was utilised for three different rigid, shape-controlled aggregates while hydrated lime was used as a filler in the mixtures. Herein, gyratory compactor with gyration rate of 30 rpm, and gyration angle of 1.25° was utilised on the PAM specimens. The three mix designs, namely A-Cube, A-Cylinder, and A-Sphere, satisfied the requirements of drain-down and Cantabro tests, as presented in Tables 5.5., and 5.6. The influence of aggregate angularity on PAM was assessed according to the results of compacting effort, Marshall test, resilient modulus, and creep test.

Table 5.5 Drain-down test results at 5% binder content

Specimen	*Drain-down (%)	Specification (%)
A-Cube	0.15	< 0.30
A-Cylinder	0.18	
A-Sphere	0.23	

*average values were computed as 3 specimens

Table 5.6 Cantabro abrasion test results at 5% binder content

Specimen	*Abrasion Loss (%)	Specification (%)
A-Cube	7.8	< 20
A-Cylinder	11.3	
A-Sphere	14.2	

*average values as computed from 3 specimens

5.2.3. Third independent shape characteristic: surface texture

In the third study, coarse aggregates with varying degrees of surface texture were produced by treating steel slag in Los Angeles abrasion machine. Steel slag was selected as coarse aggregates (19.0 – 2.36mm) because of its rough surface, thereby it is possible to achieve different degrees of roughness by abrasion method. Moreover, steel slag has stronger mechanical properties than natural aggregates which alleviates the change of aggregate form and/or angularity during abrasion process. Meanwhile, granite was utilised as fine aggregates (2.36 – 0.075mm).

Los Angeles (LA) abrasion machine was utilised to produce different roughness level of steel slag with the number of rotations at 1000, 1500, and 2000 revolutions. For each batch of abrasion process, approximately five kg of steel slag was put inside the LA abrasion machine to undergo the treatment with the corresponding number of rotations. No steel ball was utilised during the abrasion process so as to mitigate the change of aggregate form and/or aggregate breakages.

The surface texture of steel slag for each treatment was measured by utilising MR200 surface roughness tester, as shown in Figure 5.5. MR200 surface roughness tester provides 28 measuring parameters that are compatible with four standards,

namely ISO, DIN, ANSI, JIS. In this study, two roughness parameters, namely mean roughness (R_a) and maximum height of profile (R_z), were utilised to define the state of aggregate surface texture, as explained in Section 2.5.5.1. The measurement range of MR200 surface roughness tester is 17.5mm, thereby the measurement of aggregate surface texture can only be done on steel slag with size range 19.0 – 13.2mm. The surface texture of ten steel slag samples for each treatment was measured by taking two readings from two sides of each piece to ensure valid measurement. The values in the average surface texture for each treatment are summarised in Table 5.7. The treatment results for 1000, 1500, and 2000-rotations were not significantly different, especially the mean roughness (R_a) values. Herein, 500-rotations and 2000-rotations treatments were selected for use in the final mix designs.

Figure 5.5 MR200 surface roughness tester

Table 5.7 Average values of roughness parameters

Number of rotations	R_a [μm]	R_z [μm]
0	75.9	224.4
500	56.4	176.4
1,000	45.3	150.8
1,500	41.7	142.0
2,000	40.1	141.1

Three mix designs of steel slag at three different degrees of surface texture were fabricated, namely original-state (SS-Original), after 500-rotations treatment (SS-500rotations), and after 2000-rotations treatment (SS-2000rotations). Gradation G_f was utilised and hydrated lime was selected as filler in the mixtures. PG-76 asphalt binder was utilised with 5.5% of binder content for the three mix designs. A

gyratory compaction machine, with gyration pressure of 600 kPa, gyration angle of 1.25°, and gyration rate of 30 rpm, and 50 numbers of gyratory counts was utilised to compact PAM specimens. The results of drain-down and Cantabro tests showed that the selected binder content was sufficient as it met the requirements, as presented in Table 5.8. The film thickness of the three mix designs was calculated to ensure the cohesivity of the mixtures was at similar level, as shown in Table 5.9

Table 5.8 Properties of PAM with 5.5% binder content

Treatment	Drain-down (%)	Cantabro loss (%)	Film thickness (µm)
SS-Original	0.002	7.8	11.97
SS-500rotations	0.011	6.5	12.25
SS-2000rotations	0.015	5.1	12.41

5.3. Laboratory measurements results

5.3.1. Volumetric properties

The volumetric properties of the three separate studies are given in Table 5.9. The results of the first study indicated that PAM with disk-shaped aggregates had significantly lower voids content. There are two possibilities that could lead to this observation. The first possibility is that the gradation suffered aggregate breakages during compaction. Flat and/or elongated particles tend to restrain the re-orientation during compaction (Vavrik et al. 2000; Gong et al. 2018). For hard aggregates, flat and/or elongated particles need higher compaction energy to achieve the same voids content with cubical-shaped aggregates. Jurong sedimentary rock is a more brittle aggregate than granite (see Table 3.1). The restraining of flat and/or elongated aggregates to re-orient may result in aggregate breakages thereby increasing the proportion of fine aggregates in the mixtures. Herein, Gyratory compactor was utilised instead of Marshall compactor to mitigate harsh external loading during compaction and hence minimise aggregate breakages. The second possibility is that flat and elongated particles are easier to re-orient during compaction when high binder content is used in the mixtures. Jaya et al. (2014) stated that generally flat and elongated particles are harder to compact, however flat and elongated particles are easier to re-orient than cubical-shaped particles when more lubricant (binder content > 4.5%) is present in dense-graded

mixtures. In this study, the second possibility is more likely to be the cause of cubical-shaped aggregates having the highest VTM since 5% binder content was utilised. The aggregates were well-lubricated, hence disk and blade-shaped aggregates were easier to re-orient than cubical-shaped aggregates. Herein, voids content is a significant property for PAM as it has close correlation with permeability. Therefore, it is important to ensure PAM has sufficient voids content to optimise its drainage performance. Utilising cubical-shaped aggregates in PAM can achieve the desired VTM and minimise aggregate breakages that would shift on aggregate gradation, especially for weak aggregates.

Table 5.9 Volumetric properties of PAMs

Type	VTM (%)	Standard Error (%)
First study: form (overall shape)		
F-Cubical	19.48	0.19
F-Blade	18.47	0.25
F-Disk	16.58	0.23
Second study: angularity		
A-Cube	17.36	0.26
A-Cylinder	17.74	0.31
A-Sphere	17.53	0.28
Third study: surface texture		
SS-Original	19.74	0.14
SS-500rotations	19.51	0.19
SS-2000rotations	19.42	0.17

*n = three specimens for each mix design

In the second study, the designed-VTM was set to 17% to avoid over-compacted specimens for sphere-shaped aggregates. Gyration pressure of 600 kPa was applied on PAM with cube-shaped and cylinder-shaped aggregates as recommended by Superpave mix design. Meanwhile, PAM with sphere-shaped aggregates was compacted by applying gyratory pressure of 100 kPa as sphere-shaped aggregates were significantly much easier to compact. PAM with sphere-shaped aggregates attained the design VTM with only one gyration count when applying the pressure

of 600 kPa. Herein, the gyration pressure was turned down for sphere-shaped aggregates to ensure PAM specimens were compacted evenly. Therein, the VTM of the three mixture designs were at about the same level.

Meanwhile, the results of the third study suggested that aggregate surface texture may not significantly influence the volumetric properties of PAM. The three PAMs with varying degrees of surface texture possessed similar density level.

5.3.2. Permeability test

The drainage function of PAM can be directly indicated by coefficient of permeability. The results for permeability test by utilising falling head apparatus are represented in Figure 5.6. For the first series of mixture designs, coefficient of permeability for PAM with cubical-shaped aggregates was the highest compared with others. These results are in line with the volumetric properties of the specimens, in which the higher the voids content of PAM the higher is its coefficient of permeability. Meanwhile, the results of the second series of mix designs showed that the coefficients of permeability of A-Sphere was notably lower despite having similar VTM with other mix designs. From the third study, the results exhibited that the three mix designs possessed similar coefficient of permeability. These results are understandable as the three mix designs generated similar density level of packing.

Beside voids content, voids connectivity is another factor that is related to coefficient of permeability. The ability of PAM to permeate water will be less if the mixtures have more tortuous voids distribution. Kozeny-Carmen's Equation (5.1) expresses the correlation between coefficient of permeability and tortuosity state of voids. The summaries of shape factor function of tortuosity (λ) for PAM with varying aggregate shapes are shown in Table 5.10.

$$k = (\lambda \cdot \beta) \left[\frac{n^3}{(1-n)^2} \right] \quad (5.1)$$

$$\beta = \left(\frac{\rho_w g}{\eta_w S_v^2} \right) \quad (5.2)$$

k = permeability of PAM, m/s;

λ = form factor function of tortuosity;
 β = empirical constant of permeable medium;
 n = porosity of permeable medium;
 ρ_w = density of water, kg/m³;
 g = acceleration due to gravity, m/s²;
 η_w = viscosity of water, kg/m.s;
 s_v = volumetric specific surface area of permeable medium.

Figure 5.6 Permeability test results of PAM with varying aggregate shape properties: (a) form; (b) angularity; (c) surface texture (average $\pm$ standard error)

Table 5.10 Tortuosity state of voids in PAM

Mixture design	Permeability (k)	λ
First study: form (shape)		
F-Cubical	0.0178	1.98 β
F-Blade	0.0146	1.55 β
F-Disk	0.0131	1.57 β
Second study: angularity (roundness)		
A-Cube	0.023	3.05 β
A-Cylinder	0.022	2.73 β
A-Sphere	0.018	2.26 β
Third study: surface texture		
SS-Original	0.023	1.84 β
SS-500rotations	0.022	2.01 β
SS-2000rotations	0.022	2.04 β

The results of the first study showed that PAM containing cubical-shaped aggregates had the highest form factor function of tortuosity (λ) compared with others, while cube-shaped aggregates was the highest in the second study. A higher λ means the mixtures have less tortuous voids as λ generally has a positive correlation with coefficient of permeability. Herein, cubical-shaped and more angular aggregates (cube-shaped) are recommended as they creates more even voids distribution in aggregate packing resulting in better voids connectivity. On the other hand, rougher aggregates (SS-Original) generated more tortuous voids connectivity.

5.3.3. Marshall test

Two different Marshall tests were performed, namely un-conditioned and moisture-conditioned, and the results are presented in Figures 5.7. It is observed that aggregate shape properties had greatly influenced the Marshall stability both in un-conditioned and moisture-conditioned. From the first experimental group, cubical-shaped aggregates had the best rupture resistance compared with other forms.

These results are understandable, as blade and disk aggregates have flaky particles that can more readily break down when the load is applied.

