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Pavement materials are made of particles – why are we still treating them as uniform layers?

Andrew Dawson

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A little background

Some problems for, and limitations of, particulate materials

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    unif
- **Time**

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Challenge of Recycling / Reuse

- >70% of Construction & demolition waste is recyclable to aggregate (NL experience)
- Could command 25-30% of aggregate market
- What about marginal & industrial by-product sources?
- Needs understanding
  - Often does not behave the same as conventional aggregates
  - Treating as a homogenous layer won't help our understanding!

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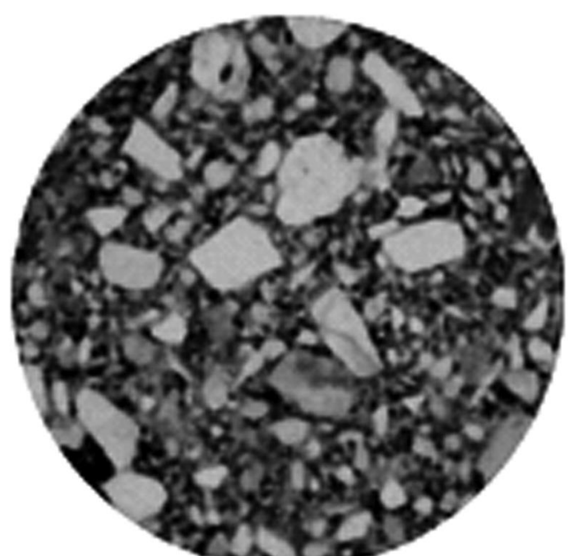
Fundamentals of particulate materials

- Particles of different sizes
- Contact points
  - Carry compressive & shear forces
  - Have very varied orientations
  - Resist shear by friction
  - Contribute to modulus
- Binder provides
  - Adhesion against tensile forces
  - Major modulus contribution
  - Important fatigue resistance



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A little aggregate history

- To overcome the problems and limitations we need
  - To be able to describe material response to the 'loadings' of today and tomorrow
  - To be able to specify solutions that maximise beneficial use
- This is nothing new! Past and present have done so:
  - Ancient Engineers (accidentally successful?)
  - Macadam (the first particulate materials engineer?)
  - Marshall / CBR (classifying experience)
  - Modulus (of layers)
  - Distinct Particle Methods (but not very practical?)
  - And what next?

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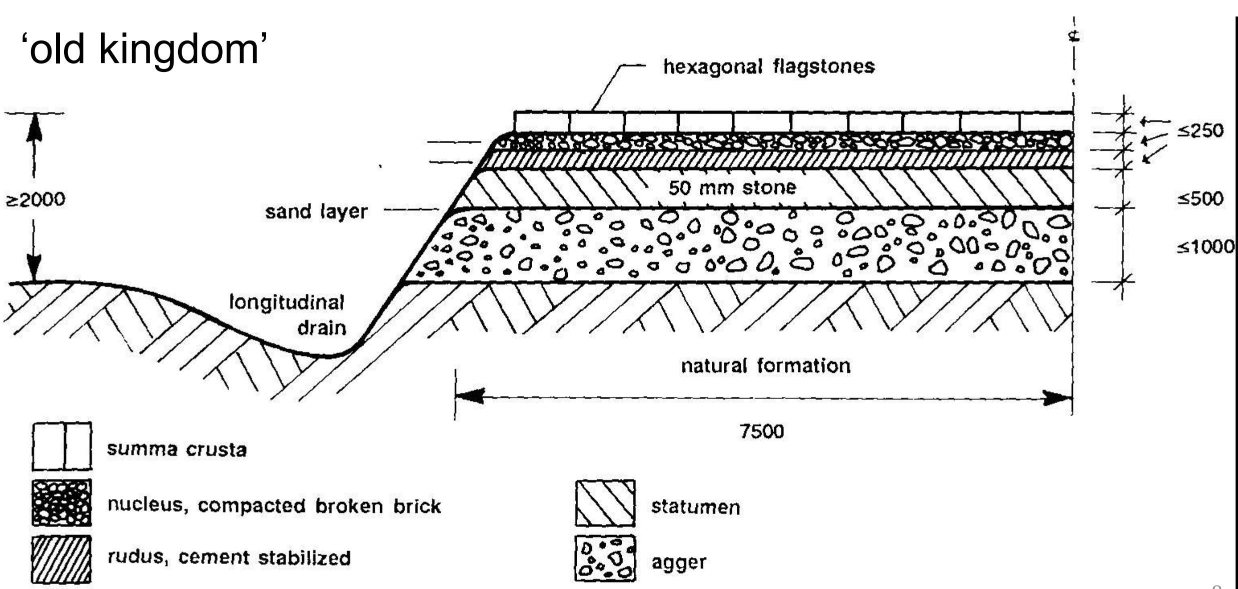
Roman road x-section (ideal)

'old kingdom'



