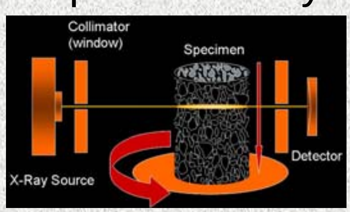
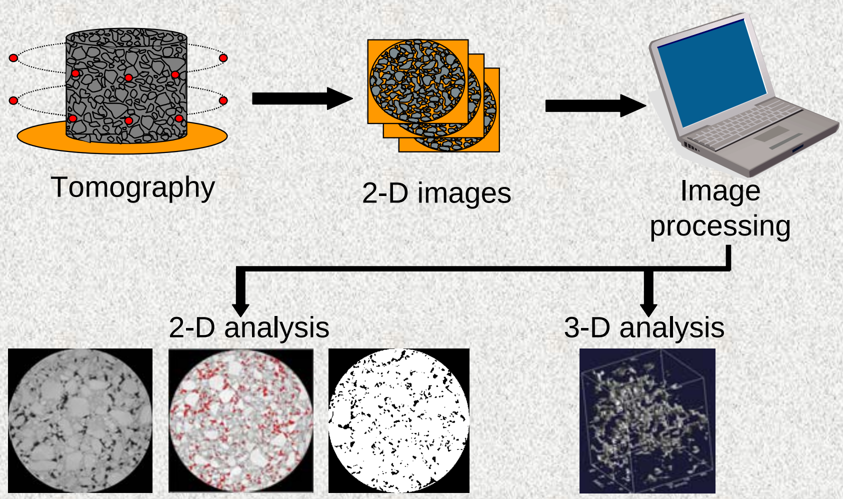
Microstructure Characterization Using X-ray Computed Tomography

Description of X-ray CT



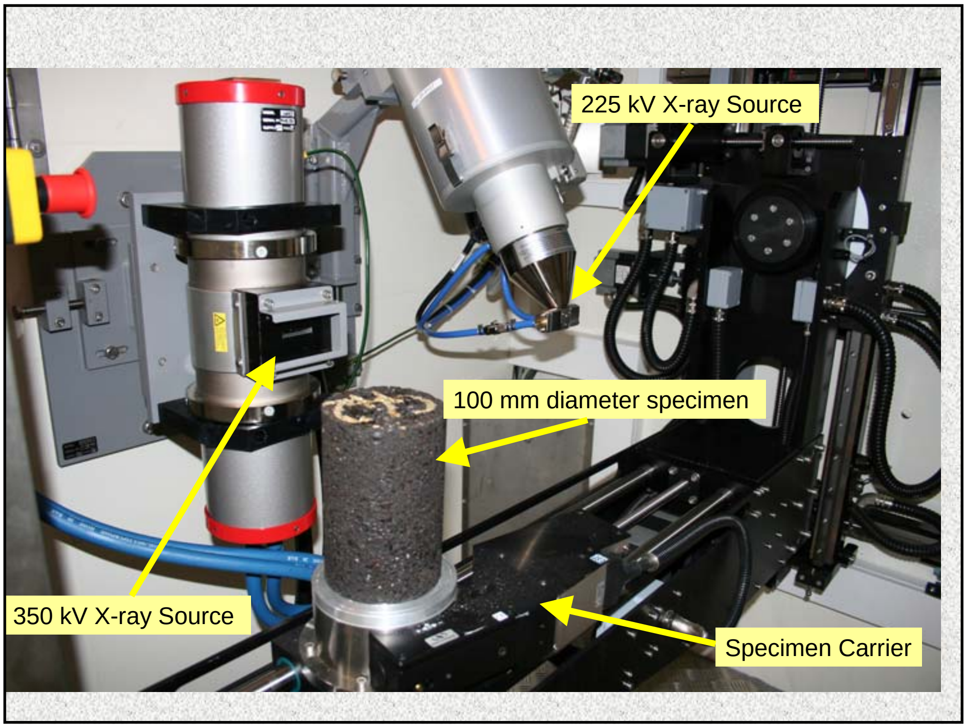
- X-ray CT is a nondestructive technique used for materials microstructure characterization
- The scan procedure is as follows:
  - » A source transmits X-rays with certain intensity
  - » Part of the radiation gets absorbed, part gets scattered, and the rest penetrate through the specimen
  - » The intensity of the transmitted X-rays are measured by the X-ray detector
  - » The specimen rotates 360 to transmit rays from all possible directions
  - » The linear attenuation coefficients (μ), which are a property of the material, are used to estimate the different phases of the specimen and to construct the images: $I = I_o \, exp \int_{ray} -\mu(x,y)\, ds$

