Investigation of Granular Materials Deformations
under an Unconfined Compaction
with X-Ray Computed Tomography

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The behavior of the asphalt mixtures under large deformations, for example an unconfined compaction is of high practical importance. Quantitative measurement of the spatial distribution of internal structure of asphalt mixtures is crucial to study deformation behavior of asphalt mixtures. Deformation of granular material under an unconfined compaction is investigated in this study, as a groundwork for further research on deformation behavior of asphalt mixtures. Two sets of 3D images of specimens are obtained using X-Ray computed tomography (CT) under an unconfined compaction. Digital image analysis procedure is developed to segment different phases for characterizing spatial distribution of internal structure. Comparative volumetric relationship before and after compaction showed that air void distribution is not changed heavily due to absence of interlocking. Initial and final spatial positions of individual granules are investigated to trace their movement under compaction. It is shown that X-Ray CT could be a useful tool to characterize internal structure of asphalt mixtures and its evolution during deformation.

Key words: X-Ray Computed Tomography, Unconfined compaction, Digital image analysis, Deformation analysis
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1 Introduction

1.1 Background

Internal structure in asphalt mixtures refers to aggregates, bitumen, and air voids. It affects mechanical properties of asphalt mixtures significantly, therefore, influencing dramatically the mixtures performance in the field (Onifade, 2013). Deficient internal structure of asphalt results in pavement failures, such as rutting, fatigue cracking, potholes and blisters. Aggregates are the prominent part of asphalt mixtures, which constitutes roughly 95% of the mixture weight-wise. The shape of aggregates, aggregate gradation, aggregate-to-aggregate interlocking and contact friction provide a primary load carrying mechanism in compression and shear. Bitumen-based binder keeps aggregate particles together and its distribution control tensile stiffness and fracture resistance of the asphalt mixtures. Changes in mechanical and geometrical parameters of aggregates and binder will affect the overall stress-strain distribution in asphalt mixture. Air void distribution influences mixture permeability, resistance to bleeding and ageing. Furthermore, too much air void reduces compressive strength of asphalt mixture (Zelelew, 2008).

The X-ray computed tomography (CT) provides a unique way to characterize the internal structure of asphalt in 3D. The method has been initially proposed by Sir Godfrey Hounsfield and Allan McLeod Cormack, in developing this diagnostic technique in 1970s (Hounsfield, 1973). The principle of X-Ray CT is “An image on a closed plane can be reconstructed if projections in all directions through any points on the plane are given” (Fujii & Uyama, 2004). It is a nondestructive technique that allows visualization of the internal structure of objects, determined mainly by variations in density and atomic composition, aiming to get detailed information on 3D internal structure down to a micro level. It was adopted quickly in medical industry. Stimulated by success of medical X-Ray CT, it started to be applied to industrial application. Industrial X-Ray CT having higher penetrating ability and higher spatial resolution makes it possible to quantify and characterize the internal structure of different materials and products via its accurate images of opaque structures (Fujii et al., 2004).

There have been number of attempts to characterize asphalt mixtures internal structure using X-Ray CT, including rapid measurement of aggregate texture (Fletcher et al., 2002), aggregate gradation (Bhasin, 2010), mathematical analysis of aggregate shape (Garboczi, 2002), sensitivity of aggregate size (Adhikari et al., 2011), air voids characterization (Masad et al., 2002; Wang et al., 2003, 2004a; Kutay et al., 2007; Arambula et al., 2007; Walubita et al., 2012). Furthermore, X-Ray CT
combined with an image processing procedure, is also adopted to present internal structure of asphalt mixtures as input for computational modeling, including aggregate characteristics for viscoplastic modeling (Masad et al., 2005; You et al., 2012), 3D discrete element models (You et al., 2009) and finite element models (Wang, 2008; Dai, 2011).

However, only few studies exist focusing on investigating the deformation behavior of asphalt mixtures using X-Ray CT. For example, (Tashman et al., 2002) characterized air void distribution in superpave gyratory compacted specimens; (Partl et al., 2003) investigated the change and differences in homogeneity and isotropy in asphalt concrete specimens during gyratory compaction; (Hunter et al., 2004) examined variation in aggregate orientation and distribution within asphalt mixtures under different compaction methods; (Azari et al., 2004) checked the degree of vertical inhomogeneity, which was defined as the separation of the original mix design gradation into finer and coarser gradations along the depth of the specimen on compressive properties; (Gatchalian et al., 2006) evaluated aggregate characteristics and the resistance of aggregates to degradation (fracture and abrasion) before and after compaction.

In this study, granular materials deformation under an unconfined compaction is investigated with X-Ray computed tomography and digital image analysis, volumetric composition of samples is measured and deformation patterns during compaction are identified. This study is a first step in a large project which has an aim for further study of granular materials behavior at large deformations and in the end asphalt mixtures. The main goal of the large project is to improve compaction methods and giving an insight into evolution of expansion joint area in the pavement.

1.2 Objectives

The main purpose of this study is to develop a procedure for evaluating granular materials deformations under an unconfined compaction. This involves image acquisition (X-Ray scan of specimen), image enhancement (shading correction and noise reduction), image segmentation, numerical analysis. Detailed objectives are as follows:

- Perform comparative X-Ray scans of the specimen before and after compaction.
- Develop a procedure for digital image analysis of the scanned datasets based on commercial software AvizoFire®.
- Perform comparative volumetric analysis of scanned specimens before and after compaction.
- Develop a procedure to track the movement of individual beads during compaction.
1.3 Layout

The layout of the rest of the report is as follows. In the second Chapter, the state-of-the-art progress in field of industrial X-Ray CT is reviewed. In the third Chapter, detailed information on experimental procedure is presented. In the fourth Chapter, step-by-step image processing procedure is presented with AvizoFire®, a 3D image analysis software for material science. In the fifth Chapter, results of comparative volumetric analysis are presented and discussed along with the deformation measurement results from tracing of one bead track under compaction. In the sixth Chapter, conclusions are given as well as recommendations for further study.
2 Literature review

In the present chapter recent attempts to apply the X-Ray CT to characterize the internal structure of stones and stone-based materials are summarized. A more general account of using X-Ray CT in material science is given in Stock (2009).

