Performance Model for Unbound Granular Materials in Pavements

Licentiate Thesis

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Abstract

Recently, there has been growing interest on the behaviour of unbound granular material in road base layers. Researchers have studied that the design of a new pavement and prediction of service life need proper characterization of unbound granular materials, which is one of the requirements for a new mechanistic design method in flexible pavement.

Adequate knowledge of the strength and deformation characteristics of unbound layer in pavements is a prerequisite for proper thickness design, residual life determination, and overall economic optimization of the pavement structure. The current knowledge concerning the granular materials employed in pavement structures is limited. In addition, to date, no general framework has been established to explain satisfactorily the behaviour of unbound granular materials under the complex repeated loading which they experience.

In this study, a conceptual method, packing theory-based model is introduced; this framework evaluates the stability and performance of granular materials based on their packing arrangement. In the framework two basic aggregate structures named as Primary Structure (PS), and Secondary Structure (SS). The Primary Structure (PS) is a range of interactive grain sizes that forms the network of unbound granular materials. The Secondary Structure (SS) includes granular materials smaller than the primary structure. The Secondary Structures fill the gaps between the particles in the Primary Structure and larger particles essentially float in the skeleton.

In this particular packing theory-based model; the Primary Structure porosity, the average contact points (coordination number) of Primary Structure, and a new parameter named Disruption Potential are the key parameters that determine whether or not a particular gradation results in a suitable aggregate structure.

Parameters mentioned above play major role in the aggregate skeleton to perform well in terms of resistance to permanent deformation as well as load carrying capacity (resilient modulus). The skeleton of the materials must be composed of both coarse enough and a limited amount of fine granular materials to effectively resist deformation and carry traffic loads.

**Keywords:** Unbound granular materials; Aggregate; Packing theory; Gradation; Primary Structure; Secondary Structure; Permanent deformation; Resilient modulus.
Dedication

To my new upcoming baby
Acknowledgements

I am heartily thankful to my supervisors, Prof. Björn Birgisson, Asst.Prof. Denis Jelagin and Dr. Alvaro Guarin whose encouragement, guidance and support from the initial to the final level enabled me to develop an understanding of the subject.

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For more reasons than one, I could not have completed this project without the support of my loving family. I thank my wife, Zini for her daily motivation to complete this thesis. The constant encouragement of my mother and brothers in Ethiopia has also provided me to be more committed in my educational life.

Lastly, I offer my regards and blessings to all my colleagues who supported me in any respect during the completion of the Thesis.

Tatik F. Yideti

Stockholm, June 2012
**List of Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS</td>
<td>Primary Structure</td>
</tr>
<tr>
<td>SS</td>
<td>Secondary Structure</td>
</tr>
<tr>
<td>DASR</td>
<td>Dominant Aggregate Size Range</td>
</tr>
<tr>
<td>AASHTO</td>
<td>American Association of State Highway and Transportation Office</td>
</tr>
<tr>
<td>USCS</td>
<td>Unified Soil Classification System</td>
</tr>
<tr>
<td>DP</td>
<td>Disruption Potential</td>
</tr>
<tr>
<td>DF</td>
<td>Disruption Factor</td>
</tr>
<tr>
<td>DF_T</td>
<td>Total Disruption Factor</td>
</tr>
<tr>
<td>$V_{PS}$</td>
<td>Volume of PS Primary Structure aggregates</td>
</tr>
<tr>
<td>$V_{SS}$</td>
<td>Volume of PS Secondary Structure aggregates</td>
</tr>
<tr>
<td>$V_{agg&gt;PS}$</td>
<td>Volume of aggregates bigger than Primary Structure</td>
</tr>
<tr>
<td>DM</td>
<td>Disruptive Materials</td>
</tr>
<tr>
<td>$V_{DM}^{SS}$</td>
<td>The volume of disruptive material</td>
</tr>
<tr>
<td>$V_{free}^{PS}$</td>
<td>The free volume within the primary structure</td>
</tr>
<tr>
<td>$V_{PDM.o}$</td>
<td>The volume of disruptive materials for octahedral structure</td>
</tr>
<tr>
<td>$V_{PDM.t}$</td>
<td>The volume of disruptive materials for tetrahedral structure</td>
</tr>
<tr>
<td>$V_{v,PS.o}$</td>
<td>The volumes of voids in PS for octahedral structure</td>
</tr>
<tr>
<td>$V_{v,PS.t}$</td>
<td>The volumes of voids in PS for tetrahedral structure IC interstitial Component</td>
</tr>
<tr>
<td>CCP</td>
<td>Cubic Close Packing</td>
</tr>
<tr>
<td>HCP</td>
<td>Hexagonal Close Packing</td>
</tr>
<tr>
<td>2-D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>3-D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>SST</td>
<td>Sand Stone</td>
</tr>
<tr>
<td>CONC</td>
<td>Crushed Concrete</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Gr and GR</td>
<td>Granite</td>
</tr>
<tr>
<td>S&amp;G</td>
<td>Sand and Gravel</td>
</tr>
<tr>
<td>$D_{w,avg}$</td>
<td>Weighted average of two consecutive sieve sizes</td>
</tr>
<tr>
<td>$d_{w,avg}$</td>
<td>Weighted average of void size of two consecutive sieve sizes</td>
</tr>
<tr>
<td>$\phi_1$ and $\phi_2$</td>
<td>The percentage retained in two consecutive sieve sizes</td>
</tr>
<tr>
<td>r</td>
<td>The radius of sphere</td>
</tr>
<tr>
<td>a</td>
<td>The length of the cubical structure</td>
</tr>
<tr>
<td>$D_1$ and $D_2$</td>
<td>The two consecutive sieve sizes</td>
</tr>
<tr>
<td>H</td>
<td>The diagonal length in cubical structure</td>
</tr>
<tr>
<td>h</td>
<td>The distance between particles</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>US STD</td>
<td>United State Standard</td>
</tr>
<tr>
<td>BS</td>
<td>British Standard</td>
</tr>
</tbody>
</table>
Table of contents