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An Agger today

“Stane Street” at Gumber Corner

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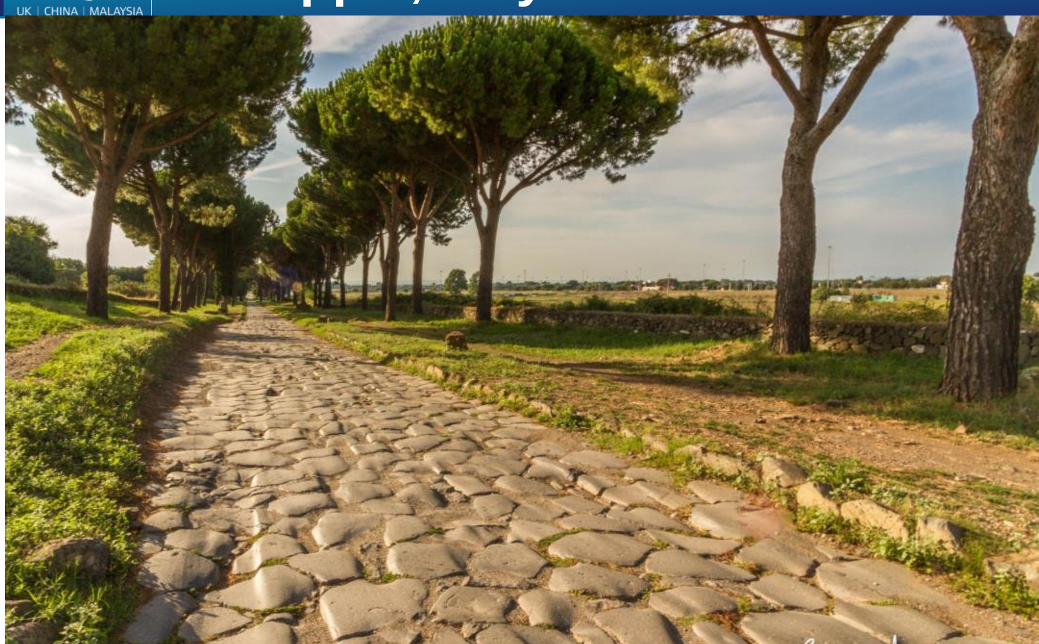
Via Appia, Italy



Old technology didn't survive ….!

- 1703 – Habsburg emperor Charles VI travels 80km from London to Petworth (S)
  - coach overturned 12 times!
- Knowledge of particulate materials at an all-time-low!

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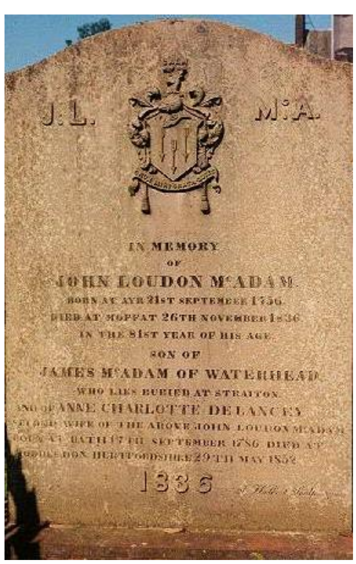
John Loudon Macadam

born 1756
died 1836



- Commenced work on roads in 1787
- Developed the idea of particulate packing
- First used in 1823 in USA
  - adopted as standard for National Roads in 1825
- Used throughout Europe by 1840.
  - By 1870 > 700 000km

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1939-1946

CBR / Marshall

- Need for rapid airfield construction
- Design methods introduced for in-experienced engineers
- They provided a means for experience to be passed on
- CBR widely used (idea from O. James "Pappy" Porter, California State Highway Department, 1938)
- Bruce Marshall of the Mississippi Highway Department developed the Marshall mix design in 1939
- Concept of '*every element must meet the minimum*' begins to replace the 'I know how to make my material work'

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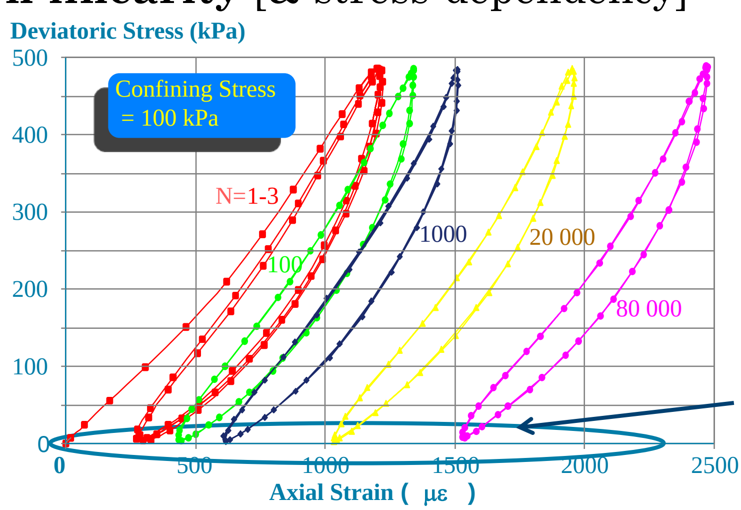
Resilient Modulus approach (from '60s)

Unbound materials:

a) non-linearity [& stress-dependency] **b) hysteresis**



c) plastic strain over many cycles

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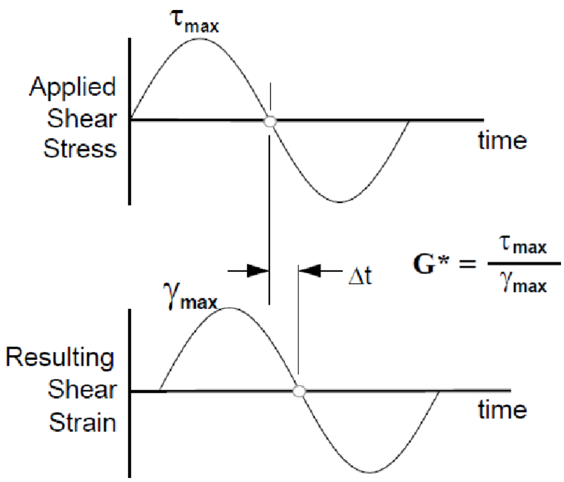
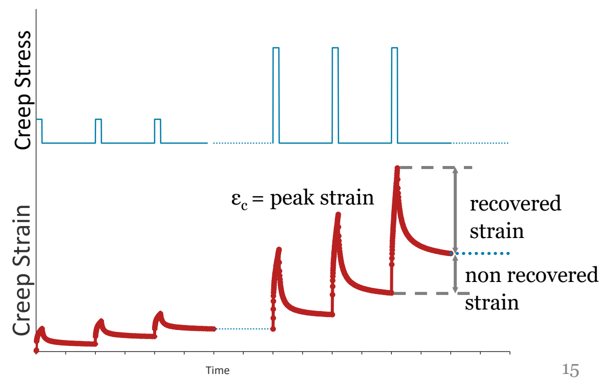
Resilient Modulus