X-Ray CT method is an inverse analysis in which one numerically obtains two-dimensional density information based on X-Ray beam attenuation in the object (Avinash and Malcolm, 1988). As X-Ray passed through scanned object, signal is attenuated by scattering and absorption. The simplest expression for attenuation of a monochromatic X-Ray beam through a homogeneous material is

\[ I = I_o \exp(-\mu x) \]  

where
\[ I \] is the final X-Ray intensity
\[ I_o \] is the initial X-Ray intensity
\[ \mu \] is the linear attenuation coefficient of scanned object
\[ x \] is the length of the X-Ray path

Typically, \( \mu \) is given in \( cm^{-1} \). Given relationship between mass density \( \rho \) (\( g/cm^3 \)) and \( \mu \) (\( cm^{-1} \)), mass attenuation coefficient \( \mu/\rho \) (\( cm^2/g \)) can be obtained. Thus, Equation (1) can be rewritten as, (Stock, 2009):

\[ I = I_o \exp((-\mu/\rho)px) \]  

Normally, mass attenuation coefficients can be found from XCOM database managed by National Institute of Standards and Technology (NIST, http://www.nist.gov/pml/data/xcom/index.cfm). The linear attenuation coefficient of one specific component is proportional to its mass density, which is the principle to distinguish different components of one object represented by X-Ray CT images (Ketcham and Carlson, 2001). An X-Ray CT image consists of voxels, the minimum addressable elements for computer. For each voxel, it carries corresponding numerical density information. These raw density data can be converted to CT values, which will be assigned to each voxel. Therefore, CT images are presented with dark color for low CT value and white color for high CT value (Mukunoki et. al 2004). It is common in medical scanners to normalize the X-Ray attenuation data to that of water:

\[ CTvalue = \frac{1000(\mu - \mu_w)}{\mu_w} \]  

(3)
where

\[ \mu_t : \text{Linear absorption coefficient of X-ray at scanning point} \]

\[ \mu_w : \text{Linear absorption coefficient of X-ray for water} \]

Here, the CT value of air is -1000 because the linear absorption coefficient of air is almost 0, and then the CT value of water is 0 (Johns et al., 1993). However, absolute numerical CT values can be defined variously according to different requirements, for example, in industrial CT system, CT values are sometimes normalized so that air, water and aluminum are set to have CT values of 0, 1000 and 2700 respectively (Johns et al., 1993; Ketcham and Carlson, 2001).

Beam hardening effect and the partial volume effect are the two main issues that will influence the qualitative analyze. For the beam hardening effect, it causes the edges of an object to appear brighter than the center area. Normally, there are a number of possible remedies for beam hardening, ranging from sample and scanning preparation to data processing. One way is to use the higher energy beams which are generated by more than 300kV to reduce the beam hardening effect. For the partial volume effect, the X-ray CT value can be the average CT value number if one voxel contains objects with different density. It can be reduced by choosing the appropriate grain size of the sample corresponding to the voxel size (Mukunoki et. al 2004).

In recent years, more and more important applications have been done with the X-ray CT. In particular, X-Ray CT has been actively applied to characterize microstructure, quantify material permeability, and detect shear bands in rocks, soils, concretes and asphalt mixtures, as reviewed below.
2.1 Rock

Porosity refers to ratio between void space and total volume of the rock. It is a fraction of volume of voids over the total volume and it can be obtained as:

$$\phi = \frac{V_v}{V_T}$$  \hspace{1cm} (4)

where

$\phi$ is porosity

$V_v$ is the volume of void space (pore space)

$V_T$ is the total volume of rock

It is a value between 0-1, or multiplied by 100 it can be expressed as a percentage. It is one of the most important petrophysical properties that determine the storage capacity of hydrocarbons. It is also a key factor controlling fluid flow in rock. (Taud et al., 2005).

(Taud et al., 2005) presented the grey level method to estimate the porosity of rocks from CT imaging by a single scan. The basic idea of their method is by integrating the CT values instead of traditional way by using subjective segmentation techniques in image analysis (Ashbridge et al., 2003; Sheppard et al., 2004). In their study, CT image is symbolized as a Digital Terrain Model (DTM), grey level $r$ also represents elevation in DTM. The volume of terrain can be estimated through (Taud et al., 2005):

$$V = s^2 a \sum_{r_{\text{min}}}^{r_{\text{max}}} (r_i - r_{\text{min}})H(r_i)$$  \hspace{1cm} (5)

where

$s^2$ is the 2D pixel size on XY space

$a$ is the pixel size in Z direction

$r_i$ is one grey level (elevation)

$H(r_i)$ is the histogram of the image with grey levels in the range $[r_{\text{min}}, r_{\text{max}}]$.

The porosity $\phi$ then can be expressed as:
\[
\phi = \frac{V_E}{V_T} = \frac{\sum_{r=0}^{r_{\text{max}}} (r_{\text{max}} - r_i)H(r_i)}{\sum_{r=0}^{r_{\text{max}}} r_{\text{max}}H(r_i)}
\]

(6)

where

\( \phi \) is the porosity

\( V_E \) is the volume of the empty space, corresponding to complementary solid volume

\( V_T \) is the total volume of the rectangular parallelepiped including DTM and empty space

Grey level (CT value) in a voxel reflects not only the density and composition in a voxel, but also those in neighbouring voxels, because the spatial resolution is larger than the voxel size. Each voxel must be considered to estimate porosity. The porosity distribution can be calculated based on the following formula,

\[
\phi(l) = \frac{\sum_{l=0}^{l_{\text{max}}} (l - r_i)H(l)}{lH_{a}(l)}
\]

(7)

where

\( l, \) ranging from 0 to \( r_{\text{max}} \)

\( H_{a}(l) \) is the accumulative histogram of image

When there are several isolated points with very high CT value, ratio between \( V_E \) and \( V_T \) is disproportionate. Then the minimum of distribution \( \phi(l) \) curve gives the value of the estimated porosity.

Fracture aperture \( \beta \), it is the perpendicular width of an open fracture. In effect, fracture aperture is the void geometry distribution resulting from the separation or mismatch between the two surfaces of a fracture. It is an important parameter in determining the flow and transport characteristics of fractured media (Keller, 1998; Kulatilake et al., 2006).