1.0 INTRODUCTION ...........................................................................................................................................1
  1.1 Background .....................................................................................................................................................1
  1.2 Objectives ......................................................................................................................................................1
  1.3 Scope ............................................................................................................................................................1
2.0 LITERATURE REVIEW ......................................................................................................................................2
  2.1 Unbound Granular Material ..........................................................................................................................2
  2.2 Mechanical properties of Unbound Granular Materials ..............................................................................2
  2.3 Porosity ........................................................................................................................................................4
  2.4 Coordination number of particles ................................................................................................................4
  2.5 Disruption Factor of aggregates ................................................................................................................4
3.0 THEORETICAL FRAMEWORK .......................................................................................................................6
  3.1 Primary and Secondary Structure ................................................................................................................6
    3.1.1 Identification of Primary Structure ......................................................................................................6
    3.1.2 Primary Structure Porosity ...................................................................................................................6
    3.1.3 Primary Structure Coordination number ............................................................................................7
  3.2 Disruption Potential .......................................................................................................................................8
4.0 MATERIALS FOR VALIDATION ......................................................................................................................8
5.0 FRAMEWORK EVALUATION ...........................................................................................................................9
  5.1 Effect of Disruption Potential (PAPER I) ....................................................................................................9
  5.2 Effect of Secondary Structure on Permanent deformation (PAPER I) .......................................................9
  5.3 Influence of PS Porosity on the Resilient Modulus (PAPER II) .................................................................10
6.0 CONCLUSIONS ...............................................................................................................................................12
References ............................................................................................................................................................13
List of Publications

Paper I
Tatek F. Yideti, B. Birgisson, D. Jelagin and A. Guarin, “Packing theory-Based Framework to evaluate Permanent deformation of Unbound Granular Materials”


Paper II

1.0 INTRODUCTION

1.1 Background

Unbound granular base and subbase layers have a major impact on the long term performance and load carrying capacity of pavements. Aggregate size distribution plays a key role on the performance of granular materials; this relationship must be understood in order to improve pavement design and construction procedures (Thom and Brown, 1988; Dowson et al., 1996 and Kolisoja, 1998, Lekarp, 1999, and Ekblad, 2007).

In this study, particle size distribution, packing arrangement, disruption of coarse aggregate load carrying fraction, porosity, and contact points per particle are used to evaluate permanent deformation, resilient modulus and strength of unbound granular materials.

1.2 Objectives

The main objectives of this study are:

- Develop a generalized packing theory-based framework for unbound materials
- Identify the load carrying aggregate particles from the aggregate size distribution
- Investigate the stability nature (Disruption Potential) of load carrying aggregate particles
- Study the porosity and contact points of load carrying aggregate structure
- Evaluate mechanical properties of unbound materials (resistance to permanent deformation and resilient modulus) based on the developed framework.