Asphaltic materials:

a) visco-elastic b) visco-plastic (time/temperature dependency)





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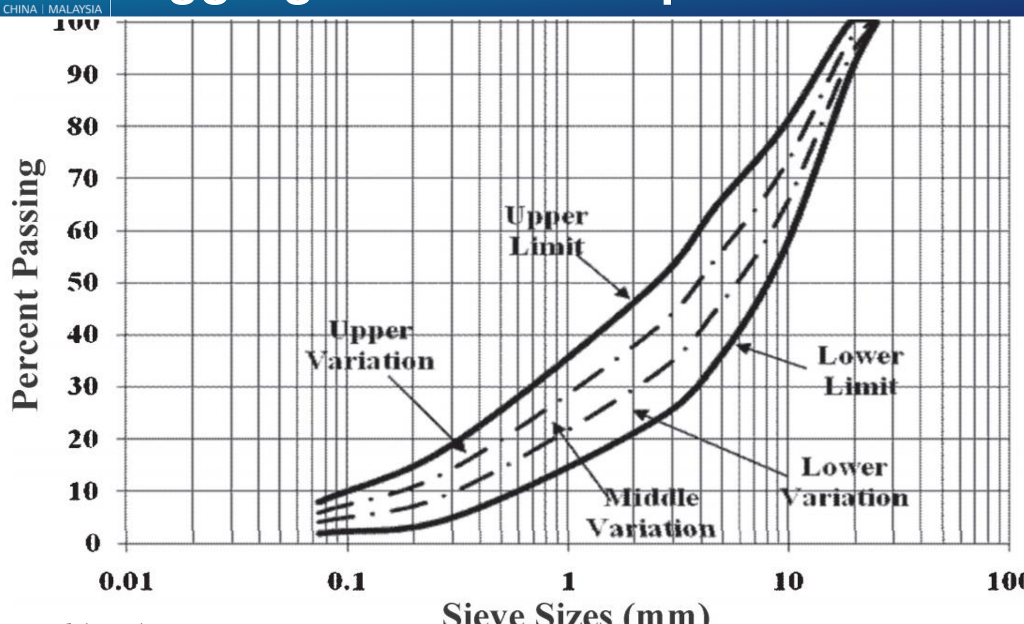
Aggregate affects Asphalt



Golalipour et al (2012)

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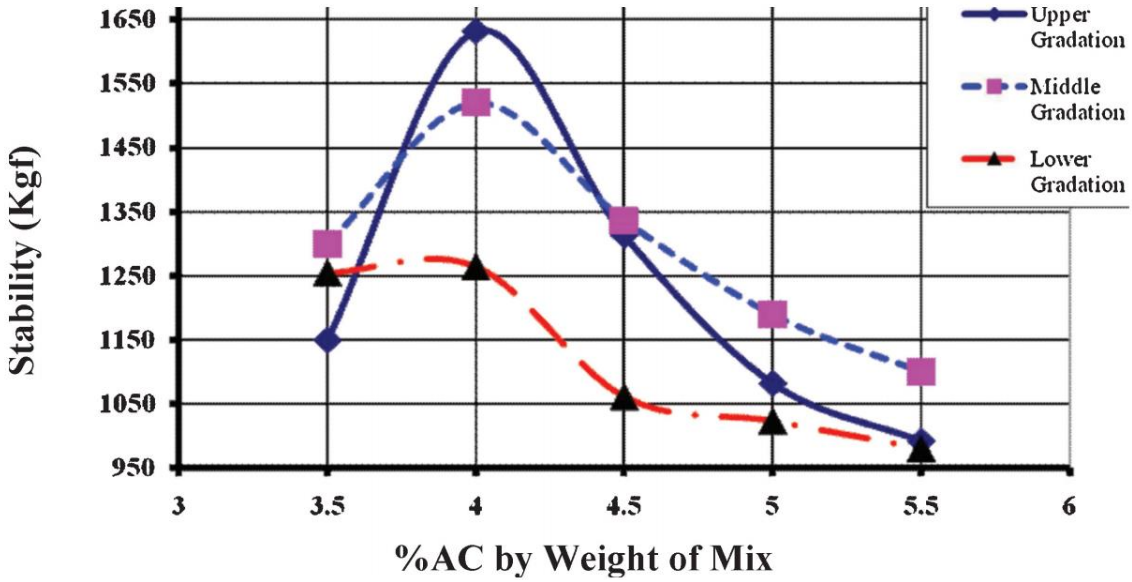
Marshall stability as a function of grading



Golalipour et al (2012)