(Yoshino et al., 2003) examined aperture distribution with X-Ray CT by comparing fracture tomography and permeability of a cubic granite rock block obtained by two other methods. Fracture tomography is measured by a 3D censor (Bright710: Mitsutoyo Co., Ltd.), it uses 1 mm diameter ruby ball at the tip of the
sensor and it moves with 1mm increments on orthogonal surface (XY plane). Permeability is measured by hydraulic test which will be discussed below.

In Figure 1, the concept of fracture aperture in 3D is illustrated following Yoshino et al., 2003. $A$ is height of specimen, $C_1$ and $C_2$ are heights of upper and lower part of specimen at corresponding XY plane, fracture aperture $\beta_{3D}(x, y)$ can be obtained as:

$$\beta_{3D}(x, y) = A(x, y) - \{C_1(x, y) + C_2(x, y)\}$$  \hspace{1cm} (8)

![Figure 1. Fracture aperture at a slice, Yoshino et al., 2003](image1)

![Figure 2. Front view of specimen in hydraulic test, Yoshino et al., 2003](image2)
In Figure 2, the front view of specimen in hydraulic test is illustrated following Yoshino et al., 2003. Plastic plates are glued by silicon material to avoid water leak from edges. Holes are for water injection and head measurement. In Figure 3, the sketch of hydraulic test system is illustrated following Yoshino et al., 2003. Head value is measured by manometer at injection and withdrawal hole. Flow rate is measured by electric balance meter automatically.

In Figure 4, boundary estimation procedure used by Yoshino et al., 2003 is shown. CT value of 1000 was assumed as boundary between rock matrix and fracture in order to avoid the influence from noise in data. Noise of CT values might be caused by several minerals in granite rock with different density.

The result of X-ray CT showed that fracture surface were more uneven, the
variation of $\beta$ were larger and there were more contact areas comparing with result of 3D sensor. On the other hand, the representative permeability by the numerical simulations using $\beta$ with CT is nearly zero, which was consistent with much rough fracture surface. These results might be caused by the noise and too coarse resolution of CT data (0.293 mm x 0.293 mm x 0.5 mm).

(Sato et al., 2003) introduced a new effective method for the crack opening measurements of heterogeneous materials with the 3D data given by X-ray CT. In their method, two images were constructed under different conditions: the inside of crack is filled with air and the crack is filled with water. In the end, image substraction method was more effective when comparing with crack projection method.

In Figure 5, the sketch of the analysis region is illustrated following Sato et al., 2003. Crack opening along X-axis is denoted by $w$, two crack surfaces are parallel to Y-axis at the position $x = \pm \omega / 2$. By taking logarithms of Equation (1), project $p$ can be rewritten as:

$$p = \ln \left( \frac{I_0}{I} \right) = \mu x$$

(9)

Then, projection along X-axis for two cracks with material $\alpha$ and $\beta$ respectively can be expressed as:

$$p^\alpha = \mu^\alpha (p - \omega) + \mu_e \omega$$

(10)
\[ p^\beta = \mu^\alpha (p - \omega) + \mu_\beta \omega \]  

(11)

where

\( p^\alpha \) is the projection on condition that filled material in crack is \( \alpha \)

\( p^\beta \) is the projection on condition that filled material in crack is water \( \beta \)

\( \mu \) is the linear attenuation coefficient of rock matrix

\( \mu_\alpha \) is the linear attenuation coefficient of material \( \alpha \)

\( \mu_\beta \) is the linear attenuation coefficient of material \( \beta \)

The heterogeneity of the material can be eliminated by subtraction of X-ray CT images and the crack opening \( \omega \) can be represented by the projection and CT values.

\[ \omega = \frac{p^{(\alpha)} - p^{(\beta)}}{C^{(\alpha)} - C^{(\beta)}} \]  

(12)

where

\( \omega \) is the cracking opening

\( C^{(\alpha)} \) is mean CT values for material \( \alpha \)

\( C^{(\beta)} \) is mean CT values for material \( \beta \)

Mean CT value \( g(i) \) at \( i \) and projection along x-axis \( p \) is given by

\[ g^{(\alpha)}(i) = \frac{\sum_j \sum_k C^{(\alpha)}(i,j,k)}{\tilde{S}} \]  

(13)

\[ g^{(\beta)}(i) = \frac{\sum_j \sum_k C^{(\beta)}(i,j,k)}{\tilde{S}} \]  

(14)

\[ p^{(\alpha)} = \sum_i g^{(\alpha)}(i)d \]  

(15)

\[ p^{(\beta)} = \sum_i g^{(\beta)}(i)d \]  

(16)

where

\( \tilde{S} \) is number of pixels in projection area

\( d \) is the length of the pixel side

\( p \) can also be expressed by CT values.

Furthermore, the stacking plural images taken at same situation were used to reduce
the noise influence due to the stable state of crack in rock.

(Takemura et al., 2004) used X-Ray CT to study the distribution of two types of micro-cracks in rock. One is grain boundary cracks, which microcracks developed along mineral grains; The other one is sharp microcracks, whose orientation is parallel to axial stress direction. The maximum aperture was measured by image analysis after confirmation of proposed failure mechanism and microstructural model (Oda et al., 2002a, Takemura and Oda, 2002, 2004). A new confining pressure vessel was made of carbon fiber which had high tensile strength as well as low specific gravity. It allowed for observation of the microcrack growth and the aperture change directly. It also mentioned a triaxial compression cell equipped with microfocus X-Ray CT will be developed in future to trace fluid flow associated with failure.

(Lenoir et al., 2007) observed localized deformation directly using the volumetric digital image correlation method applied to X-Ray CT images. A set of triaxial compression tests on specimens of argillaceous rock was performed with X-Ray CT. Local deformation can be seen directly from X-Ray images if volumetric strain is large enough, resulting in measurable variation of mass density. If there is no essential change in volume, volumetric digital image correlation method is needed to be used with 3D images to obtain development of shear bands. Their method can obtain the spatial displacement of a set of points from one 3D image to another and corresponding incremental strain field from von Mises equivalent strain (Ranson et al., 1985). Two computed 3D strain fields are selected from vertical cut along the axis and horizontal cut close to the bottom end. Strain localization with conical shape can be detected in the pre-stress-peak increment phase and shear band with a more planar mechanism can be detected in the post-stress-peak increment phase, which are hidden in direct visualization. However, thickness of shear band is largely over evaluated, which cannot be smaller than subset size (280 \( \mu m \)). Tested specimens are typically less than 70 \( \mu m \) (Lenoir et al., 2006). They also suggested the quality of images as well as signal-to-noise ratio should be high in order to get a rather satisfying result.