*n = three specimens for each mix design
(c)

Figure 5.7 Marshall stability values of PAM with varying aggregate shape properties: (a) form; (b) angularity; (c) surface texture (average $\pm$ standard error)

Meanwhile, the influence of aggregate angularity showed similar trends, in which the more angular the aggregate shape the higher the Marshall stability of PAM (Figure 5.7b.). The existence of edges or corners in aggregate shape strengthens aggregate interlocking in aggregate packing, thereby increasing the skeleton strength of asphalt mixtures. Herein, cube-shaped aggregates that possess more sharp edges generate more stable packing framework and result in PAM having the best resistance on fracture. The results also indicated that surface texture exhibited a positive influence on Marshall stability, for both un-conditioned and moisture-conditioned. Increasing the roughness of aggregate surface texture increased the un-conditioned and moisture-conditioned Marshall stabilities of PAM (Figure 5.7c.). Cui et al. (2018) suggested similar results in which rougher surface aggregates may improve the mechanical properties of asphalt mixtures, namely flexural strength, Marshall and dynamic stabilities.

Moisture susceptibility is a major concern in PAM, especially this type of HMA deliberately allows water to permeate the pavement surface. The retained Marshall stability (RMS) of each aggregate shape was calculated to evaluate PAM's resistance on the moisture susceptibility, and the results are summarised in Table 5.11. The first experimental group results indicated that PAM containing cubical-shaped aggregates is the most desirable as it had the highest RMS value, therefore the best resistance on moisture damage. Moisture damage is generally caused by the loss of adhesion between aggregates and asphalt binder due to the presence of water (Brown et al. 2001). Herein, PAM with cubical-shaped aggregates created more stable stone-on-stone aggregate interlocking resulting in stronger skeleton framework. Therefore, PAM with cubical-shaped aggregates experienced less moisture damage as compared with other aggregate forms despite the adhesion loss.

The results of second experimental groups suggested that the angularity of aggregates also had notable influence on the moisture susceptibility of PAM. PAM with more angular aggregates tend to have better resistance on moisture damage. The adhesion between asphalt mastic and aggregates deteriorates in the presence of water, thereby the responsibility to carry the external load will be borne mostly by

the aggregate framework. Cube-shaped aggregates which has more angular shape established better aggregate interlocking and stronger skeleton strength, hence PAM with cube-shaped aggregates had the best moisture susceptibility than PAM with cylinder and sphere-shaped aggregates.

Table 5.11 Retained Marshall Stability (RMS) of PAM

	un-conditioned (kN)	moisture-conditioned (kN)	RMS (%)
First study: form (shape)			
F-Cubical	11.19	8.37	74.81
F-Blade	6.77	4.58	67.64
F-Disk	5.76	3.55	61.55
Second study: angularity			
A-Cube	6.27	3.93	62.74
A-Cylinder	3.77	2.12	56.41
A-Sphere	3.23	1.46	45.11
Third study: surface texture			
SS-Original	7.3	5.4	74.3
SS-500rotations	6.8	5.1	75.0
SS-2000rotations	6.5	4.8	74.9

*average values were computed as 3 specimens

Meanwhile, The RMS results of the third experimental group exhibited that aggregate surface texture may not have additional influence on moisture susceptibility of PAM as the RMS results for the three treatments were similar. Feng et al. (2015) showed that aggregate mineralogy exert a greater influence on the interfacial strength between aggregates and asphalt binder than aggregate surface texture in the presence of water. In this study, the three mix designs contained the same type of aggregate mineralogy, thereby the three mix designs suffered similar deterioration level of aggregate-asphalt binder bond. Nevertheless, the influence of rougher aggregates on the improvement of moisture-conditioned Marshall stability is a desirable characteristic that may increase the service life of PAM.

5.3.4. Resilient modulus by indirect tensile test

Resilient modulus represents the stiffness of asphalt mixtures. It also represents the ability of asphalt mixtures to recover on deformation upon receiving external loading/unloading. Herein, two readings were taken at 0° and 90° for each specimen. Then, the orthogonal average resilient modulus was calculated. The resilient moduli of PAM are shown in Figure 5.8. In the first study, PAM with cubical-shaped aggregates (F-Cubical) had the highest resilient modulus. These results indicated that the skeleton framework created by cubical shaped aggregates is more solid and stronger compared with other shapes.

The second experimental groups indicated that PAM with more angular aggregates (lower roundness) possessed a higher resilient modulus. As the three mixtures contained the same amount of binder and filler, the change of resilient modulus would mostly be caused by the difference in the aggregate packing structure. Herein, cube-shaped aggregates which had the most angular form created the stiffest aggregate framework and resulted in the PAM with cube-shaped aggregates having the highest resilient modulus (A-Cube) compared with PAM containing cylinder and sphere-shaped aggregates. PAM with rougher surface texture also exhibited better resilient modulus, and the results indicated that PAM with rougher aggregates had better recoverability from strain and/or deformation under cyclic loading.

5.3.5. Creep test

The result of creep test was represented by the total permanent strain of specimens after under-going 40,000 cycles of repeated load, as shown in Figure 5.9. A higher value of total permanent strain indicates that the specimens suffered higher permanent deformation. For the first experimental group on form, F-Disk had the highest total permanent strain with the same amount of loading. This shows that particles of disk-shaped aggregates are easier to be crushed and compacted. The second experimental group on angularity showed that PAM's resistance on deformation increased when more angular aggregates (lower roundness) were utilised. Meanwhile, the third experimental group on surface texture indicated that utilising rougher aggregates alleviated the permanent strain (deformation) of PAM.

As PAM with rougher aggregates had better recoverability (higher resilient modulus), it is understandable that the total permanent strain of PAM with rougher aggregates was lower. These results are in line with the notion that aggregate with rougher surface texture improves the interface strength between aggregate and asphalt binder, thereby improving the mechanical properties of asphalt mixtures (Feng et al. 2015).

*n = three specimens for each mix design

(c)

Figure 5.8 Resilient modulus results of PAM with varying aggregate shape properties; (a) form; (b) angularity; (c) surface texture (average $\pm$ standard error)

loading period : 0.5 ± 0.05 seconds;
pulse repetition period: 2.0 ± 0.05 seconds

(c)

Figure 5.9 Creep test results of PAM with varying aggregate shape properties: (a) form; (b) angularity; (c) surface texture

5.4. DEM simulations

The PAM model was generated by following the procedures described in Chapter 3. Clump template was utilised to simulate steel slag in PAM model. Herein, three parameters were analysed on the packing structure of PAM, namely (1) coordination number, (2) proportion of effective particles (PEP), and (3) average contact force (ACF).

5.4.1. Clumps

Several clump templates were generated to model the realistic shape of aggregates. Clump templates were utilised to simulate coarse aggregates (19.0 – 2.36mm) in PAM model. Meanwhile, balls with diameter 1.6mm were used to represent the fine aggregates. The details of clump templates for each mixture design group are explained in this section.

(a) First independent characteristic: form

Three clump templates which possess similar shape properties with the actual aggregates were generated, namely cubical, blade, and disk, as shown in Figure 5.10. The shape properties of the clumps are presented in Table 5.12. Meanwhile, the mechanical properties of clump templates were assigned according to the properties of sedimentary rocks, namely elastic modulus of 30 GPa, coefficient of friction of 0.40, and Poisson ratio of 0.2.

Figure 5.10 Clump templates of aggregates model with form: (a) cubical; (b) blade; (c) disk

Table 5.12 Shape properties of the clump templates

No	Clump	Form factor (F)	Sphericity (Ψ)	Roundness (R)
1	Cubical	0.920	0.796	0.302
2	Blade	1.15	0.518	0.289
3	Disk	0.798	0.673	0.323

(b) Second independent characteristic: angularity

In the second study, three clumps templates were generated, namely cube, cylinder, and sphere, as illustrated in Figure 5.11. The clump templates possess the same shape properties with the rigid shape-controlled aggregates, as shown in the earlier Table 5.4. The properties of aluminium bar (AL 6061-t6511) were assigned on the clump templates of cube and cylinder, namely elastic modulus of 69 GPa, coefficient of friction of 0.3, and Poisson ratio of 0.33. Meanwhile, the properties ball bearing (303 SST) were assigned on the clump template of sphere, namely elastic modulus of 198 GPa, coefficient of friction of 0.3, and Poisson ratio of 0.25.

Figure 5.11 Clump templates of aggregate model with shape: (a) cube; (b) cylinder; (c) sphere

(c) Third independent characteristic: surface texture

A clump template that has similar shape of steel slag was generated in the third study, as shown in Figures 5.12. The shape properties of the clumps were based on the average measurement of ten pieces of steel slag, and the shape properties of the clump are summarised in Table 5.13. The properties of clump template were assigned according to the properties of steel slag, namely elastic modulus of 72.5

GPa, and Poisson ratio of 0.25. Meanwhile, the coefficients of friction were 0.54, 0.50, and 0.48 for SS-Original, SS-500rotations, and SS-2000rotations, respectively.

Figure 5.12 Designed clump

Table 5.13 Average shape properties of clump template

Parameters	Value
Form Factor (F)	0.91
Sphericity (Ψ)	0.86
Roundness (R)	0.45

5.4.2. Validation of DEM model

DEM model was utilised to assess the packing condition of PAM. The results of laboratory measurements and DEM simulations were compared to evaluate the feasibility of DEM model to simulate PAM. The validation of DEM model was evaluated according two aspects, namely (a) voids content, (b) total permanent strain.

(a) voids content

Comparison of the results of voids content of PAM showed that the average differences between DEM model and laboratory measurements were within $\pm 1\%$ error value (see Figure B2.1 in Appendix B2). DEM model was deemed to reach the same density level with PAM specimens, therefore DEM models are appropriate to represent the aggregate configurations in PAM.

(a) total permanent strain

Total permanent strains obtained from creep test were compared with DEM simulations, and the results showed that the strain curves of PAM model followed

similar trends with laboratory measurements, with difference within $\pm 5\%$ error value (see Figure B2.2. in Appendix B2). Despite the simplification and limitation to build the DEM models, the simulation results are acceptable to illustrate the visco-elastic behaviour of PAM in terms of load distribution and load bearing.

5.4.3. DEM simulation results

Three parameters, namely coordination number, proportion of effective particles (PEP), and average contact force of particles (ACF) were obtained to evaluate the quality of packing structure of PAM.

(a) First independent characteristic: form

The coordination number for PAM with each aggregate shape was measured and the results are presented in Figure 5.13. Herein, cubical-shaped aggregates generated more particle contacts than other aggregate shapes as PAM with cubical-shaped aggregates had the highest coordination number. From DEM simulations, the distribution of normal contact force for each PAM model was acquired and the results are shown in Figure 5.14. The thickness of the line represents the magnitude of normal force that is transmitted between a pair of particles. Herein, the force chain of disk-shaped aggregates was notably less dense than the other two.

Figure 5.13 Coordination number of PAM with varying aggregate shape (form)

Figure 5.14. Normal contact force of PAM models containing (a) cubical; (b) blade, (c) disk

From normal contact force data, PEP and ACF for each PAM model were calculated and the results are summarised in Table 5.14. PAM with cubical-shaped aggregates had the highest PEP value which indicated that packing structure established by cubical-shaped aggregates had better loading distribution. Meanwhile, PAM with disk-shaped aggregates possessed the lowest PEP value compared with the other shapes. Therein, the contact force distribution of PAM with disk-shaped aggregates was the least dense as many ineffective particles are only space filler.