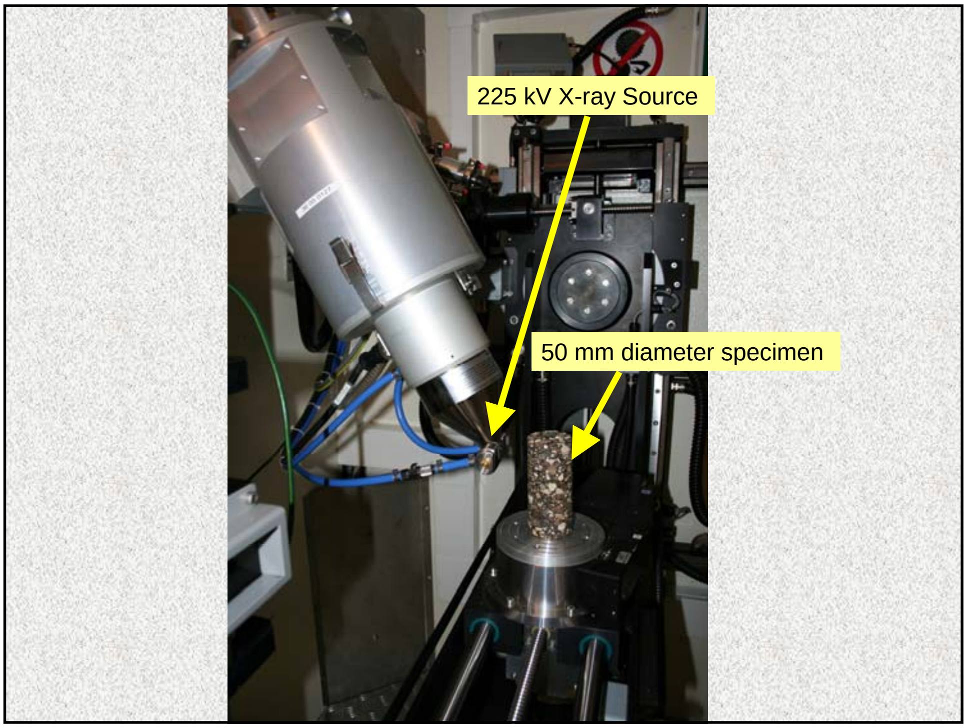
X-ray CT Process



X-ray CT Equipment

- The X-Tek X-ray Core Scanner offers both microfocus-CT and high power mini-CT within the same cabinet system.
- By utilising the precision manipulator to move the sample between two adjacent beam lines the system provides an intuitive method of interchanging between microfocus-CT and mini-CT.
- The system is capable of taking microfocus data up to 225kV and scatter free data (at resolutions up to 200mm/pixel) up to 350kV on denser samples.


225 kV X-ray Source
100 mm diameter specimen
350 kV X-ray Source
Specimen Carrier


225 kV X-ray Source
50 mm diameter specimen

X-ray CT Equipment

- **X-ray source specification**
  - **Source 1:** X-Tek 350 kV Mini-focus X-ray Source

    X-ray Tube: Metal/Ceramic 350/0.5
    Target: Tungsten
    Power: 600W
    Focal spot: 0.5mm to EN 122543
    Cooling: Closed Loop air-oil

  - **Source 2:** X-Tek 225 kV Micro-focus X-Ray Source

    X-ray tube: Fitted with 225-Watt air cooled target
    Voltage: 20 to 225kV
    Beam current: 0 to 2mA max
    Power: 225W
    Focal spot size: 3 - 5μm

X-ray CT Equipment

- **CT Manipulator specification – 350kV cabinet**
  - The system is fitted with a high precision 5-axis manipulator with the following specifications:
    - ✓ Precision stepper motor driven ball screws with joy-stick and CNC control Options capable of 10000:1 speed variation
    - ✓ X,Y,Z axis travel 600mm (0.0025mm to 25mm/sec)
    - ✓ Rotate axis – continuous rotation stage (72 degrees/sec to 8.3×10^{-4} degrees/sec)
    - ✓ Max loading capacity 25kg
    - ✓ Precision over whole scan area better than +/- 0.2mm

X-ray CT Equipment

- **Imaging Specification**
  - » **Imaging System 1:** Microfocus beam-line Imaging System