2.2 Soil

(Matsushima et al., 2004) evaluated irregular grain shape of Toyoura sand. In their study, erosion technique was adopted to separate each grain from the others after thresholding, then eroded pixels were attributed to one of the identified grains inversely, which is called a grain identification method. In Figure 6, the erosion process is illustrated following Matsushima et al., 2004. White pixel represents grain while dark part represents void. Erosion process means white pixels would be changed to black pixels if they had one or more black neighbouring pixels, which are the pixels with “*” in the center.
After three successive repeat erosion steps, remaining pixel groups are considered as identified grain. Then, list of eroded pixels at earlier erosion process is used for attribute themselves to closet identified grain groups. Three times of erosion were found to give most satisfying result based on comparison of the percentage of grain with diameter located at range from 0.1mm to 0.2mm, which fit real diameter range of specimen. Contact area is defined by neighbor pixels attributed to different grain groups. This kind of contact relationship observation can contribute to understanding of the grain shape effect on mechanical behavior of granular materials. However, during attribution process, some pixels could never be attributed to grain groups due to erosion process, leading to some lost grains; some pixels wrongly attributed to a new grain group, it was argued by Matsushima et al., 2004 that it is necessary to remove the processing errors to achieve accurate segmentation results.

Permeability is the measure of a porous media’s ability to allow water to flow through pores or voids. Coefficient of permeability is denoted by $k$ and it is also known as hydraulic conductivity, it is in the dimension of velocity, however, it is various in different fields and in geotechnical field it is $cm/sec$. It is a very important physical property for porous materials and it can be used to estimate the quantity of underground seepage. (Das, 2008).

(Kikuchi et al., 2004) discussed permeability of light-weight soils (LWS) made of high water content clays mixed with air foam and cement. Initially proposed hypothesis that air void in LWS can be considered impermeable is verified by permeability experiment with triaxial apparatus (Das, 2008). Seepage test showed that water seeped to area without air at first then air void would be filled with water after air void was surrounded by absorbed area (Otani et al., 2001). In Figure 7, mechanism of absorption is illustrated following Kikuchi et al., 2004. (a) the initial state of specimen, (b) water starts to seep into zone around air void, (c) water starts to seep

Figure 6. 2D schematic erosion process, Matsushima et al., 2004
Figure 7. Image of mechanism of absorption to LWS

Figure 8. Outline of permeability test apparatus, Kikuchi et al., 2004

into air void, (d) water continuously seeps into air void. Permeability experiment with X-Ray CT showed air foam would be compressed after a long time and be saturated by water with absorption. Specimens of LWS consists of cemented clay and cement treated clay are used.

In Figure 8, the sketch of permeability test apparatus is used by Kikuchi et al., 2004 is shown. One side of specimen is sealed, one end of specimen is open for absorption, the other end of specimen is covered with porous stone and a cap (a pipe for expelling water outside of the cell). Income velocity is calculated by change of included water with time, which can be seen as change of white area from CT images. Then permeability can be estimated from the final expanding velocity. It proved that the coefficient of permeability of the cemented clay part of LWS was the same as the coefficient of permeability of cement treated clay.
2.3 Concrete and similar materials

(Wong and Chau, 2004) investigated evolution of air voids in concrete specimen under uniaxial loading. In their study, specimen before loading and under loading of 50% and 85% of estimated ultimate strength were scanned, then overall air content measured from the pressure method was compared with calibrated CT data. A sensitivity study was used to obtain an appropriate thresholding CT value (1300) for an accurate estimation of air voids content. Authors pointed out that their CT method could be more effective if pixel size of 0.25 mm x 0.25 mm was reduced, which meant more micro-crack could be distinguished. Air voids were grouped by population of various pore sizes. Increasing rate among each group varied under different loading condition due to nucleation or growth or micro-cracking. This implied that concrete under axial compression may reduce its durability and resistance against chemical diffusion and corrosion.

(Temmyo et al., 2004) estimated structural characteristic of RCC (Roller Compacted Concrete), specimens of different compaction levels (12 and 16 times respectively) were scanned, manual binarization was performed and ratio of aggregates (sum of area of aggregates to whole cross-section area for each slice) were adopted to check segmentation of materials and effect of vibrating compaction. Distribution of void ratio can also be obtained since CT value of air is defined less than zero. It showed that void moved up from lower part to upper part due to a vibration roller action. The remain area except the areas of aggregate and void represented the mortar. From distribution of the mean CT value of mortar, density in the lower part is higher than that in the upper part, bleeding might occur near upper part in one specimen with compaction of 16 times.
3 Experimental procedure

In the present section, the experimental procedure used in this study is to evaluate deformations of granular media under an unconfined compaction described in detail.

KTH X5000-CT X-Ray CT scanner is utilized for scanning specimen before and after compaction; the system used is shown in Figure 9. It is a seven-axis universal X-Ray imaging system designed for scanning large objects with a flat panel digital plate. The system is equipped with two X-Ray tubes macro-focus 450 kV and micro-focus 225 kV. It can produce X-Ray intensity at maximum value of 450 kV.

![X-Ray CT scanner](image)

**Figure 9.** X-5000 X-Ray CT machine

**Table 1.** Specification of X-Ray CT used in this study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>135 kV</td>
</tr>
<tr>
<td>Current</td>
<td>2.251 μA</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1078mm x0.1078mm x0.1078 mm</td>
</tr>
<tr>
<td>Focal spot size</td>
<td>1 μm</td>
</tr>
<tr>
<td>Sampling</td>
<td>1400 angular projections</td>
</tr>
<tr>
<td>X-ray filter</td>
<td>3 mm copper</td>
</tr>
</tbody>
</table>
The parameters used for image acquisition in this study are shown in Table 1.

Specimens with dimensions of (15 cm x 15 cm x 10 cm) are fabricated as a mixture of glass beads and bitumen. Glass beads have a spherical shape and most of them have a diameter of 16 mm or 17 mm. Among them, some of the glass beads have a color strip inside which has a different density and is thus visible in X-Ray scan. This allows for a convenient way to identify the individual beads. However, it also brings an adverse effect on digital image processing, which will be discussed in the Chapter 4.