Table 5.14 Simulation parameters of PAM models

Aggregate form	PEP [%]	ACF [N]		
		19.0 – 6.3 mm	19.0 – 4.75 mm	19.0 – 2.36 mm
Cubical	84.8	216.4	91.2	54.1
Blade	73.8	213.8	102.6	76.7
Disk	67.2	209.9	113.1	91.8

The next parameter is ACF. It can be seen that PAM with cubical-shaped aggregates had the lowest ACF of the mixtures ($ACF_{19.0-2.36mm}$). The ACF values of cubical-shaped aggregates dropped significantly when finer fractions of coarse aggregates (size 6.3 – 2.36mm) were added. These results indicated the number of effective particles in 6.3 – 2.36mm size fractions of cubical-shaped aggregates were more than the other aggregate shapes, resulting in the skeleton framework experiencing less stress when external loading was applied.

(b) Second independent characteristic: angularity

The coordination number results of the second group are presented in Figure 5.15. PAM with cube-shaped aggregates had the highest coordination number, thereby its aggregate packing structure was established by more particle contacts. From PAM model, the distribution of normal contact force was derived and the results are presented in Figure 5.16. The force chain of sphere-shaped aggregates notably had fewer thin force lines than others. These results indicated that a lot of ineffective finer particles existed in the packing structure of sphere-shaped aggregates as low forces are generally carried by finer fractions.

Meanwhile, the results of PEP and ACF for each PAM model are summarised in Table 5.15. The results exhibited that PAM with less angular aggregates tended to have lower PEP value in the mixtures. Herein, cube-shaped aggregates, which had the most angular shape, created aggregate skeleton framework with more effective particles. The last packing parameter to be observed is ACF. It can be seen in Table 5.15 that PAM with less angular aggregates had higher ACF values while PAM with sphere-shaped aggregates experienced the highest stress.

Figure 5.15 Coordination number of PAM with varying degree of angularity

Figure 5.16 Normal contact force of PAM models containing (a) cube; (b) cylinder, (c) sphere

Table 5.15 Simulation parameters of PAM models

Aggregate angularity	PEP [%]	ACF [N]		
		19.0 – 6.3 mm	19.0 – 4.75 mm	19.0 – 2.36 mm
Cube	80.6	194.8	86.3	60.2
Cylinder	72.2	201.3	104.8	87.1
Sphere	60.1	182.1	117.6	97.2

(c) Third independent characteristic: surface texture

The coordination number for PAM in the third study was obtained and the results are shown in Figure 5.17. Herein, SS-Original generated packing structure with more particle contacts as it had the highest coordination number. Meanwhile, the distribution of normal contact force for each mix design was obtained and the results are presented in Figure 5.18.

Figure 5.17 Coordination number of PAM models

Figure 5.18 Normal contact force of PAM models containing (a) SS-Original; (b) SS-500rotations, (c) SS-2000rotations

The results of PEP and ACF are summarised in Table 5.16. The PEP values of SS-2000rotations were the lowest, while PEP values of SS-Original were the highest. The results indicated that more particles participated on load transmission throughout the aggregate packing for rougher aggregates when external loading was applied. The ACF value of the mixtures was observed and the results showed that ACF value of PAM ($ACF_{19.0 - 6.3 \text{ mm}}$) increased when smoother aggregates were utilised in PAM.

Table 5.16 Simulation parameters of PAM models

Treatments	$R_a [\mu\text{m}]$	PEP [%]	$ACF_{19.0 - 2.36 \text{ mm}} [\text{N}]$
SS-original	75.9	85.5	53.3
SS-500rotations	56.4	82.8	57.5
SS-2000rotations	40.1	81.5	60.4

5.5. Discussion

In this section, further discussions about the influence of aggregate shape properties are presented. The relationship between laboratory measurements and DEM simulations are also explained.

5.5.1. Statistical Analysis

Analysis of variance (ANOVA) with significance level of 0.05 ($\alpha = 0.05$) was adapted to statistically evaluate the influence of aggregate shape properties on the performance of PAM. The linear model for the statistical analysis is given in Equation (5.1).

$$y_{ij} = \mu_i + \varepsilon_{ij} \quad (5.1)$$

y_{ij} = i^{th} observation of response variable

μ = mean value of responses;

ε_{ij} = error term.

Similarly, the null hypothesis (H_0) was that the mean value of the response variable (i.e. VTM, coefficient of permeability, Marshall stability, coordination number, PEP) remained the same despite the specific combination of two factors

(i.e. proportion of coarse and fine aggregates). The confidence level of 95% was selected. Herein, H_0 should be accepted if resultant F -statistic (F) value was no greater than a threshold value of F -critical (F_c), which is corresponding to a P value at 0.05. In this research, the Levene's and Shapiro-Wilk tests were conducted before performing ANOVA to ensure the homogeneity and normality of variance of the data. As the p -values of observed Levene's and Shapiro-Wilk statistics were more than 0.05, the null hypothesis was rejected as there was no significant difference and the data were deemed to satisfy the homogeneity and normality requirements.

The results of the first, second, and third studies are presented in Tables 5.17., 5.18, and 5.19, respectively. The results showed that generally there is a notable influence of aggregate shape properties on the performance and packing structure of PAM at 0.05 significance on both laboratory measurements and DEM simulations. For the first study, aggregate form had the greatest influence on the mechanical properties of PAM, particularly on the resistance of permanent strain (deformation) according to the P -value. While in DEM simulation results, aggregate form had the biggest influence on ACF value of packing structures.

Table 5.17 Summary of analysis of variance (ANOVA) for the first study
(aggregate form)

Parameters	df	F-value	P-value	error (MS)
Laboratory measurements				
VTM	2	9.5	0.014	0.65
Coefficient of permeability	2	22.33	0.002	0.44
Marshall stability	2	44.88	2.5×10^{-4}	0.18
Total permanent strain	2	97.06	3×10^{-5}	0.10
Resilient modulus	2	31.64	6.5×10^{-4}	0.07
DEM simulations				
Coordination number	2	426.94	2×10^{-6}	0.04
PEP	2	1981.15	6.3×10^{-10}	0.00
ACF	2	1832.66	8.1×10^{-9}	0.00

*df=degree of freedom, F = F -static value, and MS=mean square

From the second and third groups, The PAM specimens with varying angularity levels and degrees of surface texture possessed the same level of density, thereby it is understandable that the voids content and permeability of all mixture designs were similar. Aggregate angularity and surface texture had the greatest effect on the resistance of permanent strain (deformation) of PAM according to the P-value. Meanwhile, aggregate surface texture showed a positive correlation on resilient modulus, as illustrated in Figure 5.8(c). even though it did not exert influence at 0.05 significance. For packing parameters, aggregate angularity had the biggest influence on ACF value, while coordination number was greatly affected by aggregate surface texture. In short, aggregate form exerted the greatest influence on the overall performance of PAM according to the P-values ((P-value_{form} < P-value_{angularity} < P-value_{texture}). Herein, utilising a recommended aggregate form in PAM is the most efficient solution to obtain optimum properties of PAM.

Table 5.18 Summary of analysis of variance (ANOVA) for the second study
(aggregate angularity)

Parameters	df	F-value	P-value	error (MS)
Laboratory measurements				
VTM	2	2.33	0.155	0.78
Coefficient of permeability	2	4.45	0.065	0.71
Marshall stability	2	9.97	0.002	0.67
Total permanent strain	2	34.2	6.8×10^{-4}	0.21
Resilient modulus	2	26.27	0.001	0.24
DEM simulations				
Coordination number	2	1872.5	4.1×10^{-9}	0.03
PEP	2	1601.1	5.7×10^{-9}	0.00
ACF	2	1457.3	8.6×10^{-9}	0.00

*df=degree of freedom, F = F-static value, and MS=mean square

Table 5.19 Summary of analysis of variance (ANOVA) for the third study
(aggregate surface texture)

Parameters	df	F-value	P-value	Significant at 5% (Y/N)?
Laboratory measurements				
VTM	2	1.92	0.283	0.670
Coefficient of permeability	2	1.73	0.328	0.740
Marshall stability	2	7.32	0.006	0.450
Total permanent strain	2	30.21	9.1×10^{-4}	0.090
Resilient modulus	2	1.72	0.257	0.640
DEM simulations				
Coordination number	2	732.4	7.1×10^{-8}	0.040
PEP	2	254.2	9.3×10^{-8}	0.000
ACF	2	332.1	9.8×10^{-8}	0.000

*df=degree of freedom, F = F -static value, and MS=mean square

5.5.2. Correlation between aggregate shape properties and packing structure of PAM

Herein, four parameters were utilised to define the aggregate shape properties, namely shape form factor, sphericity, roundness, and mean roughness (R_a). Form factor and sphericity are parameters to indicate the form (overall shape) of aggregates, while roundness refers to the degree of angularity. Correlation analysis was done to derive the correlation between aggregate shape properties and packing structure of PAM.

For the first study on form, surface texture of aggregates was not assessed as all aggregate shapes had the same degree of surface texture. Jurong sedimentary rocks generally had a smoother surface texture compared with granite. Likewise, the three aggregate shapes had similar degree of angularity, in which the roundness values of the three aggregate shapes were around 0.3 (as shown in Table 5.1.). Sphericity is the first parameter being examined to observe the influence of aggregate form on packing structure of PAM. Sphericity refers to the degree of closeness in aggregate form (overall shape) with a perfect sphere. The correlation between sphericity and aggregate packing parameters is illustrated in Figure 5.19. The results showed that sphericity does not have a clear correlation with packing

structure of PAM. This is because sphericity does not have a definite range to define each shape, as illustrated in the earlier Figure 2.2. Herein, two objects with the same form factor (F) may have different sphericity values, or vice versa. For example, tetrahedron has sphericity equal to 0.671, and this value is similar with the sphericity of blade or disk. However, tetrahedron is classified as cubical ($p > 0.6$; $q > 0.556$; $F \approx 1$) according to BS 812-105.1 and BS 812-105.2 standards. The obscurity of sphericity range values for each aggregate shape means that the correlation between sphericity of aggregates and the performance of PAM cannot be derived.

Figure 5.19 Correlation between sphericity and packing parameters

The second parameter to indicate the overall form of aggregates is form factor (F). Form factor is defined as the ratio between flatness ratio (p) and elongation ratio (q). Form factor equal to 1 refers to a perfect sphere or cube, form factor less than 1 refers to flaky particles, while form factor greater than 1 for elongated particles. The correlation between form factor and packing parameters is presented in Figure 5.20. For aggregates with similar state of angularity and surface texture, form factor of the aggregates has a polynomial correlation with aggregate packing parameters. Form factor value close to one is the most desirable packing condition, as the aggregate packing has a high proportion of effective particles (PEP) and

carries a low average contact force (ACF). These results suggested that cubical-shaped aggregates ($F \approx 1$) establish more stable skeleton framework and better aggregate interlocking compared with flat and/or elongated particles. The results of laboratory measurements had a good agreement with the findings, in which PAM with cubical-shaped aggregates had overall the best mechanical properties than the others.