1.3 Scope

The proposed framework assumes the shape of the particles to be spherical and the density of the materials to be constant throughout each sieve size. The validation of the framework has been done on nineteen unbound base and subbase materials with different mineralogical composition. The performance data were taken from previously conducted repeated loading triaxial test (RLTT). The framework considered only packing and grain size distribution, not seen further the shape, surface texture and angularity of materials. This model is generally applicable to any type of granular materials regardless of their sieve size standards.
2.0 LITERATURE REVIEW

2.1 Unbound Granular Material

Unbound Granular Material (UGM) is a frictional soil with different particle shapes and sizes; UGM is an inhomogeneous and non-isotropic material. It transmits traffic loading to the subgrade by reducing the vertical compressive stress. The performance of pavements is to a great extent defined by the characteristics of the unbound base and subbase layers. Typically in Sweden, the conventional natural gravel and crushed stones can be found in a quarry site with abundance of granite and limestone (Figure 1).

![Unbound Granular Material](image)

**Figure 1 Unbound Granular Material**

Unbound granular materials can be characterized based on their physical properties such as gradation, plasticity, hardness, durability, and on their shear strength properties. Particle size distribution of the granular material affects the most fundamental properties of unbound granular material such as resilient modulus, permanent deformation, durability, and permeability (Thom, N and Brown, S., 1988). Hicks and Monismith (1971) observed that the angularity of crushed aggregate provided a higher resilient modulus than uncrushed gravels with angular or sub-angular shaped particles. In order to establish more rational pavement design and construction, as well as prediction of service life, the effect of grain size distribution on the performance of unbound granular materials must be better understood.

2.2 Mechanical properties of Unbound Granular Materials

The mechanical properties of unbound granular materials comprise their stiffness, stability and load-bearing capacity. The stability of unbound granular materials is expressed by the permanent deformation behaviour; it can be defined as a measure of the ability to resist permanent deformation.
Resilient modulus exhibits an increasing trend with increasing dry density (Robinson, 1974). Trollope (1962) showed that the influence of density on resilient modulus for particularly uniform sand materials increased up to 50% for loose to dense specimens.

The deformation resistance of unbound granular materials depends on the applied stresses, which is dependent on the physical factors such as gradation and fines content; the effect of grading and compaction on plastic strain was also studied by Thom and Brown (1988); they concluded that the resistance to permanent strain decreased when the specimens were not compacted well for all grading types.

Barksdale and Itani (1989) studied the effect of the plasticity of fines on the deformation of granite gneiss and reported that an increase in the fines content from 0 to 10% increased the resilient modulus by 60%. In addition, they found that as the fines content increased, the amount of permanent strain also increased. Dowson et al. (1996) established that the resistance to plastic strain was higher for the densest material; he also determined that the effect of grading on plastic strain is more considerable than the degree of compaction. Kolisoja (1997) observed 20% reduction in resilient modulus by adding another material as the fines fractions. Kolisoja (1998) also argued that substantially higher permanent strain may be expected for aggregates containing extremely high fines content or at a low content of fines. He also concluded that a decrease in void content increases the number of contact points per particle with other particles (coordination number), which increases the stiffness of the material. Correspondingly, Hoff (1999) reported the maximum grain size also affects both the fundamental properties; resilient and permanent deformation of unbound granular materials. The results showed that bigger maximum grain size exhibited lower resistance to deformation.

Similarily, Lekarp, et al. (2000) presented a “state-of-art” on the permanent strain response of unbound aggregates and concluded that the effect of increase in fines content has an inverse effect on the permanent deformation resistance in granular materials and they observed an increase in density highly improved the resistance to permanent strain. The mineralogical composition and the internal structure of the particles also have a considerable impact on deformation properties (Arm, 2003). She suggested that in order to resist external load actions as well as for deformation properties to remain the same over the life of the road, the materials particle size and shape must not be changed. Additionally, Ekblad (2007) evaluated one crushed granite aggregate with four different gradations, from Skärlanda, Sweden. The study showed that the resilient modulus decreased with increasing water content and decreasing grading coefficient, i.e., the finer the material the lower the resilient modulus.
2.3 Porosity

Porosity describes the amount of open space in granular materials and is defined as the ratio of the volume of void over the total volume. It is largely influenced by factors as particle size, shape, the uniformity of the grain size, the type of granular materials, and particle interlocking.

2.4 Coordination number of particles

The coordination number, or number of particle contact points with other particles, is an important parameter to describe the geometrical arrangement of particles. It is widely used for evaluating mechanical properties of particles that related to the connectivity between particles. The strength of a mass of unbound granular materials depends on the number of particle contacts at which the capacity to carry load can be ensured.

In general, a densest packing gives a higher coordination number and a loosest packing gives a lower coordination number. A few researchers have related the coordination number to porosity (Smith, et al., 1929; Field, 1963; Gray, 1968; Ching et al., 1991).