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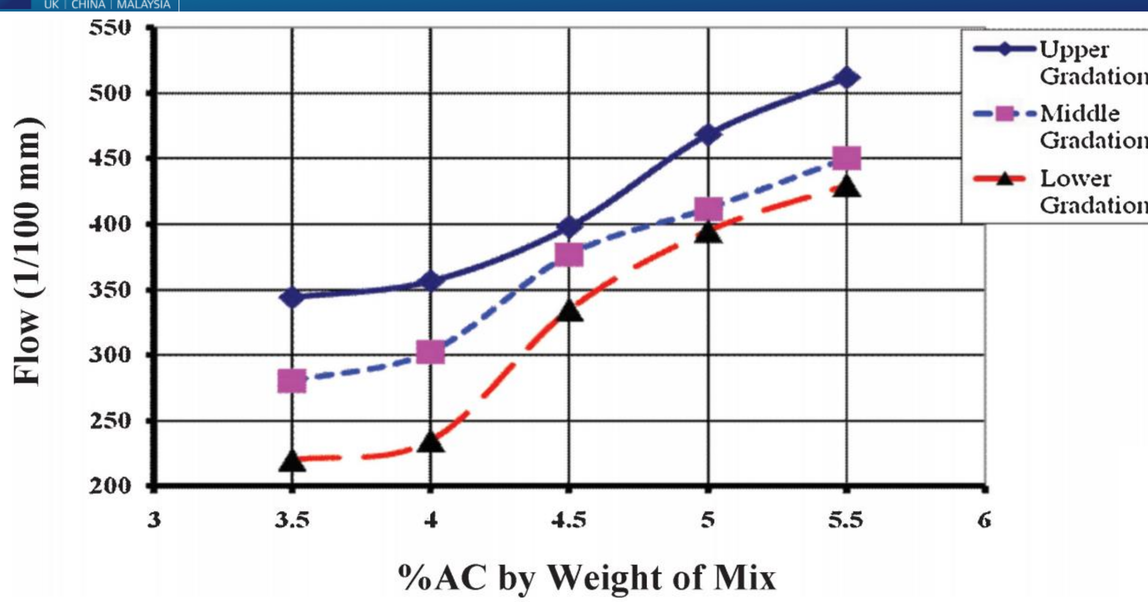
Marshall flow as a function of grading



Golalipour et al (2012)

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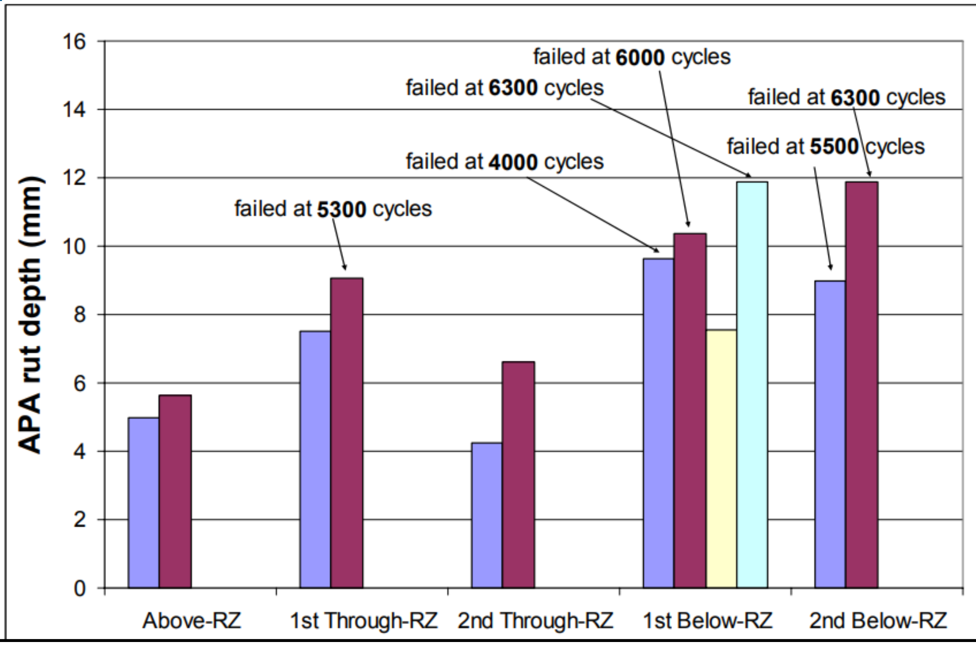
Aggregate grading and asphalt deformation



Kim, 2006 (see also Kandhal & Cooley, 2001)

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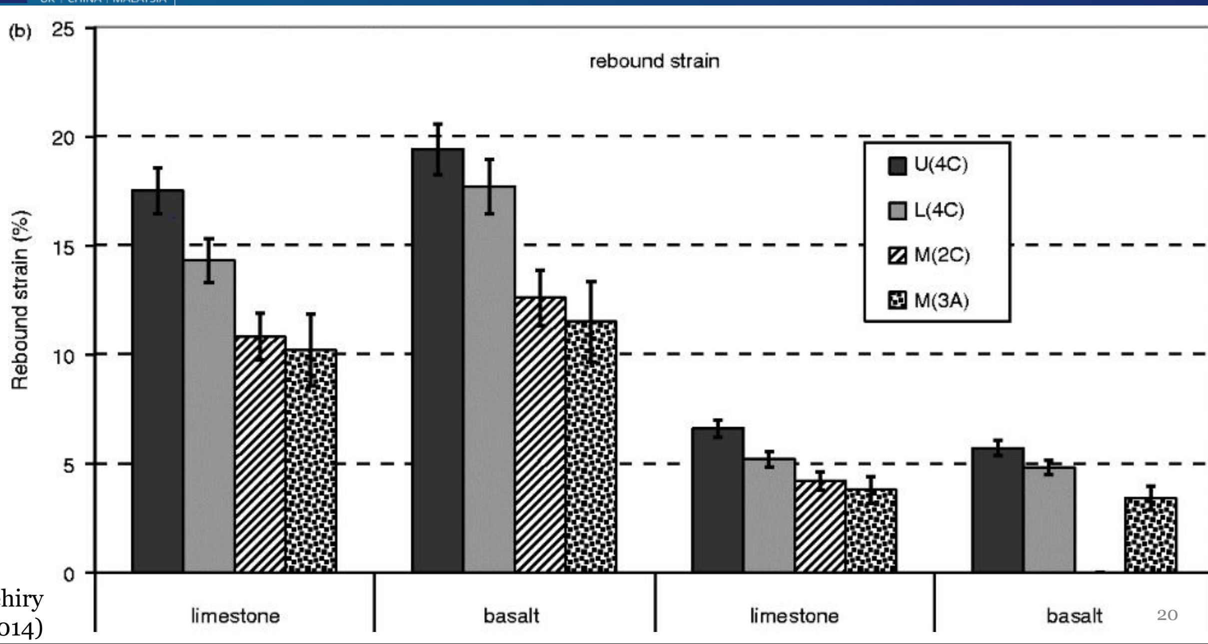
Asphalt modulus for different aggregates & gradings