Specimen was scanned initially by X-Ray at an as-prepared state and then it was scanned again after an unconfined compaction. A 100 kN dynamic load frame (MTS) has been used and the load has been applied to the specimen through a wooden plate (150 mm x 75 mm). The specimen’s temperature during the simulated compaction was approximately 120°C. Reconstruction phase was conducted to produce 2D slices with thickness of 107.8 μm from raw intensity data and CT values were determined by a computer workstation. Two sets of X-Ray 3D images with 865 slices and 937 slices respectively were prepared and were adjusted by using same range of histogram to achieve the satisfying quality of the specimen images.

In Figure 10, specimen example before mixing with bitumen and the wooden plate are shown. In order to eliminate the influence caused by uneven surface on the top, sub-volume from the center is selected in the present study for the digital image analysis. Three regions of interest are extracted for comparison:

Region 1 with dimension of 65 mm x 130 mm x 53.9 mm located in the loaded half of the specimen;

Region 2 with dimension of 75 mm x 150 mm x 78.4 mm located in the unconfined half of the specimen;

Region 3 with dimension of 75 mm x 150 mm x 53.9 mm located in the unconfined half of the specimen.
Figure 10. Specimen before mixing with bitumen and the wooden plate
4 Digital image analysis

In the present study, the internal structure of the granular material has been analyzed before and after the compaction. The procedure developed here to perform digital image analysis is reported below.

Digital image analysis aims at detecting, enhancing and analyzing images by means of computers (Qihao, 2012). Any image with different colors perceived by humans can be formed by the right brightness combination of red (R), green (G) and blue (B) color. RGB image can be converted to grey image equivalence, which only carries intensity information. A grey image is a matrix of pixel values, which are the smallest addressable components. For a (8-bit) grey-level image, the grey level range is limited from 0 to 255, corresponding to dark to white visually, but the name emphasizes that such an image will also include different shades of grey. Statistically, a histogram can be shown on distribution of pixel frequency and corresponding grey value within an image (Zhou et al., 2010).

Figure 11. Cropped data of study region 2
In Figure 11, cropped data of study region 2 of the specimen in as-prepared state is shown. Beam hardening effect with brighter edge area and darker inner area can be observed in Figure 11. In Figure 12, the corresponding gray level histogram is illustrated. The abscissa presents grey level while the ordinate presents frequency of pixels (count of pixels). The grey level more than 120 can be roughly regarded as beads since the density of beads is higher as compared to that of bitumen and air.

A 3D commercial analysis software AvizoFire® for material science is relied upon in this study for the post-processing of the scanned data. It offers a broad range of tools for obtaining and visualizing advanced qualitative and quantitative information on material structure images (Avizo User’s Manual, 2012). The techniques used for digital image analysis generally include image enhancement, image filtering, edge preserving smoothing, thresholding and segmentation. The specific digital image analysis procedure developed in this study will be illustrated below as pre-processing and filtering, segmentation, quantification and deformation tracking steps.

### 4.1 Image pre-processing and filtering

The aim of pre-processing is an improvement of the image data that suppresses undesired distortions or enhances some image features relevant for further processing and analysis task (Miljkovic, 2009).
In order to compare the before and after compaction scans in the same global coordinate system, reference points are necessary. In this study, a stitch nailed in the wood plate previously has been used as a reference point, for aligning sample to same global coordinate. A pin is nailed in wood plate beforehand has been used as the other reference point, for getting same study region of sample before and after compaction.

In Figure 13, spatial coordinate system is shown. Red axis represents X-axis, yellow axis represents Y-axis and blue axis represents Z-axis. In Figure 14 and Figure 15, reference points of stitch and pin are shown for two scanning images before and after compaction. The point in the center of the figure is the pin. The specific stitch which is close to the center point is used for aligning (within the red circle in Figure 14 and
Figure 15. Ignoring top and bottom slices, slice where stitch has the best quality of visualization are selected to be the first slice for each image respectively. It can be also seen that two scanning images have different inclining degrees.

In Figure 16 and Figure 17, the aligning of scanning images before and after compaction is illustrated. Affine transformations are conducted with *Transform Editor* to adjust scanning images. Scanning images are then rotated and shifted until the stitch line coincides with the grid line of spatial coordinate system (within the red circle in Figure 16 and Figure 17). *Resample transformed image* is applied to save the updated images.

**Figure 15.** Reference points in scanning image after compaction

**Figure 16.** Aligning of scanning images before compaction
**Figure 17.** Aligning of scanning images after compaction

**Figure 18.** Resampled images before compaction
In Figure 18 and Figure 19, images before and after compaction are resampled. Unfortunately, the exterior dark surrounding is redundant and occupy so much space which will weaken shading correction and increase computational time. Cropping operation is needed to resolve previous problem and extract the truncated study regions.
Figure 21. Cropping box for study region 1

Figure 22. Cropping box for study region 2

Figure 23. Cropping box for study region 3
In Figure 20, cropping box is shown. Subset of images can be obtained by cropping. Since subsets should be matched before and after compaction, accurate cropping regions are necessary instead of arbitrary cropping regions. In Figure 21, cropping box of study region 1 (red region) is shown. It is a rectangular box with dimension of 65 mm x 130 mm x 53.9mm (500 slices) with one side located on the center line. In Figure 22, cropping box of study region 2 (red region) is illustrated. It is a rectangular box with dimension of 75 mm x 150 mm x 78.4 mm (727 slices) with one side located on the center line. In Figure 21, cropping box of study region 3 (red region) is presented. It is a rectangular box with dimension of 75 mm x 150 mm x 53.9 mm (500 slices) with one side located on the center line.

Intensity adjustment can be achieved by adjusting brightness and contrast with the aim to have a better visualization of images, especially for discriminating areas initially having a small difference in density (Sivakumar, 2004). It include brightness/contrast, Adaptive histogram equalization, sigmoid intensity remapping. The basic principle is to rearrange pixels frequency with different grey level in grey level histogram within a range. Since the datasets have already been adjusted to get a good visualization effect by computer in working station, no change is needed here. However, beam hardening effect can be detected, as showed in Figure 22. It is hard to distinguish beads from bitumen and air, especially in the left center. Shading correction is adopted for correcting beam hardening effect by computing a background based on threshold mask and then correcting uneven brightness automatically. It can also be done with two separate operations: Bkgimg is for getting an illumination profile (the flat-field), and then correction background and flat-field is used to even the brightness. In Figure 24 and Figure 25, effect picture of shading correction for study region 2 is shown. Since it is a cropping study region, the right part of the figure is close to specimen periphery while left part is corresponding to specimen interior. It can be seen by comparing Figure 24 and Figure 25 that shading correction is rather useful to even the brightness of the image.