The correlation between aggregate angularity (roundness) and packing parameters was obtained from the second study and the results are presented in Figure 5.21. The results showed that aggregates with lower roundness (more angular) generated more stable packing structure of PAM, in which it had higher PEP and lower ACF. A low roundness value is desirable for aggregates as it refers to well angulated aggregates. Aggregate angularity has an important role in stone-on-stone interlocking between aggregates. The existence of aggregate edges or corners hinders the movement of one particle upon the other, therefore increasing the stability of aggregate interlocking. Some studies stated similar findings in which aggregate angularity has positive influence on mechanical properties of asphalt mixtures (Yeggoni et al. 2014; Tarmuzi et al. 2015; Li et al. 2019).

Figure 5.20 Correlation between form factor and packing parameters

Figure 5.21 Correlation between packing parameters with aggregate roundness

In the third study, PAM model containing coarse aggregates with surface level equal to granite ($R_a = 3.7\mu\text{m}$) was generated in PFC3D to simulate the packing structure of PAM in much lower range of aggregate surface texture. The correlation of aggregate surface texture and coordination number (C_n) is presented in Figure 5.22. Indeed, the coordination number of PAM containing rougher aggregates was higher (as shown in Figure 5.22), indicating rough particles can establish more contacts on the aggregate packing of PAM. Meanwhile, the correlation between aggregate surface texture and packing parameters are shown in Figure 5.23. The results indicated that increasing the roughness of aggregate surface increased the stability of aggregate packing structure of PAM, in which the packing structure possessed higher PEP and lower ACF.

Figure 5.22 Correlation between aggregate surface texture and C_n

Figure 5.23 Correlation between aggregate surface texture and packing parameters

5.5.3. Influence of aggregate shape properties on the properties of PAM

From DEM simulations and experiment results, aggregate shape characteristics, namely form, angularity, and surface texture, showed significant influence on the performance of PAM. The shape properties of coarse aggregates affect the configuration of aggregate packing, especially in PAM where the skeleton framework is mainly established by coarse aggregates. The final aggregate configuration after the compaction will determine the performance of PAM. Aggregate shape properties influence the performance of PAM in three ways.

Firstly, aggregate form affects the density of aggregate packing. It has been widely acknowledged that various aggregate forms require different compacting effort to achieve the same level of density, thereby influencing the workability of the mixtures. The workability of mixtures refers to the ability of the mixtures to be compacted or the ease at which the mixtures can be constructed. Flat and/or elongated particles are generally harder to compact as these particles resist to re-orientate during compaction process. Herein, flat and/or elongated particles require higher compacting effort than cubical-shaped particles to acquire the designed density. However, the aggregate packing of PAM containing flat and/or elongated particles can reach much higher density level (lower VTM) than cubical-shaped aggregates when the aggregates are well lubricated. It was found that flat and/or elongated particles have better workability when asphalt binder content is more

than 4.5% in dense-graded asphalt mixtures (Jaya et al. 2014). This value would be lower in PAM as PAM gradation contains much lower proportion of fine aggregates. The selection of aggregate shape is particularly important in PAM as high VTM is required to maintain its drainage function. Herein, the densest packing may not necessarily be desirable for the aggregate packing of PAM.

Furthermore, angular and rougher aggregates are also generally less workable and require higher compacting effort to achieve the designed VTM. Herein, the compaction effort was obtained from second study by multiplying gyration pressure with gyration count. The correlation between the average of compaction effort and roundness parameter of PAM is illustrated in Figure 5.24. The results exhibited that aggregate angularity has a clear influence on the workability of PAM with $R^2 = 0.956$. PAM with less angular aggregates (higher roundness) requires less compaction effort to obtain the same density level of the mixtures. The lack of sharp edges and corners on aggregates results in less interlocking between aggregate particles. Herein, less angular aggregates do not have much resistance to re-orientate or shift when the compacting load is applied. Several studies indicated similar results in which mixtures containing angular aggregates require a higher compaction effort to obtain the design density, thereby mixtures with angular aggregates possess higher voids content than smooth-edged aggregates with the same applied compaction effort (Guddimetla et al. 2004; Tarmuzi et al. 2015).

Figure 5.24 Correlation between compaction effort with aggregate angularity

Secondly, aggregate shape properties influence the stability of aggregate packing. The shape properties of the coarse aggregates determine the aggregate configuration on the packing structure of PAM. In aggregate packing, aggregates have roles on load bearing/distribution and/or space filling. The stability of the aggregate configuration depends on how many effective particles there are in actually contributing to load bearing in the mixtures. Higher proportion of effective particles increases the stability of packing structure of PAM as the skeleton framework suffers less stress and has higher load bearing capacity.

The packing parameters from DEM model are important parameters that cannot be easily obtained from laboratory measurements. Herein, PAM with high coordination number is more desirable as it indicates that more particles may contribute on load distribution when external loading is applied. It should be noted that not all contacts participate on load transmission; however, mixtures with a higher coordination number have a higher likelihood to possess more effective contacts that assist the load distribution process. Thereby, proportion of effective particles (PEP) and average contact force (ACF) parameters are more appropriate parameters to indicate the stability state of the packing as both directly show the quality of load distribution on the aggregate skeleton framework.

Cubical-shaped aggregates tend to have a wider surface area than flat and/or elongated aggregates with the same diameter size. The wider surface area increases the chance for particles to have more contacts with each other in the mixtures, thereby the mixtures will have a higher coordination number. Herein, cubical-shaped aggregates have the widest surface area ($SA_{\text{cubical}} > SA_{\text{blade}} > SA_{\text{disk}}$) and results in the packing structure of PAM that contains cubical-shaped aggregates having the highest coordination number ($Cn_{\text{cubical}} > Cn_{\text{blade}} > Cn_{\text{disk}}$). Meanwhile, angular (low roundness) and/or rougher aggregates possess a wider surface area than less angular (high roundness) and/or smoother aggregates ($SA_{\text{cube}} > SA_{\text{cylinder}} > SA_{\text{sphere}}$, and $SA_{\text{SS-Original}} > SA_{\text{SS-500rotations}} > SA_{\text{SS-2000rotations}}$), thereby the packing structure of PAM with angular and/or rougher aggregates can generate higher coordination number than less angular and/or smoother aggregates ($Cn_{\text{cube}} > Cn_{\text{cylinder}} > Cn_{\text{sphere}}$; and $Cn_{\text{SS-Original}} > Cn_{\text{SS-500rotations}} > Cn_{\text{SS-2000rotations}}$). The

existence of corners or edges on aggregates and the irregularity on the aggregate surface texture also increase the quality of particle contact by providing a better interlocking mechanism in aggregate packing. The aggregate interlocking of angular aggregates has higher bond strength than rounded particles (Colley and Humphrey 1967; Souza and Kim 2009). Herein, the strong interlocking on angular and/or rougher aggregates will ensure the load is transmitted from one particle to the other by the contact between aggregate particles.

Particles that only possess ineffective contacts do not participate in carrying the load, thereby these particles will only have a role to fill the space in the aggregate packing. Herein, skeleton framework of PAM with cubical-shaped, angular, and/or rough aggregates is created with higher proportion of effective particles (PEP) than flat and/ or elongated, rounded, smoother aggregates, as shown in Figures 5.20, 5.21, and 5.23. When loading is applied, the load will be distributed more evenly throughout the skeleton framework as more particles contribute on load distribution in PAM with cubical-shaped, angular, and/or rough aggregates. Therein, the packing structure of PAM with cubical-shaped, angular, and/or rough aggregates carries a lower average contact force (ACF) than smoother aggregates as observed in Figures 5.20, 5.21, and 5.23. ($ACF_{\text{cubical}} > ACF_{\text{blade}} > ACF_{\text{disk}}$; $ACF_{\text{cube}} < ACF_{\text{cylinder}} < ACF_{\text{sphere}}$; and $ACF_{\text{SS-Original}} < ACF_{\text{SS-500rotations}} < ACF_{\text{SS-2000rotations}}$). Better load distribution and lower average contact force are desirable for the packing structure of PAM, as these conditions indicate that PAM suffers less stress and thereby the packing structure of PAM will have better durability on carrying the load and resistance on deformation. The packing condition is also a major factor that will determine the overall mechanical performance of PAM. Herein, utilising cubical-shaped, angular, and/or rough aggregates are recommended to obtain an optimum packing structure of PAM.

Thirdly, aggregate packing structure determines the mechanical properties of PAM. The resultant properties of PAM greatly depend on the skeleton strength of aggregate packing. The skeleton framework which is established by higher number of effective particles distributes the load more efficiently, thereby resulting in the aggregate packing of the mixtures having a higher bearing capacity.

The results of laboratory measurements of the first study showed that PAM containing cubical-shaped aggregates has the most desirable mechanical properties, such as high Marshall stability and resilient modulus, and lower permanent strain. Marshall stability indicates the maximum load that PAM can carry until fracture, while resilient modulus measures the maximum load of PAM to achieve a target peak strain. Both properties define the strength and load bearing capacity of the asphalt mixtures. Herein, cubical-shaped aggregates create aggregate framework with the most efficient load distribution and results in the PAM containing cubical-shaped aggregates having the highest load bearing capacity. Moreover, PAM with cubical-shaped aggregates suffers less permanent strain as its packing structure experiences less stress (low ACF).

In the second study, the shape-controlled aggregates possess particularly different properties to natural aggregates, thereby the properties of PAM containing granite were obtained as comparison and the results are summarised in Table 5.20. Granite generally has weaker mechanical properties and lower ductility than the metallic aggregates. Notwithstanding, the properties of aggregates, such as ductility, would not be a substantive element for the assessed properties range of PAM as several laboratory measurements are non-destructive tests (such as resilient modulus by IDT). Meanwhile, granite possesses an irregular shape with flakiness index (FI) of 12.3% and elongation index (EI) of 20.1%. The findings showed that PAM containing granite has generally better performance than PAM containing the harder cylinder- and sphere-shaped metallic aggregates, as shown in Table 5.18. PAM containing granite has higher Marshall stability and resilient modulus, and lower permanent strain even though granite has much lower toughness and strength compared to the metallic aggregates. Herein, the shape properties of granite, which is irregular, angular, and rougher surface, are more ideal to establish a more stable aggregate packing than cylinder- and sphere-shaped metallic aggregates. Flat and elongated particles also exist in the granite, thereby the packing structure of fully cube-shaped metallic aggregate results in more desirable results than granite. Herein, the results indicate that aggregate shape properties have a greater influence on the properties of PAM than aggregate mineralogy. Similar concept about this behaviour of HMA has been reported, in which aggregates with similar shape

properties but having different mechanical properties may result in similar mixture performance, indicating that aggregate mineralogy only has a minor role in most mechanical properties of HMA (Kangkhatjitre and Kanitpong 2011; FHWA 1994; Bessa et al. 2014).