Behiry (2014)

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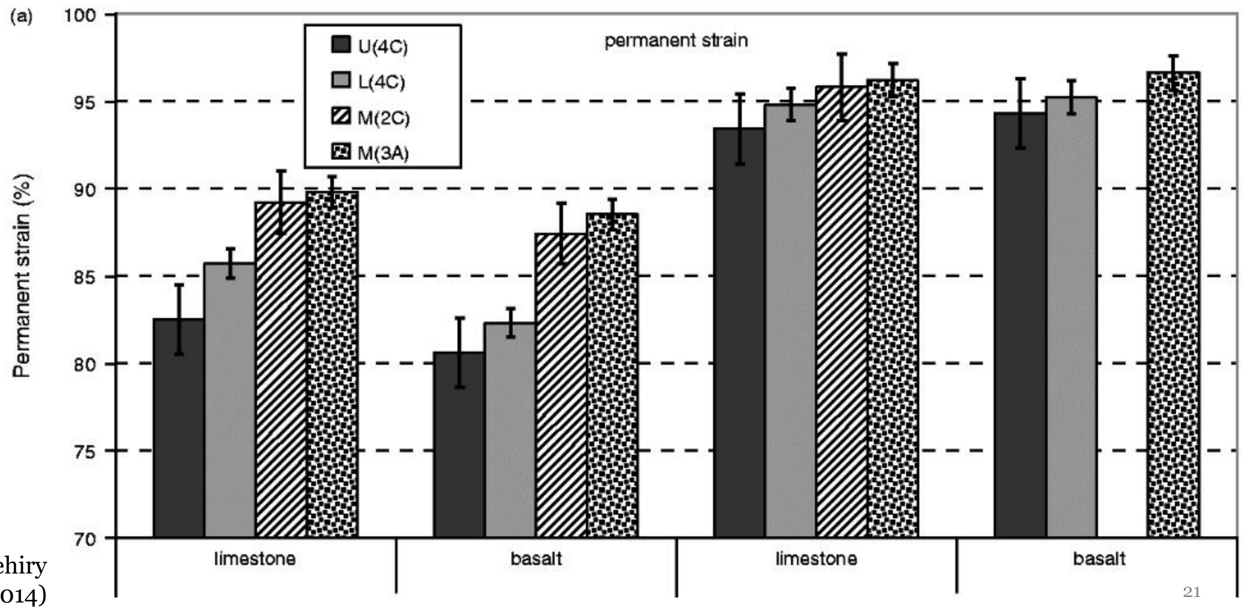
Permanent deformation for different aggregates & gradings



Behiry (2014)

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The Resilient Modulus in use

- The modulus approach feeds into Mechanistic Design
  - "Shell" method started the idea. Now implemented in much greater detail in "AASHTOWare Pavement ME"
  - Permanent deformation → rutting
    - not handled rigorously aspect in the same way as modulus
- But none of our materials are continua!
  - E, G*, M_r, *v*, describe the response of "buckets"(!) that average (somehow) the inter-particle behaviour

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But the Modulus approach is under threat!

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Idea 1
The shakedown approach to incorporate unbound layers

If we can't calculate permanent deformation, let's at least prevent it

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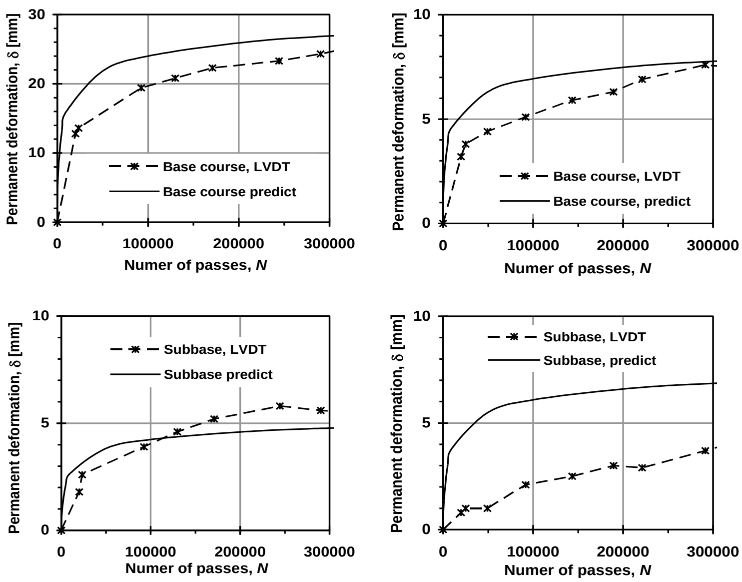
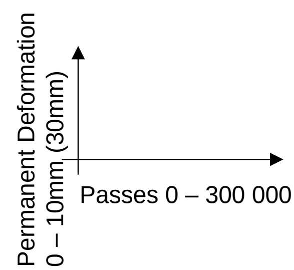
Predicting permanent deformation