2.5 Disruption Factor of aggregates

Roque (2006) developed an asphalt mixture model composed by Dominant Aggregate Size Range (DASR), which is the coarse aggregate load carrying structure, and Interstitial Component (IC), which includes aggregate particles smaller than DASR and binder. They established a procedure for DASR identification and proposed DASR porosity criterion (DASR porosity < 50%).

Guarin (2009) studied the effect of Interstitial Component on asphalt mixture performance; he introduced Disruption Factor (DF), which is a parameter to evaluate the potential of IC particles to disrupt the DASR structure and defined as the ratio of the volume of potentially disruptive IC particles over the volume of DASR void.

\[
DF = \frac{\text{Volume of potentially disruptive IC particles}}{\text{Volume of DASR voids}}
\]  

(1)

where, volume of potentially disruptive IC particles considers particles smaller than DASR and bigger than the voids of DASR; it is calculated by using volumetric relationships. Volume of DASR voids was determined as a function of the type of DASR structure (cubical or hexagonal) and the number of DASR particles. The type of packing arrangement (simple cubic
or close hexagonal) was selected according to the DASR porosity. The determination of voids in DASR as well as the volume of potentially disruptive IC particles was done based on packing arrangement and volumetric relationships of aggregates.

Guarin (2009) concluded that the volume of potentially disruptive IC particles appears to be a key factor of IC gradation that may help to control asphalt mixture rutting and cracking performance and proposed DF to be included in gradation guidelines for mixture performance.
3.0 THEORETICAL FRAMEWORK

3.1 Primary and Secondary Structure

Unbound materials are composed of stones with a size distribution determined and described through a gradation analysis. In this study, it is stated that different aggregate sizes have different roles in the load carrying and in the long term performance of a pavement structure. Accordingly, the model identifies two basic components of the skeleton of unbound granular materials which are Primary Structure (PS) and Secondary Structure (SS). PS is a range of interactive grain sizes that carry the loads and SS is a range of grain sizes smaller than the PS. PS and SS form the skeleton of unbound granular materials.

3.1.1 Identification of Primary Structure

The identification of primary structure range has been done based on the 3-D densest possible packing (cubic close packing, CCP). The PS in the skeleton is thus composed of particles having a certain size range. Equation (2) is used to identify the size range of the PS for unbound granular materials; the detail procedure is shown in Paper I.

\[
D_1 \leq d_{\text{w.avg}} \leq D_2
\]

where, \(D_1\) and \(D_2\) are the two larger and smaller consecutive sieve sizes, \(d_{\text{w.avg}}\) is the weighted average void size.

3.1.2 Primary Structure Porosity

In the framework, primary structure porosity \((n_{ps})\) is one of the key parameters used for evaluating resilient modulus of unbound granular materials; it is defined as the ratio of the volume of voids in the PS over the total volume of granular mix (skeleton). The volume of voids in PS is everything in the skeleton that is not considered to be part of the PS, and the total volume of the granular mix (skeleton) is all except the volume of particles bigger than the Primary Structure. Equation (3) is derived from ordinary porosity formula that is known in geotechnical engineering.

\[
n_{ps} = \frac{V_{PS}}{V_{TGM}} \times 100\% = \frac{V_{PS} + V_{SS}}{V_{TGM} - V_{AGG(>PS)}} \times 100\% \quad (3)
\]
where:

\( V_T \): Volume of total granular mix.

\( V_{agg(L_1)} \): Volume of granular materials retained on \( L_1 \) sieve

\( V_{SS} \): Volume of Secondary Structure (granular materials smaller than \( PS \))

\( V_v \): Volume of voids in granular mix

### 3.1.3 Primary Structure Coordination number

Porosities and their corresponding visualized theoretical contact points of four packing arrangements (cubic, orthorhombic, tetrahedral, Rhombohedral) were used as initial points to formulate the primary structure coordination number. The equation of coordination number as a function of porosity is developed by fitting the theoretical number of contact points to their corresponding porosities. The coordination numbers for four systematic packing arrangements are shown in Table 1. Equation (4) shows the derived mathematical relation for PS coordination number and PS porosity.