Table 5.20 Average values of mechanical properties of PAM

	Marshall Stability (kN)	Resilient Modulus (MPa)	Permanent Strain (%)
Cube	5.67	2577.50	0.38
Cylinder	3.77	1370.33	0.82
Sphere	3.23	817.11	1.32
Granite (irregular)	6.33	1709.50	0.75

Meanwhile, the results of Marshall stability and resilient modulus exhibited that less angular aggregates (higher roundness) have lower Marshall stability and resilient modulus. As angular aggregates produce more stable packing structure and experience lower ACF, the durability of skeleton framework of angular aggregates are greater than rounded particles. Hereby, PAM with more angular aggregates has an ability to carry higher maximum load than PAM with rounded aggregates. Several studies have reported similar findings, in which increasing the proportion of angular aggregates in the mixtures improves the stability and resilient modulus of asphalt mixtures (Yeggoni et al. 2014; Tarmuzi et al. 2015). For creep test results, PAM with angular aggregates suffers less strain than rounded aggregates despite experiencing the same external loading. Herein, utilising angular aggregates in PAM increases the deformation resistance of the mixtures. Other studies suggested similar notion in which angularity of coarse aggregate greatly influences the creep behaviour and rutting performance of asphalt mixtures (Huang et al. 2009; Yeggoni et al. 2014).

The experimental results of the third study indicated that PAM with rougher aggregates possesses more desirable mechanical properties, such as higher Marshall stability and resilient modulus, and better resistance on deformation (lower total permanent strain). Several studies have reported similar notion in which utilising rougher aggregates in asphalt mixtures may increase the mechanical

performance of the mixtures, namely flexural strength, Marshall and dynamic stabilities, and creep resistance (Feng et al. 2015; Cui et al. 2018). The roughness of aggregate surface also mitigates the slippage between aggregate particles as rougher aggregates possess a higher coefficient of friction. When external loading is applied, the particle contacts generate dynamic friction force to resist the movement of particles. The correlation between coefficient of friction and friction force can be expressed in Equation (5.2.)

$$F_k = \mu_k F_N \quad (5.2),$$

where, F_k is the friction force between two contact surfaces, μ_k refers to the coefficient of kinetic friction, and F_N is the normal force.

Rougher aggregates that have a higher coefficient of friction produce a higher friction force than smooth aggregates. Herein, the particles of rougher aggregates are harder to slide over each other when PAM experiences external loading. Thereof, PAM with rougher aggregates will have better resistance on the permanent deformation as the deformation of the mixtures is mainly caused by aggregate breakages rather than the combination of aggregate movement and aggregate breakages. Indeed, the laboratory measurement results showed that utilising rougher aggregates in PAM decreases the total permanent strain of PAM, thereby improving PAM resistance on deformation. The results of this study also suggested that utilising steel slag as aggregates generates satisfactory mechanical properties of PAM. Similar notion has been reported that utilising steel slag aggregates satisfies the requirement of asphalt mixtures in Singapore and enhances the mechanical properties of asphalt mixtures due to its higher affinity to asphalt (low stripping), higher angularity and sphericity (low rutting and shoving, high stability), better mechanical strengths and neutralisation ability (good durability) (Ramaswamy et al. 1986; Hong et al. 2015). Thereof, steel slag generated in Singapore has been 100% recycled into aggregates used in asphalt mixtures for wearing course of the road since 1994 (Sustainable Construction 2008).

Chapter 6 Conclusions, Contributions and Future Directions

6.1. Summary of findings

The main objective of this research is to understand the aggregate packing structure of PAM and the main factors influencing it. Herein, there are four main issues covered in this research, namely the roles of coarse and fine aggregates in packing structure of PAM, the influence of aggregate shape properties (form, angularity, and surface texture) on packing structure of PAM, and feasibility of discrete element method (DEM) simulation to assess packing structure of PAM. The key findings of this research are concluded as follows.

1. The roles of coarse aggregates on the packing structure of PAM

The results indicated that generally coarse aggregates can be classified into two groups, as follows:

(a) Coarser fractions of coarse aggregates (19.0 – 6.3mm)

Coarse fractions of coarse aggregates provide the main structure that determines the skeleton strength of packing structure. Herein, coarser fractions of coarse aggregates carry major load distribution throughout the aggregate packing structure. The primary size range of main structure that is interchangeable within this size range depends on which size fractions possess the highest proportion.

(b) Finer fractions of coarse aggregates (6.3 – 4.75mm)

Finer fractions of coarse aggregates generally have a function to assist coarser fractions of coarse aggregates on load bearing/transmission. The effective particles of these fractions assist to carry the forces and transmit it throughout the aggregate framework, while the rest only has the function to fill the voids by the coarser fractions.

2. The roles of fine aggregates on the packing structure of PAM

Fine aggregates (4.75 – 0.075mm) generally have a function as space filler in the aggregate packing structure. In PAM, the proportion of finer fractions of fine aggregates (< 2.36mm) is less than 10%, thereby the existence of finer fraction of fine aggregates is not critical towards establishment of packing structure of PAM. Moreover, the particles of finer fraction of fine aggregates are more likely to interact with asphalt binder to form asphalt mastic rather than contributing on aggregate packing structure. Meanwhile, the roles of coarser fractions of fine aggregates (4.75 – 2.36mm) are as follows.

- (a) Coarser fractions of fine aggregates have a function to fill the voids in aggregate packing. The coarser fractions of fine aggregates possess a close correlation with the density of the packing, in which increasing the proportion of 4.75 – 2.36mm fractions decreases the VTM of PAM.
- (b) Coarser fractions of fine aggregates contribute on transmitting the minor forces in aggregate packing structure. Introducing a higher proportion of 4.75 – 2.36mm fractions may decrease the overall stress bore by packing structure of PAM
- (c) An excessive proportion of coarser fractions of fine aggregates has potential to degrade the skeleton strength of PAM. Herein, the proportion of 4.75 – 2.36mm fractions is recommended to be 10 – 22% according to packing parameters of DEM simulation, and 10 – 20% according to gradation-based framework.

3. The influence of aggregate shape properties on packing structure of PAM

Three series of studies were performed separately to evaluate the influence of three independent shape characteristics, namely form (overall shape), angularity (roundness), and surface texture. The results indicated that aggregate shape properties affect the properties of PAM in three aspects, as follows.

- (a) Aggregate shape properties influence the density of PAM

The workability of asphalt mixtures is greatly affected by the aggregate shape properties. Herein, flat and/ or elongated particles require higher compacting effort to reach the designed VTM than cubical-shaped aggregates. However, PAM with

flat and/or elongated particles is able to gain higher density than PAM with cubical-shaped aggregates when the aggregates are well-lubricated. Meanwhile, angular and rougher aggregates are generally harder to compact than rounded and smooth aggregates.

(b) Aggregate shape properties influence the packing structure of PAM

Aggregate shape properties determine the degree of stone-on-stone interlocking between aggregate particles, thereby influencing the stability of aggregate packing structure. The results indicated that cubical-shaped, angular, and rough surface aggregates generate the most favorable packing structure of PAM. Herein, PAM with cubical shaped aggregates has approximately 30 – 40% more stable packing structure, and doubling the angularity of aggregates in PAM enhances 35% of packing stability. Meanwhile, doubling the roughness of aggregate surface increases 12% of packing stability.

(c) Aggregate shape properties influence the mechanical properties of PAM

Packing structure is a major factor that determines the properties of PAM. As aggregate shape properties have a great influence on the packing structure, the mechanical properties of PAM is subsequently affected as well. Thereof, the results of the performance tests are generally in line with the packing parameters, in which PAM with cubical-shaped, angular, and/or rougher aggregates had the most desirable properties. Herein, PAM with cubical shaped aggregates has approximately 50% higher Marshall stability and 20 – 60% better resistance on strain than PAM with disk or blade-shaped aggregates. Meanwhile, doubling the angularity of aggregates in PAM improves 50% of Marshall stability and increase resistance on strain by 65%. The results also showed that doubling roughness of aggregate surface enhances 16% of Marshall stability, and improves resistance on strain by 40%.

4. *The feasibility of discrete element method (DEM) simulation to assess packing structure of PAM*

The results of this research showed that evaluating packing structure of PAM via DEM simulation is in line with conventional packing theory, namely gradation-based framework. Compared with conventional theory, DEM simulation is a more comprehensive method to assess the packing structure of PAM as DEM includes the contact mechanism and load distribution of the packing. Subsequently, DEM simulation is deemed feasible to assess the packing structure of PAM.

6.2. Conclusions and contributions

In this section, the conclusion and contributions of this research are explained in details as follows.

- 1) The existing packing theories are mainly based on dense-graded asphalt mixtures, thereby they are not well suited for analysing the packing structure of PAM. Herein, a new method to assess the packing structure of PAM was developed by utilising DEM model. Four packing parameters were established, namely porosity, coordination number, proportion of effective particles (PEP), and average contact force (ACF). The proposed method and packing parameters can be utilised to evaluate the packing structure of all types of asphalt mixtures, such as dense-graded asphalt mixture, stone-mastic asphalt (SMA), PAM, etc. Utilising DEM simulation in asphalt mixture design shall be greatly favourable to mitigate the excessive and time consuming conventional laboratory measurements. Thereof, laboratory measurements shall be done only for validation of DEM model unlike the trial-and-error procedures in the conventional method.
- 2) The findings of this research provide an insight on the influence of aggregate gradation and shape properties on the internal structure of PAM. Whereas previous research studies into the influence of aggregate gradation and shape properties were mainly performed according to laboratory observations and empirical analyses, the findings of this research advance the current state-of-the-art. Moreover, past research studies into aggregate shape properties were conducted without properly controlling for each independent shape characteristic. For this research, a series of mixture designs was carefully planned for each independent shape characteristic to mitigate the confounding

effect of the various shape properties on the resultant properties of PAM. Thereof, clear influence of each independent shape characteristic and the magnitude of the influence can be obtained.

- 3) Aggregate gradation exerts a great impact on the packing structure and properties of PAM. The understanding on the influence and the roles of each aggregate size fraction is beneficial to design an appropriate gradation for the desired performance of PAM.
- 4) Aggregates size 4.75 – 2.36mm are critical factor that influence the overall packing structure of PAM. The proportion of 4.75 – 2.36mm fractions shall be controlled as either excessive or insufficient amount of these fractions may degrade the skeleton strength of aggregate packing.
- 5) Coarse aggregate shape characteristics, namely form (overall shape), angularity (roundness), and surface texture, have a significant influence on the packing structure and properties of PAM. Herein, aggregate shape characteristics determine the degrees of aggregate interlocking between particles. Knowledge about the impact of coarse aggregate shape characteristics on PAM and hence the recommended aggregate shape characteristics provide useful ‘guidelines’ on what aggregate characteristics shall be improved to achieve the desired performance of PAM, especially for recycled materials that may need to be pre-processed before being utilised as aggregates. For example, plastic waste is one of recycled materials that have a good potential to be utilised as aggregates and/or additives in asphalt mixtures. Herein, the degree of influence of shape properties on the performance of asphalt mixtures can be used to make a decision about what the most optimal and feasible shape is to be produced for the plastic waste.