Figure 24. Study region 2 before shading correction
Even though brightness is improved, there are many “black dots” in individual beads. These are image noise that can be regarded as isolated pixels, with unrealistic grey values. Image filter works on a small neighborhood of one pixel in an input image to produce a new grey level in the output image. Filters are used to reduce noise, enhance contrast and protect edge. Median filter removes noise by checking each pixel in an image entry by entry, sorting out surrounding pixel values in a numerical order and replacing center one with median of neighboring pixel values. All smoothing techniques are effective at removing noise but adversely affect edges. The reason for this is that the edges are areas where intensity of neighboring pixels changes abruptly. Median filter is followed by edge-preserving smoothing filter for protecting stronger edges. Edge–preserving filter models anisotropic diffusion process. Anisotropic diffusion determines new value of current voxel by comparing difference with its 6 neighbors respectively. If the difference is less than diffusion stop threshold criterion, the diffusion would happen. In this way, edge can be preserved (Avizo User’s Manual, 2012). In Figure 26, effect of median filter for study region 2 is shown. Compared to Figure 25, image noise is removed largely. In Figure 27, effect of edge preserving for study region 2 is illustrated. Stronger edges, referring to edges between beads and air voids are preserved.
Figure 26. Study region 2 after median filter

Figure 27. Study region 2 after edge preserving

Morphological filter is a way to fill up unnecessary holes and smooth boundaries. *Erosion* filter replaces value of a pixel by smallest value of neighboring pixels, while *Dilation* replaces value of a pixel by largest value of neighboring pixels. It is not hard to understand that separated parts in an image can be contracted after erosion and expanded to after dilation. *Closing* filter is for eroding the dilated image, it can fill small holes inside objects and connect close objects; while *Opening* filter is for dilating the eroded image, it can remove small objects and disconnected some objects. Due to unpredictable boundary condition of erosion and dilation function, they are not used in this study. *Hole_fill* is used to fill undesirable holes within several objects (Avizo User’s Manual, 2012). One slice from study region 2 is selected for explaining this.
In Figure 28 and 29, the effect diagram of image with \textit{hole\_fill} is shown. For two beads close to the left center, three holes are filled. Meanwhile, there are still several holes that cannot be filled. This might be caused by the color strip of beads which leads uneven density and holes are produced after filtering operations.

4.2 Segmentation

Thresholding is the first step of the segmentation procedure. It groups similar grey values (same brightness) together. Histogram shape-based method is used to get an appropriate thresholding value via analysis of the peaks, valleys and curvatures of the smoothed histogram. Factors that influence thresholding are ambient illumination, variance of grey levels within the object and the background, inadequate contrast, object shape (Sankur et al., 2001). Intensity range calibration can give a recommend thresholding value by determining several possible threshold values according to user’s choices of phase numbers. After applying a threshold value, a binary image is produced with values either 1 or 0. The part with value 1 is marked in blue.
Figure 30. Study region 2 after thresholding

In Figure 30, thresholded image for study region 2 is shown. The pixels which have higher grey level than threshold value are grouped together and marked in blue, which is largely possible separated as beads and bitumen. For other pixels which have grey level less than threshold value are in black and will be regarded as air void.

Three are three methods to conduct segmentation procedure on thresholded binary image. Watershed segmentation based on distance map is an advanced way to make an accurate separation by interactive trial and error. Watershed-segmentation is a semi-automatic function to obtain a desirable separation of different phrases. Binseperate is the simplest one with only one controllable parameter. Most of the following introduction is abstracted from (Avizo User’s Manual, 2012).

Distxxx is used to calculate distance map for image for watershed segmentation. Distance map means converting a binary image where each object pixel has a value corresponding to the minimum distance from the background by a distance function. It is very sensitive to holes in object. Maxima is the furthest part from border according to distance transformation. It is merged based on determination of contrast factor. From Figure, it can be seen obviously that bigger the contrast factor is, more maxima (summit) will be merged. Merge_maxima gathers up neighbouring local maxima values of input distance map, which are located in most inner region of object. In Figure 31, definition of contrast factor is illustrated following Avizo User’s Manual, 2012. If the contrast factor is increasing, the distance between summit and merged maxima will be bigger, it means that original two peak points will be merged as the right part in the figure. In other words, many more maxima will be merged together if contrast factor are increased.
Figure 31. Figure definition of contrast factor, Avizo User’s Manual, 2012

Figure 32. Contrast factor of 4 before compaction (slice 175)

Figure 33. Contrast factor of 7 before compaction (slice 175)
In Figure 32, merged maxima (contrast factor of 4) are shown. Only a few merged maxima are there. In Figure 33, merged maxima (contrast factor of 7) are shown. Larger contrast factor leads to more merged maxima and thus less separation. However, some merged maxima perhaps not appear in this slice could lie in other contiguous upper or lower slices in 3D.

Merged maxima can be labeled as markers with different color for computing watershed line. In Figure 34, the fast watershed principle is illustrated following Avizo User’s Manual, 2012. This principle of computing watershed line is called immersion and it is based on a simulation of the rise of water from user-defined markers. Imaging digging a hole in A and C, flooding begins happen and expands the regions according to a priority map, until two distinct fronts reach at crest point D, constituting the watershed lines along with other similar crest points. This algorithm depends on two inputs: markers created by labeling, they are used as seed areas for flooding. There will be at the end of the process as many separated object as markers labeled differently. The other one, a gray image shows priority map (altitude map). It determined watershed lines. These separations are located on the crest lines between valleys of the landscape. Immersion progressed from low regions to peak regions, which means distance map need to be reversed. If grayscale range of distance map is [0,30], arithmetic with A*(-1) will give a range at [-30,0]. Logical sub command is used to separate objects by combining thresholded image and watershed line. Watershed segmentation shows the same segmentation result with binseperate. In this study, binseperate is used which will be introduced later.