Prediction versus measurements of permanent deformation
(Erlingsson)



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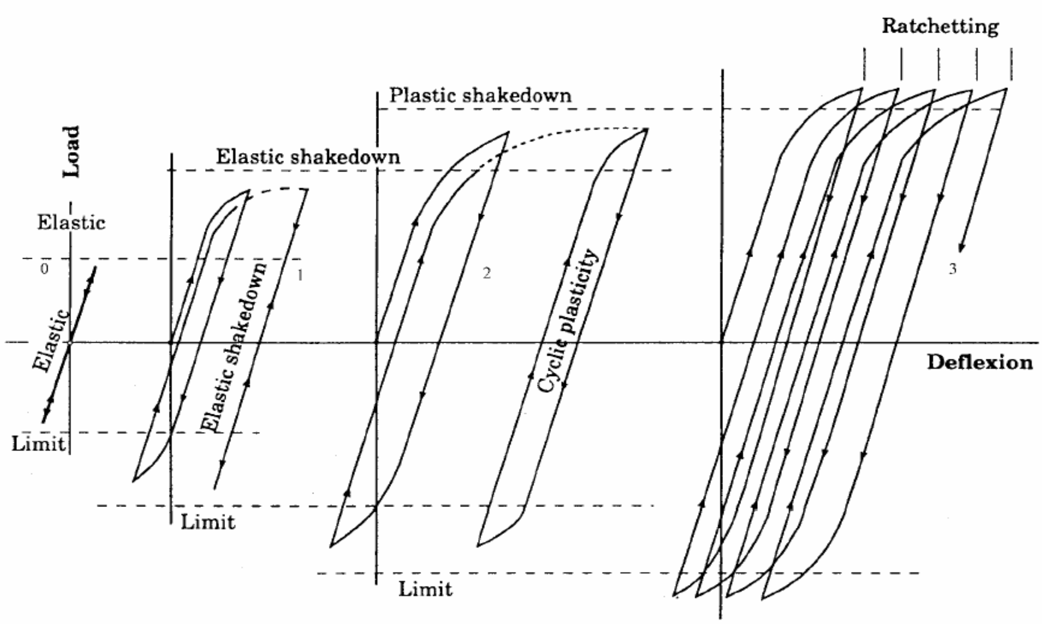
Classical shakedown concept



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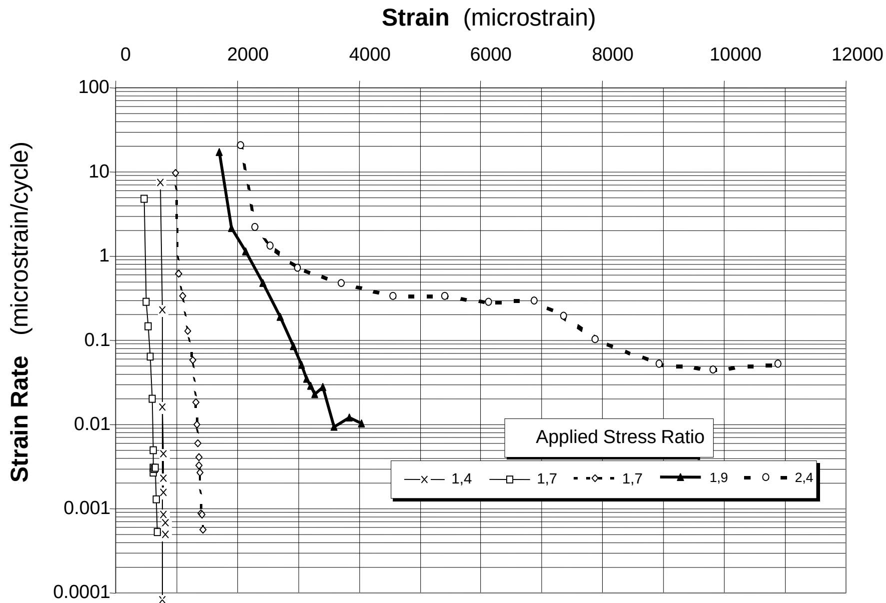
Modified Sherby-Dorn Plot



Plastic strain of a Limestone aggregate subjected to repeated loading
(Dawson 2008)

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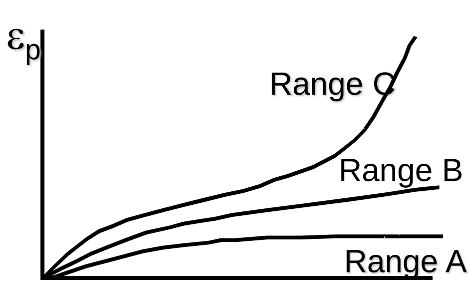
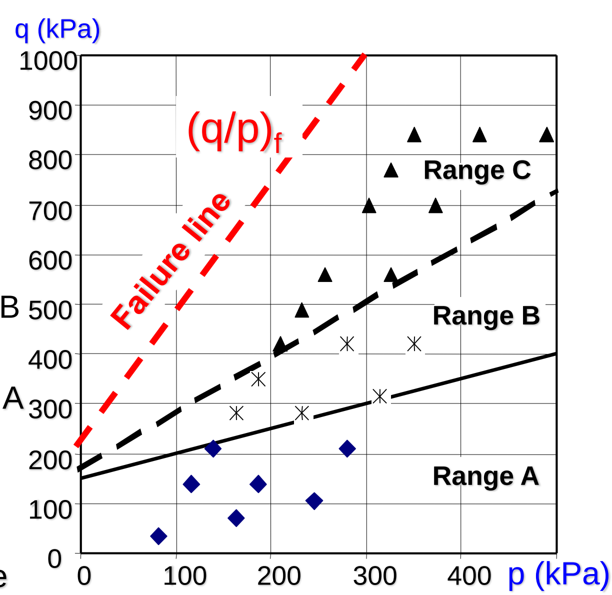
Design for Rutting