Detector type:	AREA – for Cone beam CT
Intensifier:	Industrial 6 inch X-ray image intensifier
Scintillator:	Low burn scintillator (Caesium Iodide)
Glass:	Non-browning glass
Digitisation:	10bit digitisation with OCI (on Chip Integration)
Camera:	768 x 572 pixel CCD camera

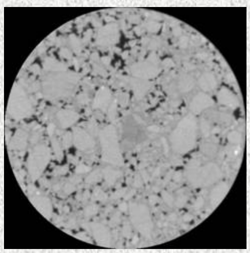
  - » **Imaging System 2:** High Energy, Scatter Free X-ray detector for mini-CT

Detector type:	LINEAR – for CT geometry and scatter rejection
Detector length:	307mm
Pixel size:	200mm x 200mm, binning X2, X4, X8
Dynamic Range:	12 bit, 4096 grey scales

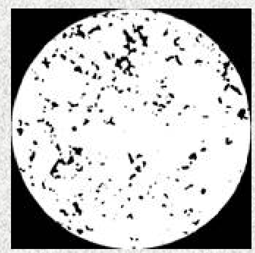
350kV radiation protection / collimation

Applications

Analysis of Air Void Distribution

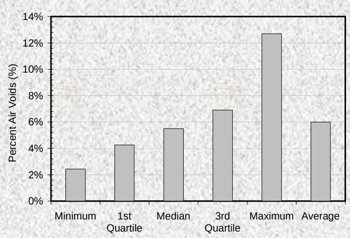


Grayscale image resulting from image processing



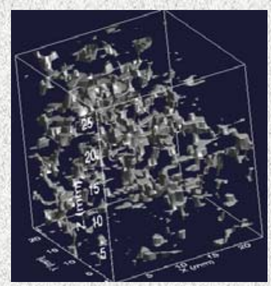
Thresholded Image to identify the amount and size of air voids

$$n = \frac{\sum_{i=1}^{N} \frac{(A_v)_i}{A_T}}{N}$$



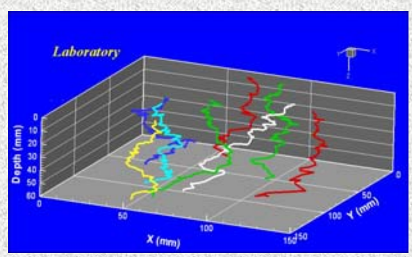
Statistical analysis of air voids

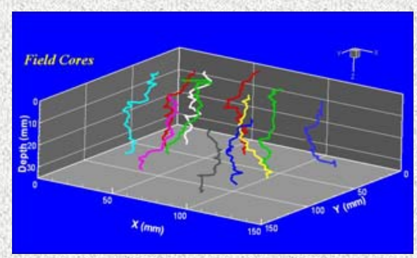
$$F(t) = 1 - e^{-\left(t/\theta\right)^{\beta}}, \qquad t > 0$$



Three dimensional air void structure

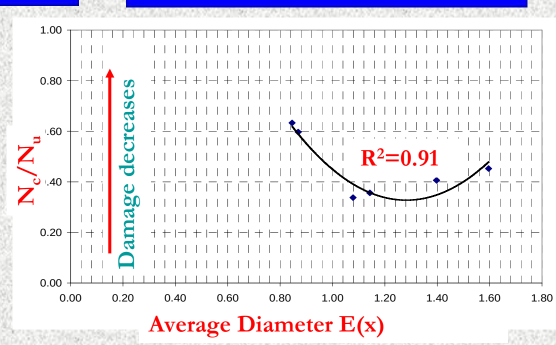
Analysis of Connectivity and Air Void Flow Paths



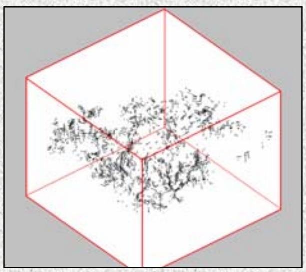


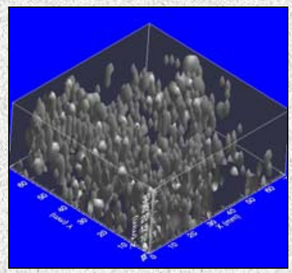
- A method was developed for the analysis of air void connectivity and flow paths.
- This method was used to relate air void structure to permeability and moisture damage.