Watershed segmentation performs an accurate segmentation of different phases by applying a watershed on the high gradient magnitude, which measures how greyscale is changing. Gradient magnitude indicates intensity discontinuities and it can be used for detect the edges. It is a semi-automatic command. At first, known information about number of phases of specimen are included (air-void, bitumen and

![Diagram of watershed segmentation](image)

**Figure 34.** The fast watershed principle, Avizo User’s Manual, 2012
beads). Then gradient magnitude is computed and areas are needed to be thresholded, meaning areas where markers cannot be set are needed to be defined. Next, different phases are needed to be thresholded. At last, watershed line is computed based on the different phases user thresholding. Dilatebasin is used to identify three phases with different colors and quantitative measurement on air void, bitumen and beads can be conducted.

Binseparate can compute watershed lines on the gray-level image for 3D objects. Instead of step-by-step watershed segmentation it is a high-level combination of the fast watershed, distance transformation and numerical reconstruction algorithms. It is rather useful and convenient in many simple cases. However, if object shape is non-convex, too many local maxima would occur (due to distance transformation), therefore more separated object. The only user-define factor is the depth of valley (difference between two maxima), which functions as contrast factor in merge_maxima. Increasing depth of valley, more maxima value will be merged, resulting in less separation (Avizo User’s Manual, 2012). 7 is selected as depth of valley to conduct Binseparate giving the best segmentation result based on comparison with the original scanning image. In Figure 35, segmentation result is shown according to binseperate.

Figure 35. Study region 2 after binseperation
Volume rendering is used for visualization of 3D data. In Figure 36, volume rendering for study region 3 before compaction is shown.

4.3 Quantification and deformation tracking

I_analyze is a command used in AvizoFire® for quantitative measurement of the specimen volumetrics. It has basic group to calculate parameters such as volume of 3D segmented objects, maximum and minimum Feret length of distribution, angle of the maximum of the Feret Diameters over a range of angles, orientation of the particle (principal inertia axis) in degrees. In this study, Length3d, volume3D, BaryCenterX, BaryCenterY and BaryCenterZ are added to one user-defined measurement group. Length3d is used to obtain the maximum Feret diameter of one object, which is the largest distance between any two points belong to the boundary over a range of angles (Nicoletto et al., 2012). Volume3d is used to obtain air void content by subtracting volume of each individual objects from total volume of study region.

In the theoretical case, Volume3D is defined as:

$$ V(X) = \int_{R^3} (I(x, y, z)dx dy dz) $$  \hspace{1cm} (17)

While in actual case, Volume3D is estimated by the amounts of pixels in X, so Equation (17) can be rewritten as:

$$ V(X) = \sum_{i,j,k} I(x_i, y_j, z_k) $$  \hspace{1cm} (18)

where
\( I(x_i, y_j, z_k) \) is the intensity of the pixel with the coordinate \( x_i, y_j, z_k \) (Visilog 7 Reference Guide).

\( BaryCenterX, BaryCenterY, BaryCenterZ \) is calculated for spatial position of the center of gravity and then track movement by comparing change of position under deformation. Furthermore, \( Measure \) is used to get total area of air void in each slice respectively to study air void distribution under compaction. The results of the quantitative analysis performed will be illustrated in the Chapter 5.
5 Results and discussion

In this section, results regarding relevant volumetric information obtained by the use of I\_analyze are performed. Length3d and Volume3D are two parameters can be used for filtering according to given information regarding the size of beads. The accuracy of filtering lies in edge effect, which means that many beads intersect the boundary of cropped study region and their size can be underestimated.

The volume of one bead should be 2.14 cm$^3$ if they have a diameter of 1.6 cm. Filter criteria is set up by Volume3d $>$ 2.14 cm$^3$ or Length3d $>$ 1.6 cm, otherwise they are treated as bitumen and air void. In Table 2, amounts of existed separated objects are shown on condition of no filter, filter criteria with Length3d $>$ 1.6 cm and filter criteria with Volume3D $>$ 2.14 cm$^3$ for three study regions. Take region 1 as an example, with the filter criteria Length3d $>$ 1.6 cm, 149 out of 727 are regarded as beads while with the filter criteria Volume3D $>$ 2.14 cm$^3$, only 82 out of 727 are treated as beads, 67 other objects are also regarded as bitumen.

**Table 2. Comparison of amounts of objects**

<table>
<thead>
<tr>
<th>Region</th>
<th>Amounts of objects</th>
<th>Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No filter</td>
<td>Length3d &gt; 1.6cm</td>
</tr>
<tr>
<td>Region 1</td>
<td>Before compaction</td>
<td>727</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>1133</td>
</tr>
<tr>
<td>Region 2</td>
<td>Before compaction</td>
<td>305</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>425</td>
</tr>
<tr>
<td>Region 3</td>
<td>Before compaction</td>
<td>523</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>1680</td>
</tr>
</tbody>
</table>

**Figure 37.** Filtered beads with filter criteria Volume3D $>$ 2.14 cm$^3$ (Slice 500)
These 67 objects are actually beads, however, they just lie in edge part like the filtered beads in Figure 37. In Figure 37, filtered beads for study region 3 based on filter criteria Volume3D > 2.14 cm³ is shown. It is from slice 500, where the cropped intersection edge. There are 5 more edge surfaces like this and beads can be mistaken as bitumen like this.

On the condition of filtered result, air voids volume is obtained. It is still a little bit over-estimated due to edge boundary effect. In Table 3, for study region 1, although loaded part is affected directly by compaction, less than 1% change happened. It can be explained by the factor that beads cannot be squeezed into one another, thus beads from loaded part under compaction will be pushed to the unloaded part to find a new space. The whole volume moves like a unity. For study region 2, 4.5% change is observed. Unloaded part went up due to push by beads belong to loaded part. Beads have self-weight and it is difficult for beads from lower part to push bead upward. They have to occupy space originally belonging to air voids if there is larger air void space. For study region 3, 4% change is observed. It is the center part of specimen. Most of the volumetric changes happened here. For beads located in the part, above the center part, they are just pushed higher as a whole.

In Figure 38, Figure 39 and Figure 40, air void distribution with depth for study region 1, study region 2 and study region 3 is illustrated. The air void distribution before compaction is marked in blue while that after compaction is marked in red. Slice with stitch is considered as the bottom of specimen. The height starts from 0 to 53.9 mm for 500 slices, to 78.4 mm for 727 slices. It is a piece of evidence that beads will be forced to move to other free space. From Figure 39, top and bottom surface are not even according to the larger air void ratio. It is also proved that it is suitable to study the region with slices of 500 where air void are quite consistent with that of lower part.