Granodiorite



No. of load applications
A: plastic stable
B: plastic creep
C: incremental collapse



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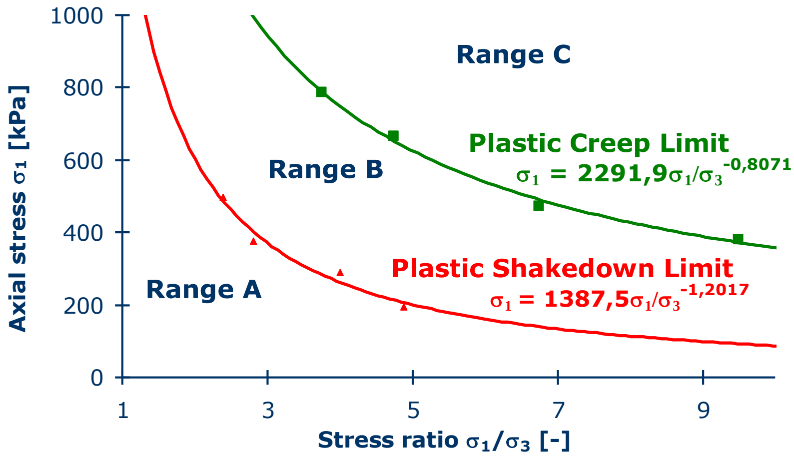
Shakedown-Limits

Granodiorite

D_{pr} = 100 %; moisture content = 4 %



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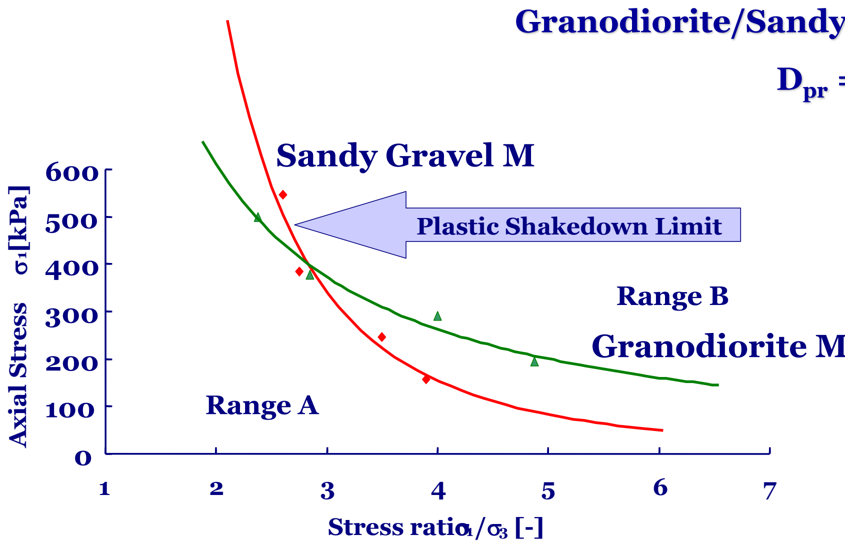
Shakedown-Limits

Granodiorite/Sandy Gravel

D_{pr} = 100 %



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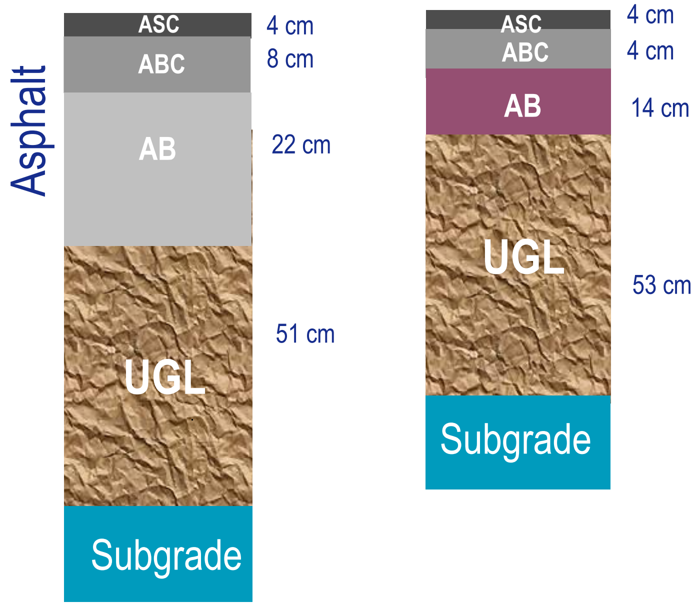
Sample use in design

ASC = Asphalt Surface Course

ABC = Asphalt Base Course

AB = Asphalt Base

UGL = Unbound Granular Layer



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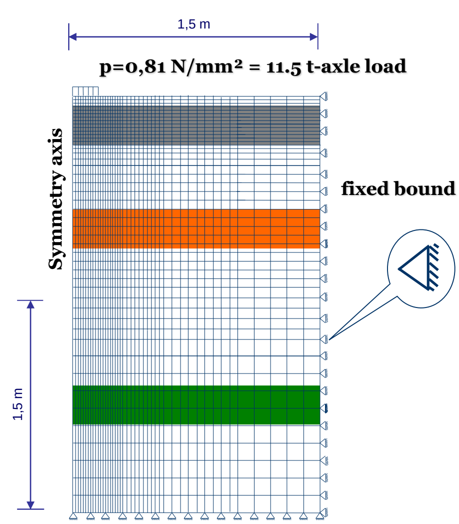
FE Stress Calculation