$$k = \frac{n^3}{c.T^2.S^2}\frac{\gamma}{\mu}$$

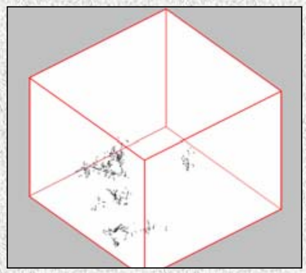


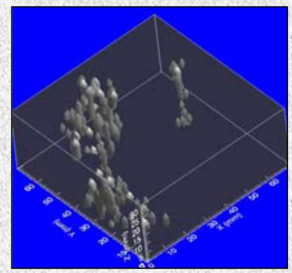
Simulation of Fluid Flow and Permeability





- Input:
  - » X-ray CT image
  - » Microstructure dimensions
  - » Fluid properties



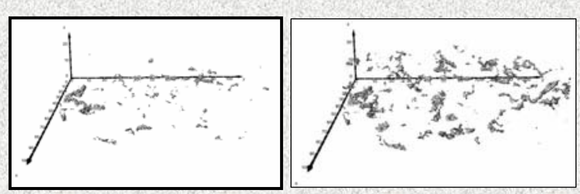


- Output:
  - » Flow fields
  - » Permeability directional distribution

Measurements of Moisture Transport

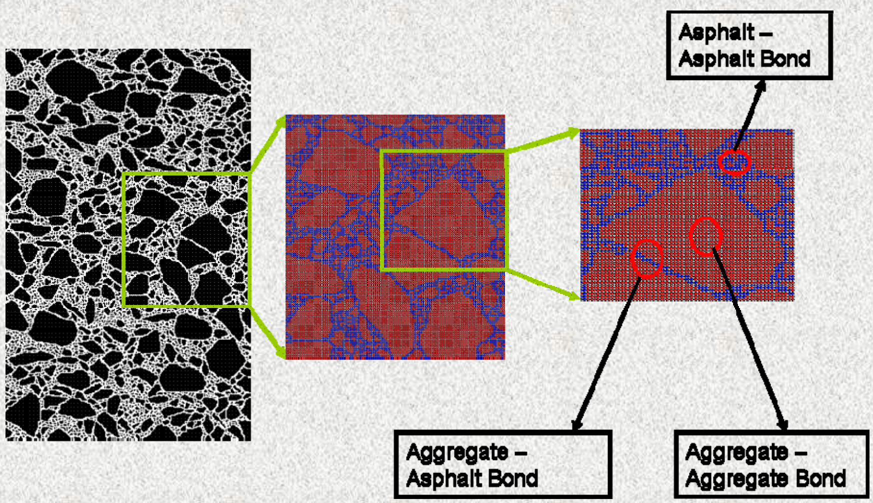
- An experimental setup using X-ray CT was used to:
  - » Monitor water transport in asphalt mix
  - » Calculate capillary rise
  - » Estimate the capillary contact angle of the asphalt mix

Saturated specimen during X-ray CT scanning

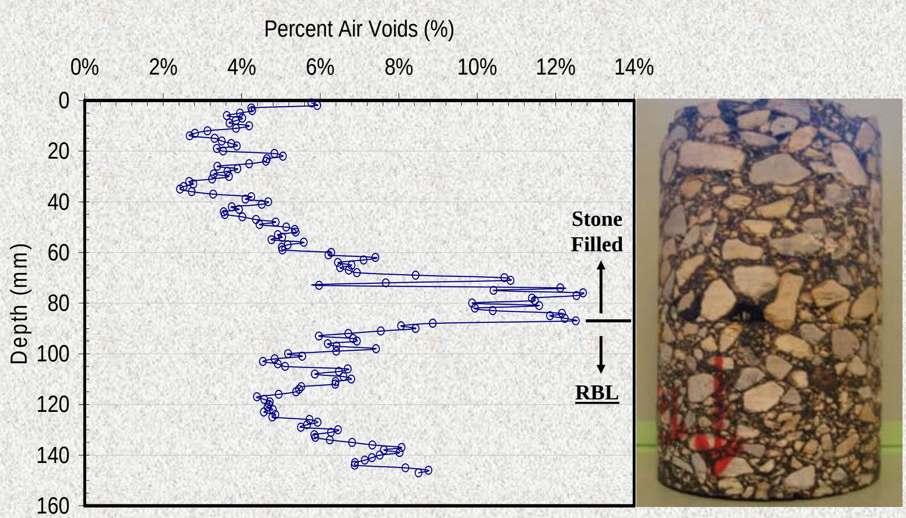


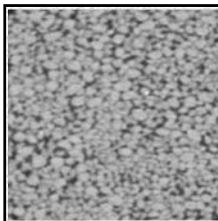
Three dimensional view of the air voids filled with water due to capillary action after different soaking periods