**Table 1 Four Packing Arrangements**

<table>
<thead>
<tr>
<th>Packing Arrangements</th>
<th>Coordination number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Cubic Packing</td>
<td>6</td>
</tr>
<tr>
<td>Orthorhombic</td>
<td>8</td>
</tr>
<tr>
<td>Tetrahedral</td>
<td>10</td>
</tr>
<tr>
<td>Rhombohedral</td>
<td>12</td>
</tr>
</tbody>
</table>

\[
 cn_{ps} = 2.827 \left( \frac{n_{ps}}{100} \right)^{-1.069} \quad \text{(4)}
\]

where, \( cn_{ps} \) is the PS coordination number and \( n_{ps} \) is the PS porosity in percent.
3.2 Disruption Potential

A small percentage of fines fraction (SS) may fail to provide an adequate support to the coarse aggregates (PS), while too high a percentage of fines material may result in PS particles loosing contact with each other, thus reducing load carrying capacity of the materials and eventually the PS aggregates likely to disrupt. In Paper I, a parameter so called, Disruption Potential (DP) shows the ability of SS to disrupt the PS; it can be defined as the ratio of the volume of potentially disruptive fine material over the free (available) volume within the primary structure. The mathematical expression for DP is illustrated in the following Equation (5).

\[ DP = \frac{V_{DM}^{SS}}{V_{free}^{PS}} \]  

(5)

where, \( V_{DM}^{SS} \) is the volume of Disruptive Material and \( V_{free}^{PS} \) is the free volume within the primary structure

4.0 MATERIALS FOR VALIDATION

The validation of the framework was done using different unbound granular materials from two different countries (Sweden and USA). Among these, seven materials data were collected from two KTH studied references (Ekblad, 2007 and Lekarp, 1999). These Swedish originated materials composed of granite (Granite 1-4, GR), sand and gravel (S&G) and crushed concrete materials (CONC). S&G material typically used as a subbase materials but the rest materials are mainly used as base course. The experimental data for the remaining thirteen USA granular base materials, including three Louisiana State base materials and ten Missouri base materials are used in the model validation.
5.0 FRAMEWORK EVALUATION

5.1 Effect of Disruption Potential (PAPER I)

Disruption Potential (DP) plays a major role on the resistance to permanent deformation behaviour of unbound granular materials. As shown in Figure 2, it was hypothesized that increasing DP values influences the stone to stone contact between the load carrying particles and leading to higher permanent deformation. On the other hand, when there is too low volume of fines fraction leads to low DP values and there will not be enough fines material that can support the load carrying particles and eventually the granular material composition becomes less resistant to permanent deformation.

![Figure 2 Relationship between DP and Permanent deformation](image)

5.2 Effect of Secondary Structure on Permanent deformation (PAPER I)

Figure 3 shows the relationship between the normalized permanent strain and the volume of SS. It can be seen that low and high percent volume of SS has a great effect on the deformation behaviour of unbound materials. Good performance is observed for materials with optimum amount of SS that can support the PS in the overall skeleton of granular materials.
Figure 3 Relationship between the volume of Secondary Structure and permanent deformation (PAPER I)

5.3 Influence of PS Porosity on the Resilient Modulus (PAPER II)

The PS porosity of the nineteen evaluated materials satisfactorily correlated with their corresponding resilient modulus (Figure 4). It can be observed that increasing the porosity of the primary structure results in a decrease in the resilient modulus. This general trend is common as a matter of fact for any granular material and an increase of pore space within the aggregates tends to lower resilient modulus. There is a stone-to-stone contact between particles when the PS is between 26% and 48%; these porosities correspond to porosities of rhombohedral and simple cubic packing arrangement respectively. In general, granular materials having PS porosities closer to the densest possible packing, showed higher resilient modulus values.
Figure 4 Relationship between PS porosity and Resilient Modulus (PAPER II)
6.0 CONCLUSIONS

A generalized granular material framework has been developed in this study. The model is based on packing theory. Unbound granular materials in base and subbase layers properties are required factors for the deformational behaviour of the whole pavement structure. As observed, in order to have good resistance to permanent deformation, the coarse aggregate particles should be interlocked well with the help of optimum amount of fines fraction. These can be attained by keeping the Disruption Potential value of the load carrying structure (PS) to be in an optimal range.

In addition, the influence of inter-particle contacts and pore spaces on resilient modulus was investigated. A decrease in PS porosity and an increase in coordination number for the nineteen unbound materials showed a significant increase of the resilient modulus. Materials with $n_{ps}$ smaller than 47.95 % and $cn_{ps}$ greater than 6 (simple cubic coordination number) showed resilient modulus value of more than 400 MPa.

The study showed that the developed framework is a satisfactory and simple method to assess the risk against permanent deformation and load bearing capacity. It can also be concluded that the framework is capable of capturing experimentally observed characteristics of granular materials. It is also a promising step towards a better understanding of granular material behaviour.
References


Ching S. C., Anll M., and Sivanuja S. Sundarum, 1991. Properties of granular packings under low amplitude cyclic loading, Department of Civil Engineering, University of Massachusetts, Amherst, MA 01003, USA.