6.3. Limitations and future directions

Based on the findings presented in this research, there are several potential studies that can be performed in future in order to extend the present findings.

As steel slag has very angular and rough surface texture, it is not possible to alter its surface texture onto very smooth state by abrasion method. Thereof, different materials and polishing method shall be utilised to obtain varying degrees of

roughness for aggregates. Rigid-controlled shape aggregates also shall be fabricated with more varying shape properties to investigate further the influence of aggregate shape characteristics across a wider spectrum. Thereby, the impact of each shape characteristic will be better calibrated over a broader range value of corresponding shape parameters.

In this research, the mechanical properties of PAM were evaluated by Marshall stability, indirect tensile stiffness modulus and creep tests. However, these tests would not be as reliable for predicting the rutting resistance of asphalt mixtures in the field as compared to Asphalt Pavement Analyser and Hamburg Wheel Tracker tests. It is recommended that future evaluation studies shall also apply the latter tests to have additional projection on the resistance to permanent deformation of PAM in the field.

In terms of aggregate packing, voids connectivity is an important characteristic to indicate aggregate configuration of packing structure, as well as PAM's ability to permeate water. In this research, the voids connectivity of PAM was estimated by applying Kozeny-Carmen's Equation (5.1). Herein, more extensive study to investigate the influence of aggregate gradation and aggregate characteristics on voids connectivity shall be conducted by utilising image-based analysis software to better evaluate voids distribution in the aggregate packing structure.

Experimental method to assess the clogging potential of PAM shall be developed. As aggregate gradation and shape properties significantly impact the configuration of aggregate packing, voids shape and voids connectivity of packing structure shall be affected as well. Thereby, aggregate gradation and shape properties shall indirectly influence the clogging potential of PAM. The clogging potential of PAM should be carefully investigated as clogging is one of the key disadvantages for the application of PAM.

For DEM simulation, simplification has been applied in this research to overcome the limitation of computing efficiency. By utilising computer with higher level performance, a better DEM model can be generated to obtain more comprehensive results in simulating asphalt mixture behaviour. Meanwhile, simulation model that

can be used to simulate the real conditions of other relevant performance tests shall be developed as well.

References

- Abbas, A., Masad, E., Papagiannakis, A. T. and Shenoy, A. (2005} "Modelling Asphalt Mastic Stiffness Using Discrete Element Analysis and Micromechanics Based Models", International Journal of Pavement Engineering, Vol. 6, pp. 137-146.
- Adhikari, S., and You, Z. (2010) "3D Discrete Element Models of the Hollow Cylindrical Asphalt Concrete Specimens Subject to the Internal Pressur". International Journal of PAVement Engineering, Vol.11, No.5, pp. 429-439.
- AI (1997). Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types. Lexington, KY : Asphalt Institute.
- Al-Khateeb, G.G., Ghuzlan, K.A., and Al-Barqawi, M.O. (2017) "Effect of Superpave Restricted Zone on Volumetric and Compaction Properties of Asphalt Mixtures", International Journal of Pavement Research and Technology, Vol. 10, pp. 488-96.
- Al Rousan, T. M. (2004) "Characterization of Aggregate Shape Properties", Ph.D. Thesis, Texas A&M University, Texas.
- Al-Suhaibani, A., Al-Mudaheim, J. and Al-Fozan, F. (1992), "Effect of Filler Type and Content on Properties of Asphalt Concrete Mixes", ASTM Special Technical Publication, Issue. 1147, pp. 107-130.
- Alvarez, A.E., Martin, A.E., Estakhri, C., and Izzo, R. (2010) "Evaluation of Durability Tests for Permeable Friction Course Mixtures", International Journal of Pavement Engineering, Vol. 11, No.1, pp. 49–60.
- Alvarez, A.E., Mahmoud, E., Martin, A.E., Masad, E., and Estakhri, C. (2010} "Stone-on-Stone Contact of Permeable Friction Course Mixtures", Journal of materials in civil engineering, Vol. 22, pp. 1129-38.
- Alvarez, A.E., Martin, A.E., Estakhri, C., Button, J.W., Glover, C.J., and Jung, S.H. (2006} "Synthesis of Current Practice on the Design, Construction, and Maintenance of Porous Friction Courses". FHWA/TX-06/0-5262-1, Texas Transportation Institute, Texas.
- Arambula-Mercado, E., Hill, R. A., Caro, S., Manrique, L., Park, E. S., and Fernando, E. (2016) "Understanding Mechanisms of Raveling to Extend

- Open Graded Friction Course (OGFC) Service Life”, Rep. BDR74-977-04, Texas A&M Transportation Institute, College Station, TX.
- Barrett, P.J. (1980) "The Shape of Rock Particles, a Critical Review", Sedimentology, Vol. 27, pp. 291–303.
- Bendtsen, H., and Andersen, B. (2005) "Noise Reducing Pavement-State of the Art in Denmark, Road Directorate, Danish Road Institute, Denmark Ministry of Transport, Denmark
- Bessa, I.S., Verônica, T. F., Branco, C., and Soares, J.B. (2015) "Aggregate Shape Properties and Their Influence on the Behavior of Hot-Mix Asphalt", Journal of Materials in Civil Engineering, Vol. 7, No. 7.
- Brown, E.R., Kandhal, P.S. and Zhang, J. (2001) "Performance Testing for Hot Mix Asphalt.National Center for Asphalt Technology" NCAT Report 2001-05, Alabama.
- Cai, W., McDowell, G.R., and Airey, G.D. (2014) "Discrete Element Visco-elastic Modelling of a Realistic Graded Asphalt Mixture", Soils and Foundations. Vol. 54, No. 1, pp. 12-22.
- Charbeneau, R. J., Klenzendorf, J. B. and Barrett, M. E. (2011) "Methodology for Determining Laboratory and In Situ Hydraulic Conductivity of Asphalt Permeable Friction Course", Journal of Hydraulic Engineering, Vol. 13, No. 1, pp.15-22.
- Chen, J.S., Hsieh, W., and Liao, M.C. (2013). "Effect of Coarse Aggregate Shape on Engineering Properties of Stone Mastic Asphalt Applied to Airport Pavements." International Journal of Pavement Research and Technology, Vol. 6, No. 5.
- Chen, J.S., Chen, S.F., and Liao, M.C. (2015). "Laboratory and Field Evaluation of Porous Asphalt Concrete." Asian Transport Studies, Vol. 3, No. 3, pp. 298–311.
- Chen, J.S., and Yang, C.H. (2020). "Porous asphalt concrete: A review of design, construction, performance and maintenance." International Journal of Pavement Research and Technology, Vol. 13, pp. 601–612. Chen, M., Javilla, B., Hong, W., Pan, C., Riara, M., Mo, L., and Guo, M. (2019}

- "Rheological and Interaction Analysis of Asphalt Binder, Mastic, and Mortar", Materials.
- Chen, M.J. (2016) "Design and Performance of Porous Asphalt Mixture for Pedestrian/Cyclist Applications in Singapore", PhD Thesis, Nanyang Technological University, Singapore.
- Chen, M.J., and Wong, Y.D. (2016a) "Evaluation of the Development of Aggregate Packing in Porous Asphalt Mixture Using Discrete Element Method Simulation", Road Materials and Pavement Design, Vol. 18, pp. 64-85.
- Chen, M.J., and Wong, Y.D. (2016b) "Gradation Design of Porous Asphalt Mixture (PAM) for Low-Strength Application in Wet Environment", International Journal of Pavement Engineering, Vol. 19, pp. 611-22.
- Cheung, C. Y., and Cebon, D. (1997) "Thin Film Deformation Behaviour of Power-Law Creeping Materials", Journal of Engineering Mechanics, Vol. 123.
- Cho, N., Martin, C. D., Sego, D. C., and Jeon, J. (2010) "Dilation and Spalling in Axially Compressed Beams Subjected to Bending", Rock Mechanics and Rock Engineering, Vol. 43.
- Chowdhury, A., Button, J.W., and Grau, J.D.C. (2001) "Effects of Superpave restricted zone on permanent deformation", Report No. 201-2, Texas Transportation Institute, Texas.
- Colley, B. E., and Humphrey, H. M. (1967) "Aggregate Interlock at Joints in Concrete Pavements." Proc., Highway Research Board 46th Annual Meeting, Highway Research Record 189, Highway Research Board, National Research Council, Washington, D.C., 1-18.
- Cooley Jr, L.A., Zhang, J., Kandhal, P.S., Hand, A.J. and Martin, A.E. (2002) "Significance of Restricted Zone in Superpave Aggregate Gradation Specification", Report No. E-C043, Transportation Research Circular, Washington.
- Cui, P., Xiao, Y., Yan, B., Li, M., and Wu, S. (2018) "Morphological Characteristics of Aggregates and Their Influence on the Performance of Asphalt Mixture", Construction and Building Materials, Vol. 186, pp 303-312.

- Cundall, P.A., and Strack, O.D.L (1988) "Modelling of Microscopic Mechanism in Granular Material", Mechanics of Granular Materials: New Models and Constitutive Relations, pp. 113-23.
- Ding, X., Ma, T., and Huang, X, (2018). "Discrete-element contour-filling modeling method for micromechanical and macromechanical analysis of aggregate skeleton of asphalt mixture," Journal of Transportation Engineering., Part B: Pavements, Vol. 145 , No 1.
- Dondi, G., Vignali, V., Pettinari, M., Mazzota, F., Simone, A., and Sangiorgi, C. (2013) "Modelling the DSR Complex Shear Modulus of Asphalt Binder using 3D Discrete Element Approach", Construction and Building Materials, Vol. 54, pp.236-246.
- Elkhalig, Y.G., Napiah, M.B., and Kamaruddin I. (2012) "The Effect of Aggregate Packing Interlocking in the Performance of Bituminous Mixtures", Recent Advances in Engineering, pp. 217-22.
- Feng, H., Pettinari, M., and Stang, H. (2015) "Study of Normal and Shear Material properties for Viscoelastic Model of Asphalt Mixture by Discrete Element Method", Construction and Building Materials, Vol. 98, pp. 366-375.
- Florida Department of Transportation [Florida DOT]. (2004). Florida Method of Test for Measurement of Water Permeability of Compacted Asphalt Paving Mixture (FM5-565). Florida: Department of Transportation.
- Florkova, Z., and Jambor, M. (2017) "Quantification of Aggregate Surface Texture Based on Three Dimensional Microscope Measurement", Procedia Engineering, Vol. 192, pp. 195-200.
- Florkova, Z., and Komacka, J. (2015) "Usage of Microscope Method for Detection of Aggregate Microtexture", Procedia Engineering, Vol. 111, pp. 209-314.
- Fuller, W.B., Thompson, S.E. (1907) "The Laws of Proportioning Concrete", Transactions of the American Society of Civil Engineers, pp. 59:67
- Garcia, A., Aboufoul, M., Asamoah, F., and Jing, D. (2019) "Study the Influence of the Air Void Topology on Porous Asphalt Clogging", Construction and Building Materials, Vol. 227. DOI: 10.1016/j.conbuildmat.2019.116791