Discrete Element Analysis of Asphalt Mix Microstructure

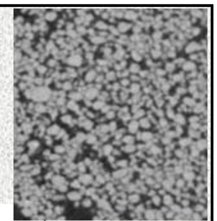


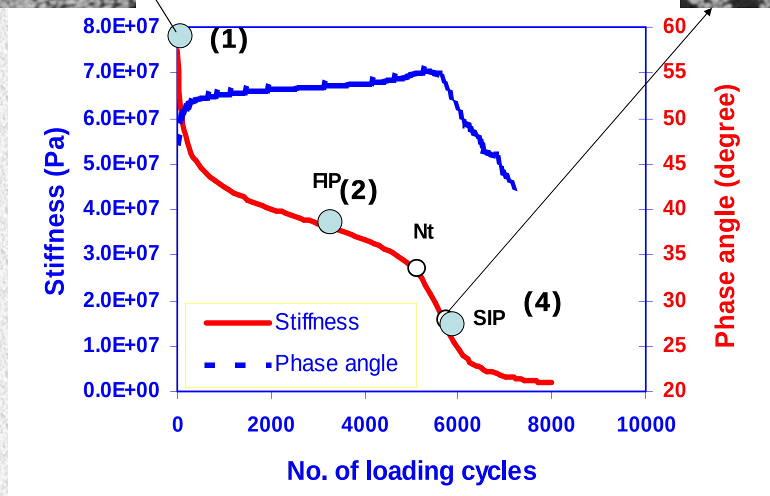
Forensic Evaluation of Compaction



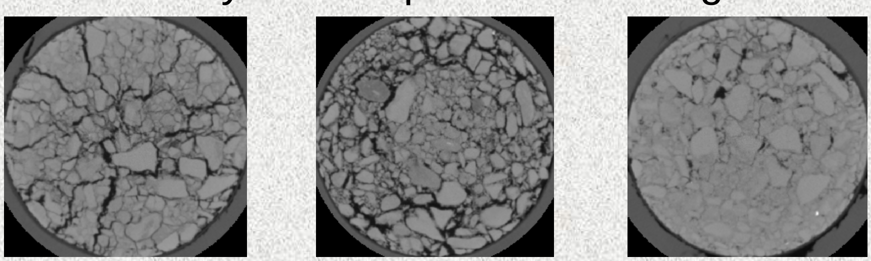


Analysis of Mastic Damage

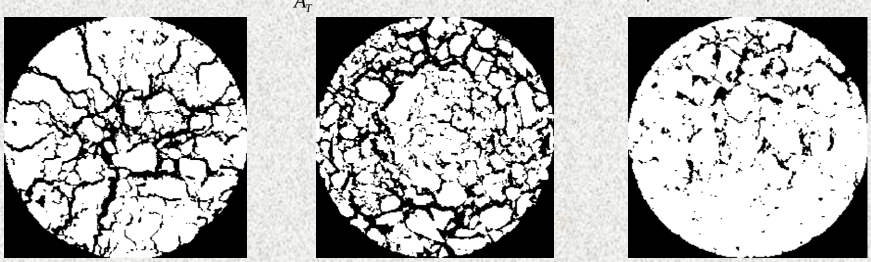




Analysis of Asphalt Mix Damage



$$Void\ Content = \frac{\sum_{i=1}^{M} A_v}{A_T} \qquad Roundness = \frac{P^2}{4\pi A_v}$$

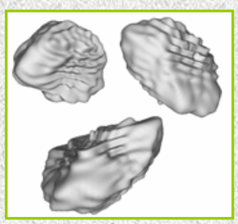


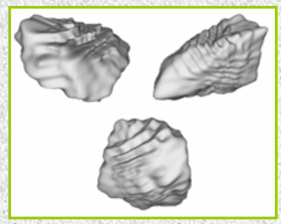
Analysis of Aggregate Shape

Traprock

Limestone

Uncrushed Gravel





$$r(\theta,\phi)=\sum_{n=0}^{\infty}\sum_{m=-n}^{n} a_{nm} Y_n^m(\theta,\phi) \qquad Y_n^m(\theta,\phi)=\sqrt{\frac{(2n+1)(n-m)!}{4\pi(n+m)!}}\, P_n^m(\cos(\theta))\, e^{im\phi} \qquad a_{nm}=\int_0^{2\pi}\int_0^{\pi} d\phi\, d\theta \sin(\theta)\, r(\theta,\phi)\, Y_n^{m*}$$

Three-Dimensional Distribution of Aggregates Due to Compaction and Loading

The aggregate distribution is included in a mechanistic model for predicting asphalt pavement performance