### Table 3. Volume of air voids before and after compaction

<table>
<thead>
<tr>
<th>Region</th>
<th>Before compaction</th>
<th>Volume of air-voids (cm³)</th>
<th>Total volume (cm³)</th>
<th>Percentage(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>184.2</td>
<td>456</td>
<td>40.45</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>183.9</td>
<td>456</td>
<td>40.39</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>434.4</td>
<td>882</td>
<td>49.23</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>394.5</td>
<td>882</td>
<td>44.71</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>250.3</td>
<td>607</td>
<td>41.25</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>226.0</td>
<td>607</td>
<td>37.24</td>
</tr>
</tbody>
</table>
Figure 38. Air void distribution for study region 1

Figure 39. Air void distribution for study region 2
To trace the tracks of individual beads during compaction, BaryCenterX, BaryCenterX, BaryCenterX are calculated to obtain X, Y, Z coordinate of the center of gravity of individual beads. Beads are selected from lower part, middle part, higher part before and after compaction. In order to remove sensitive edge effect, which will affect the gravity of individual beads, only whole beads are chosen. Detailed information is included in the following Table 4, Table 5 and Table 6.
Table 5. Location change of three beads in different slices for study region 2

<table>
<thead>
<tr>
<th>Location</th>
<th>Condition</th>
<th>X(mm)</th>
<th>Y(mm)</th>
<th>Z(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom</td>
<td>Before compaction</td>
<td>121.67</td>
<td>106.62</td>
<td>6.71</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>124.71</td>
<td>105.06</td>
<td>6.80</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>3.04</td>
<td>-1.56</td>
<td>0.09</td>
</tr>
<tr>
<td>Middle</td>
<td>Before compaction</td>
<td>123.29</td>
<td>107.97</td>
<td>33.12</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>126.16</td>
<td>105.45</td>
<td>34.37</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>2.87</td>
<td>-2.52</td>
<td>1.25</td>
</tr>
<tr>
<td>Top</td>
<td>Before compaction</td>
<td>121.13</td>
<td>118.59</td>
<td>45.66</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>124.54</td>
<td>116.35</td>
<td>46.40</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>3.41</td>
<td>-2.24</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Table 6. Location change of three beads in different slices for study region 3

<table>
<thead>
<tr>
<th>Location</th>
<th>Condition</th>
<th>X(mm)</th>
<th>Y(mm)</th>
<th>Z(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom</td>
<td>Before compaction</td>
<td>112.40</td>
<td>120.77</td>
<td>6.46</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>117.09</td>
<td>119.61</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>4.69</td>
<td>-1.16</td>
<td>0.04</td>
</tr>
<tr>
<td>Middle</td>
<td>Before compaction</td>
<td>113.28</td>
<td>121.15</td>
<td>30.58</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>119.63</td>
<td>120.39</td>
<td>31.52</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>6.35</td>
<td>-0.76</td>
<td>0.94</td>
</tr>
<tr>
<td>Top</td>
<td>Before compaction</td>
<td>139.90</td>
<td>51.59</td>
<td>42.59</td>
</tr>
<tr>
<td></td>
<td>After compaction</td>
<td>144.07</td>
<td>49.23</td>
<td>43.09</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>4.17</td>
<td>-2.36</td>
<td>0.50</td>
</tr>
</tbody>
</table>
Figure 41. Deformation track at bottom location in study region 1

Figure 42. Deformation track at top location in study region 1
Figure 43. Deformation track at bottom location in study region 2

Figure 44. Deformation track at middle location in study region 2

Figure 45. Deformation track at top location in study region 2
**Figure 46.** Deformation track at bottom location in study region 3

**Figure 47.** Deformation track at middle location in study region 3

**Figure 48.** Deformation track at top location in study region 3
In Figure 4-48, deformation tracks for different slices for three study regions are shown. The intersection points of two orthogonal lines indicate the selected beads (some of intersection points might be covered by the cursor). It can be seen from Table 4-6 that each selected bead is moving to the further right along X-axis direction without any exception. It means beads tend to move towards to the free region under compaction. It is interesting to see that each bead also move closer to the coordinate origin along Y-axis. It might be caused by uneven surface. In vertical direction, almost all selected beads move downward under vertical compaction except one bead from loaded half, it moves upward surprisingly. Most likely, it can be caused by the bead rearrangement. There are some more beads appear on the top surface, under compaction, it might move downward and then push neighboring beads upward.
6 Conclusions

Granular materials deformation under an unconfined compaction is investigated with X-Ray Computed Tomography. In this study, a procedure for digital image analysis of X-Ray CT images was developed based on software AvizoFire®. An idealized granular material - glass beads mixed with bitumen is prepared for X-Ray scanning before and after compaction. Digital image analysis including image acquisition, image enhancement, image segmentation, numerical analysis has been developed applying to two scanning datasets. The main findings are as follows.

In order to perform volumetric relationship before and after compaction, volume of air void is calculated by subtracting volume of aggregate and bitumen from total volume. Air void content of loaded region is not decreased under compaction which can prove that beads will move to other space instead of assuming a denser packed configuration. In the opposite way, air void content of unloaded region is increasing.

Air void distribution is also measured along the depth of the specimens for three study regions. Top and bottom surface are not even according to air void distribution.

Procedure for tracking individual beads under deformation is also developed in the present by comparing their spatial location before and after compaction. It has been observed that most of the beads are moving away from loaded part and squeezing to free space. Furthermore, some beads from initial region without compaction are forced to move upwards when other beads occupied their space.

X-Ray CT was found to be a very promising tool to obtain quantitative information regarding the internal structure and its evolution during deformation. However, in order to get a more precise result, there are some applicable suggestions for future work. In particular, beam hardening effect is obvious in scanning images, even though shading correction can reduce the effect, it is still needed to weaken the beam hardening effect. Sample preparation and scanning procedures need to be improved regarding the sensitivity to differentiating phases i.e. beads, bitumen and air void. A general analysis procedure has to be developed to mark the beads so that deformation map for all the beads can be generated and in a more objective and automated way.
7 Bibliography