- Goode, J.F., Lufsey, L.A. (1962) "A New Graphical Chart for Evaluating Aggregate Gradations", Proceedings of the Association of Asphalt Paving Technologists, Vol. 31, pp.176–207
- Gong, F., Liu, Y., Zhou, X., and Yao, Z. (2018) “Lab Assessment and Discrete Element Modeling of Asphalt Mixture During Compaction with Elongated and Flat Coarse Aggregates”, Construction and Building Materials, Vol. 182, pp. 573-579. DOI: 10.1016/j.conbuildmat.2018.06.059
- Hainin, M.R., Yusoff, N.I., Jaya, R.P., and Yaacob, H. (2013) "Aggregate Degradation Characteristics of Stone Mastic Asphalt Mixtures", Jurnal Teknologi, Vol. 65, No. 3, pp. 111–114.
- Hamzah, M. , Lo, S., You, Z., Hasan, M., and Abdullah, N. (2014) "Effects of Geometrically Cubical Shaped Aggregate on the Engineering Properties of Porous Asphalt", Sains Malaysiana, Vol. 43, pp. 303-312.
- Holt, R. M., Kjolass, J.K., Larsen, I., Li, L., Pilliteeri, A.G. and Sonsteo, E.F. (2005) "Comparison between Controlled Laboratory Experiments and Discrete Particle Simulations of the Mechanical Behaviour of Rock", International Journal of Rock Mechanics and Mining Sciences, Vol. 42.
- Hong, Y., Siah, K.B., See, S.L., Fwa, T.F., and Yoong, C.C. (2015). “Steel slag aggregate for asphalt pavement.” 9th International Conference on Road and Airfield Pavement Technology, Dalian, China.
- Hosking, R. (1992) "Road Aggregate and Skidding", HMSO, London.
- Huang, B., Shu, X., Chen, X., and Masad, E. (2009) “Effects of Coarse Aggregate Angularity and Asphalt Binder on Laboratory Measured Permanent Deformation Properties of HMA”, International Journal of Pavement Engineering, Vol. 10, No. 1, pp. 19-28.
- Itasca. (2008) "PFC3D Version 4.0", Itasca Consulting Group Inc.: Minneapolis, Minnesota.
- Jaya, P.R., N. AbdulHassan, and M. Mahmud. (2014) "Effect of Aggregate Shape on the Properties of Asphaltic Concrete AC14", Jurnal Teknologi, Vol. 71, pp. 69-73.
- Jaeger, H.M., Nagel, S.R. (1992) "Physics of the Granular State", Science, Vol. 255, No.5051, pp. 1523–1531

- Jomoor, N.B., Fakhri, m., and Keymanesh, M.R. (2013) "Comparing the Effect of Skid Resistance on Porous Asphalt Mixes and Conventional Hot-Mix Asphalt", Journal of Basic and Applied Scientific Research, Vol. 3, pp. 838-42.
- Kandhal, P.S. (2001) "The Restricted Zone in the Superpave Aggregate Gradation Specification", Report No. 464, National Cooperative Highway Research Program, Washington.
- Kandhal, P.S. (2002) "Design, Construction, and Maintenance of Open-Graded Asphalt Friction Courses", Information series 115, National Asphalt Pavement Association, Maryland.
- Kandhal, P.S., Motter, J. B., and Khatri, M.A. (1991) "Evaluation of Particle Shape and Texture: Manufactured Versus Natural Sands", Transportation Research Record, Vo. 1301, pp. 48-67.
- Kandhal, P. S., Lynn, C. Y. and Parker, F. (1998), "Characterization Tests for Mineral Fillers Related to Performance of Asphalt Paving Mixtures", NCAT Report, No. 98-2.
- Kangkhajit, C., and Kanitpong, K. (2011) "Effect of Aggregate Characteristics on Texture and Skid Resistance of Asphalt Pavement Surface", Journal of the Eastern Asia Society for Transportation Studies, Vol. 9, pp. 1210-1224.
- Khalid, H., and Jimenez, P.F.K. (1995) "Performance Assessment of Spanish and British Porous Asphalts Performance and Durability of Bituminous Materials", Spon Press, London.
- Kim, J., Roque, R., and Byron, T. (2009) "Viscoelastic Analysis of Flexible Pavements and Its Effects on Top-Down Cracking", Journal of materials in civil engineering, Vol. 21, pp. 324-32.
- Kim, S., Roque, R., Birgisson, B., and Guarin, A. (2009) "Porosity of the Dominant Aggregate Size Range to Evaluate Coarse Aggregate Structure of Asphalt Mixtures", Journal of materials in civil engineering, Vol. 21, pp. 32-39.
- Kim, Y.R. (2006) "Restricted-Zone Requirements for Superpave Mixes Made with Local Aggregate Sources", Report No. 57, Nebraska Department of Transportation Research, Nebraska.

- Kusumawardani, D.M., and Lin, J.D. (2014) "Evaluations of Performance and Thermal Properties in Porous Asphalt Concrete Containing Steel Slag", Advanced Materials Research, Vol. 1025-1026, pp. 688-92.
- Lawrence, A. M., Tia, M., Ferraro, C.C., and Bergin, M. (2012) "Effect of Early Age Strength on Cracking in Mass Concrete Containing Different Supplementary Cementitious Materials". Experimental and Finite-Element Investigation, Vol. 24, pp. 362-72.
- Lees, G. (1964) "The Measurement of Particle Shape and Its Influence in Engineering Materials", Journal of the British Granite and Whinestone Federation, pp. 1-22.
- Li, H., Harvey, J., and Jones, D. (2013) "Cooling Effect of Permeable Asphalt Pavement Under Dry and Wet Conditions", Journal of the Transportation Research Board, No. 2372, pp. 97-107.
- Li, J., Zhang, J., Qian, J., Zheng, J., and Zhang Y. (2019) "Three-Dimensional Simulation of Aggregate and Asphalt Mixture Using Parameterized Shape and Size Gradation". Journal of Materials in Civil Engineering, Vol. 31, No. 3.
- Lira, B., Jelagin, D., and Birgisson, B. (2013) "Gradation-Based Framework for Asphalt Mixture", Materials and Structures, Vol. 46, pp. 1401–1414.
- Liu, W., Gao, Y., and Li, L. (2018) "Micromechanical Simulation of Influence Factors of Indirect Tensile Test of Asphalt mIxture", Journal of Testing and Evaluation. Vol. 46, No. 2, pp. 832-841
- Liu, Y., Dai, Q., and You, Z. (2009) "Viscoelastic Model for Discrete Element Simulation of Asphalt Mixtures", Journal of Engineering Mechanics, Vol. 135, No.4, pp. 324-333.
- Liu, Y., and You, Z. (2012) "Determining Burger's Model Parameters of Asphalt Materials Using Creep-Recovery Testing Data", Symposium on Pavement, in: Mechanics and Materials at the Inaugural International Conference of the Engineering Mechanics Institute.
- Liu, Y. Zhou, X. You, Z. Yao, S. Gong, F. Wang, H. (2017) "Discrete Element Modeling of Realistic Particle Shapes in Stone-Based Mixtures Through

- MATLAB-Based Imaging Process", Construction and Building Materials, Vol. 143, pp169–178.
- Lesueur, D., Petit, J., and Ritter, H.J. (2013). "The mechanisms of hydrated lime modification of asphalt mixtures: A state-of-the-art review", Road Materials and Pavement Design, Vol. 14, No.1, pp. 1-16.
- Mahmud, M.H., Jaya, R.P., Yaacob, H., and Hassan, N.A. (2014) "Laboratory Investigation on the Effects of Flaky Aggregates on Dynamic Creep and Resilient Modulus of Asphalt Mixtures", Jurnal Teknologi, Vol. 70, No. 4, pp. 107–110.
- Mahmoud, E., Gates, L., Masad, E., ErdogAn, S., and Garboczi, E. (2010) "Comprehensive Evaluation of AIMS Texture, Angularity, and Dimension Measurements", Journal of Materials in Civil Engineering, Vol. 22, No. 4, pp369–379.
- Mallick, R.B., Kandhal, P.S., Cooley Jr, L.A., and Watson, D.E. (2000) "Design, Construction and Performance of New Generation Open-Graded Friction Courses", Report No. 2000-1, National Center for Asphalt Technology, Auburn.
- Mampearachchi, W.K., and Fernando, P.R.D. (2012) "Evaluation of the Effect of Superpave Aggregate Gradations on Marshall Mix Design Parameters of Wearing Course", Journal of the National Science Foundation of Sri Lanka, Vol. 40, pp. 183-94.
- Masad, E. (2003) "The Development of a Computer Controlled Image Analysis System for Measuring Aggregate Shape Properties", NCHRP-IDEA Project 77, Transportation Research, Washington, D.C.
- Masad, E., Al-Rousan, T., Bathina, M., McGahan, J., and Spiegelman, C. (2011) "Analysis of Aggregate Shape Characteristics and its Relationship to Hot Mix Asphalt Performance", Road Materials and Pavement Design, Vol. 8, pp. 317-50.
- Micaelo, R., Ribeiro, J. Azevedo, M., and Azevedo, N. (2011) "Asphalt Compaction Study: Micromechanical Modelling of a Simplified Lab Compaction Procedure", Road Materials and Pavement Design, Vol. 12, pp. 461-91.

- Moseley, H. (2020). "Recent advancements in the use of open-graded friction courses in Florida." Presentation at the 99th Transportation Research Board Annual Meeting, Washington, D.C.
- National Center for Asphalt Technology (NCAT). (2017). "Effect of Flat and Elongated Aggregate on Stone Mastic Asphalt Performance." NCAT Report 17-03R, Auburn.
- Nelson, P.M., and Abbot, P.G. (1990) "Accoustical Performance of Pervious Macadam Surfaces for High-Speed Roads." Transportation Research Records, No. 1265, pp. 25-33.
- Nijboer, L.W. (1948) "Plasticity as a Factor in the Design of Dense Bituminous Road Carpets", Elsevier, New York
- Noramuenena-Contreras, J., Izquierdo, E.A., Castro-Fresno, D., Partl, M.N. and Garcia, A. (2013) "A New Model on the Hydraulic Conductivity of Asphalt Mixtures", Journal of Pavement Research and Technology, Vol. 6, No. 5, pp. 488-495.
- Papagiannakis, A.T., Zelelew, H.M., and Mahmoud, M. (2018) "Simulation of Asphalt Concrete Plastic Deformation Behaviour", Journal of Materilas in Civil Engineering, Vol. 30, No. 3.
- Rajib, B.M., Prithvi, S.K., Cooley, L.A. and Donald, E.W. (2000) "Design, Construction, and Performance of New-Generation Open-Graded Friction Courses", Report No. 00-01, National Center for Asphalt Technology.
- Ramaswamy, S D., Tanaboriboon, Y., and Kheok, S C. (1986). "Utilisation of steel slag for road surfacing in Singapore." 13th Australian Road Research Board (ARRB) Conference, Adelaide, Australia.
- Rose, J. (1971) "Aggregate Shape and Skid Resistance." Kentucky Transportation Center Research, Kentucky.
- Rothenburg, L., Bogobowicz, A., Haas, R., Jung, F.W., and Kennepohl, G. (1992). "Micromechanical Modelling of Asphalt Concrete in Connection with Pavement Rutting Problems". In 7th International Conference on Asphalt Pavements.
- Roylance, D. (2001) "Engineering Viscoelasticity", M.A. Cambridge, 02139, Massachusetts Institute of Technology.

- Rungruangvirojn, P., and Kanitpong, K. (2009) "Measurement of Visibility Loss due to Splash and Spray: the Comparison between Porous Asphalt, SMA, and Conventional Asphalt Pavements." Transportation Research Board 88th Annual Meeting. Washington.
- Rungruangvirojn, P., and Kanitpong, K. (2010) "Measurement of Visibility Loss due to Splash and Spray: Porous, SMA and Conventional Asphalt Pavements", International Journal of Pavement Engineering, Vol.11, pp. 499-510.
- Santamarina, J.C., Klein, A., and Fam, M.A. (2001) "Soils and Waves: Particulate Materials Behavior, Characterization and Process Monitoring", Wiley, New York
- Shen, S. H., and H. N. Yu. (2010). "Determination of HMA Voids in Mineral Aggregate Based on the Analysis of Aggregate Gradation and Packing." In 89th TRB Annual Meeting.
- Si, C., Zhou, X., You, Z., He, Y., Chen, E., and Zhang R. (2019). Micro-Mechanical Analysis of High Modulus Asphalt Concrete Pavement. Construction and Building Materials, Vol. 220 pp128–141.
- Sirin, O., Kim, H.J., Tia, M., and Choubane, B. (2008). " Comparison of Rutting Resistance of Unmodified and SBS-Modified Superpave Mixtures by Accelerated Pavement Testing." Construction and Building Materials, Vol. 22, pp. 286–294.
- Souza, L.T., and Kim, Y. (2009) " Effects of Aggregate Angularity on Mix Design Characteristics and Pavement Performance." Report No. MPM-10, Nebraska Department of Roads.
- Sperling, L.H. (1992). Introduction to Physical Polymer Science, 2nd Edition
- Stempihar, J.J., T.P. Manzouri, K.E. Kaloush, and M.C. Rodezno. (2012). "Porous Asphalt Pavement Temperature Effects on Overall Urban Heat Island." Annual Meeting of the Transportation Research Board.
- Strategic Highway Research Program (SHRP). (1994). "Level One Mix Design: Materials Selection, Compaction, and Conditioning." SHRP-A-408, National Research Council, Washington, D.C.

- Sustainable Construction, A Guide on the Use of Recycled Materials, Building & Construction Authority (BCA), Singapore, 2008. Talbot, A.N., Richart, F.E., (1923). "The Strength of Concrete and Its Relation to the Cement, Aggregate and Water." Bulletin, Univeristy of Illinois Engineering Experiment Station, Vol. 137, pp 1–118
- Tarmuzi, N.A., R.P. Jaya, and H. Yaacob. (2015). "Aggregate Angularity Effect on Porous Asphalt Engineering Properties and Performance." Jurnal Teknologi, Vol. 73, No. 4, pp 99-104.
- Vavrik, W.R., R.J. Fries, S.H. Carpenter, and B.D. Aho. (2000). "Effect of flat and elongated coarse aggregate on characteristic of gyratory compacted samples." Federal Highway Administration (FHWA), Illinois.
- Vavrik, W.R., J.P. William, and S.H. Carpenter. (2002). "Bailey Method for Gradation Selection in HMA Mixture Design." Transportation Research Board, Washington, DC.
- Vignali, V., Mazzota, F., Sangiorgi, C., Simone, A., Lantieri, C., and Dondi, G., (2014). "Rheological and 3D DEM Characterisation of Potential Rutting of Cold Bituminous Mastics." Construction and Building Materials, Vol. 73, pp. 339-349.
- Wadell, H. (1933). "Sphericity and Roundness of Rock Particles." The Journal of Geology, Vol. 41, pp. 310– 331.
- Wang, D., Wang, H., Bu, Y., Schulze, C., and Oeser, M. (2015). "Evaluation of Aggregate Resistance to Wear with Micro-Deval Test in Combination with Aggregate Imaging Techniques." Wear, Vol. 338, pp. 288–296.
- Wang, S., Miao, Y., and Wang, L. (2020). "Investigation of the Force Evolution in Aggregate Blend Compaction Process and the Effect of Elongated and Flat Particles Using DEM." Construction and Building Materials, Vol. 258.
- Wang, X., Gu, X., Jiang, J., and Deng, H. (2018). "Experimental Analysis of Skeleton Strength of Porous Asphalt Mixture." Contruction and Building Material, Vol. 171, pp. 13-21.
- Xiao, F., Herndon, D.A., Amirkhanian, S., and He, L. (2015). "Aggregate Gradations on Moisture and Rutting Resistances of Open Graded Friction

- Course Mixtures." Construction and Building Materials, Vol. 85, pp. 127-135.
- Xue, B., Xu, J., Pei, J., Zhang, J., Li, R., and Guo, F. (2020). "Using Random Heterogeneous DEM Model to Simulate the SCB Fracture Behavior of Asphalt Concrete." Construction and Building Materials, Vol. 236
- Xue, B., Pei, J., Zhou B., Zhang, J., and Li, R. (2020). "Investigation on the Micromechanical Response of Asphalt Mixture During Permanent Deformation Based on 3D Virtual Wheel Tracking Test." Construction and Building Materials
- Yao, H., Liu, Y., You, Z., Li, L., and Goh, S.W., (2012). "Discrete Element Simulation of Bending Beam Rheometer Test for Asphalt Binder." International Journal of Pavement Research and Technology, Vol. 5, No. 3, pp. 161-168.
- Yeggoni, N., J. Button, and D. Zollinger. (1994). "Influence of Coarse Aggregate Shape and Surface Texture on Rutting of Hot Mix Asphalt Concrete." Federal Highway Administration (FHWA), Texas.
- Zezelew, H.M., and Papagiannakis, A.T., (2010). "Micromechanical Modeling of Asphalt Concrete Uniaxial Creep Using the Discrete Element Method." Road Materials and Pavement Design, Vol. 11, No. 3, pp. 613-632.
- Zhang, D., X. Huang, and Y. Zhao. (2012). "Investigation of the Shape, Size, Angularity and Surface Texture Properties of Coarse Aggregates." Construction and Building Materials, Vol. 34, pp. 330–36.
- Zhang, J., L. Cooley Jr, and G. Hurley. (2003). "Effect of Superpave Defined Restricted Zone on Hot Mix Asphalt Performance." National Center for Asphalt Technology, Auburn.
- Zhao, Y., Wang, X., Jiang, J., and Zhou, L. (2019). "Characterization of Interconnectivity, Size Distribution and Uniformity of Air Voids in Porous Asphalt Concrete Using X-ray CT Scanning Images." Construction and Building Materials, Vol. 213, pp. 182–193.
- Zulkati, A. (2013). "Composite Effect of Filler on Properties of Asphalt Concrete Mixture and Its Bonding Characteristics with Asphalt." PhD Thesis, Nanyang Technological University.

APPENDIX A. Asphalt binder content

Asphalt binder content for each gradation was determined according to the AI method, in which the aggregate surface area in each gradation was calculated to estimate the appropriate binder content of PAM (AI 1997). The aggregate surface area (SA) can be calculated in Equation (A.1), as follows:

$$SA = 0.41 + 0.41a + 0.82b + 1.64c + 2.87d + 6.14e + 12.29f + 32.77g \quad (A.1)$$

where, a , b , c , d , e , f , and g refer to the percentages by mass of aggregates passing 4.75 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm, and 0.075 mm sieves, respectively.

Then, the required weight of asphalt binder was calculated by utilising Equation (A.2), as follows:

$$\text{weight of asphalt binder} = SA \times \eta \times \text{weight of aggregates} \times SG_b \quad (A.2)$$

where, η refers to the asphalt film thickness, and SG_b is the specific gravity of asphalt binder. In this study, the asphalt film thickness was designed to be more than 10 μ m. Meanwhile, the estimated binder content can be expressed in Equation (A.3).

$$\text{estimated binder content} = \frac{\text{weight of asphalt binder}}{\text{total weight}} \times 100\% \quad (A.3)$$

Then, Cantabro and drain-down tests were performed on PAM to ensure the selected binder content is within the lower and upper limits of optimum binder content, respectively. The results of Cantabro and drain-down test for the gradations in Study A and Study B are summarised in Tables A.1 and A.2, respectively. The results indicated that the selected binder contents satisfy the requirements, in which Cantabro loss should be below 20% and drain-down should be no more than 0.3%.

Table A.1. The results of Cantabro and drain-down test for selected gradations in
Study A

Gradation	Estimated binder content (%)	Selected binder content (%)	Drain-down (%)	Cantabro loss (%)
G1	4.2	4.5	0.01	8.1
G2	4.3	4.5	0.01	9.2
G3	4.2	4.5	0.04	8.8
G4	4.2	4.5	0.08	7.6
G5	4.3	4.5	0.02	7.8
G6	4.2	4.5	0.02	8.6
G7	4.2	4.5	0.09	9.1
G8	4.3	4.5	0.03	8.3
G9	4.2	4.5	0.02	8.7

Table A.2. The results of Cantabro and drain-down test for selected gradations in
Study B

Gradation	Estimated binder content (%)	Selected binder content (%)	Drain-down (%)	Cantabro loss (%)
Ga	4.1	4.5	0.16	8.5
Gb	4.1	4.5	0.14	8.2
Gc	4.3	4.5	0.08	7.8
Gd	4.3	4.5	0.13	7.9
Ge	4.4	4.5	0.05	8.1
Gf	4.6	5.0	0.11	6.5
Gg	4.6	5.0	0.19	6.9
Gh	4.6	5.0	0.15	7.2
Gi	4.7	5.0	0.13	6.7
Gj	4.7	5.0	0.12	7.3

APPENDIX B. Validation of DEM model

B1. Influence of aggregate size and gradation on PAM's packing structure

Figure B1.1. Correlation of air voids content from DEM simulation and laboratory measurements

*(S) represents the results were obtained from DEM simulation

Figure B1.2. Comparison of total permanent strain curves of DEM simulation and laboratory measurements

B2. Impact of aggregate shape (form) on PAM's packing structure

(a)

(b)

(c)

Figure B2.1. Correlation of air voids content from DEM model and laboratory measurements for PAM with varying aggregate shape properties; (a) form; (b) angularity; (c) surface texture

(a)

(b)

*(S) represents the results were obtained from DEM simulation

(c)

Figure B2.2. Total permanent strains of DEM model and PAM specimens with varying aggregate shape properties; (a) form; (b) angularity; (c) surface texture