Asphalt layer - linear elastic
μ =0,35
E is dependent on:
- **→ 13 different surface temperatures**
- **→ Temperature regime within the Asphalt layers (2 cm sub layers)**
- **→ asphalt mix**
- **→ loading frequency (10 Hz)**

UGL – use M_R type data

Subgrade - linear elastic
E = 45 N/mm², μ =0,5



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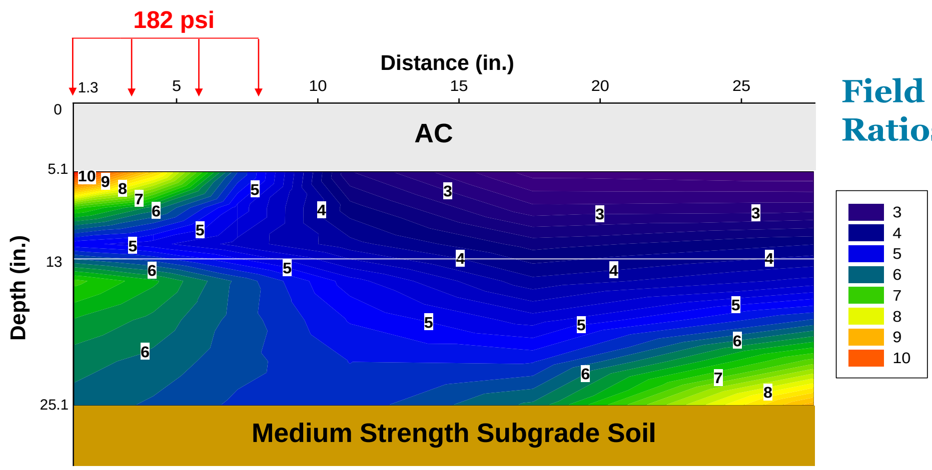
Predicting Field Stress States



GT_Pave Anisotropic Solution

Field Stress Ratios (σ_1/σ_3)

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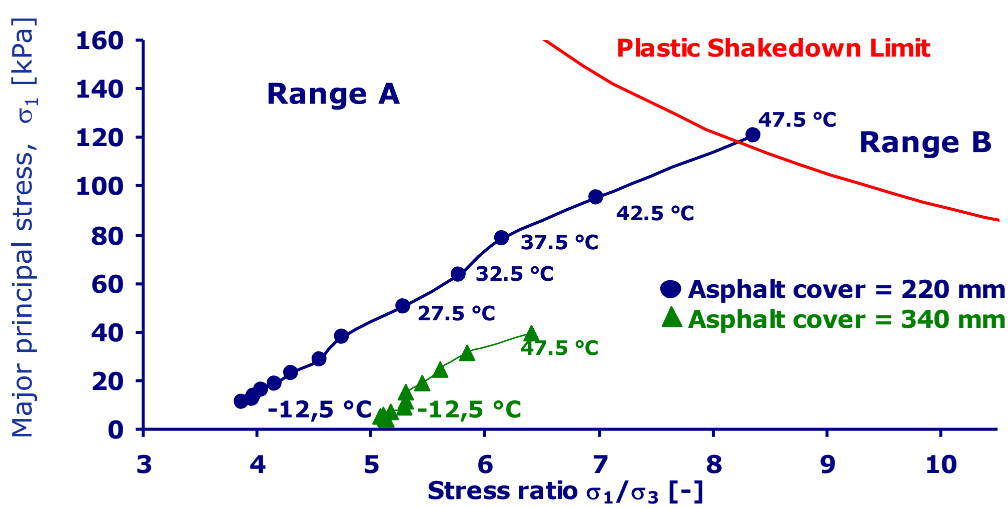
Shakedown is a tool for asphalt design

Varying thickness & temperature of the asphalt layers

Granodiorite
D_{pr} = 100 %; moisture content = 4 %



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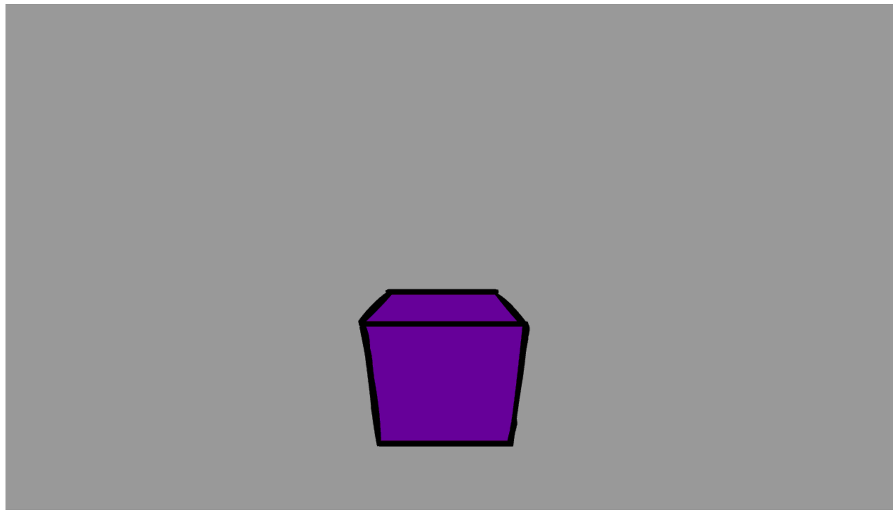
Open the box!

Shakedown may be useful today, but ‘tomorrow’ we need to ‘*open the box*’ and understand the particle behaviour.



Even if it’s scary!

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Idea 2

Packing as a tool

If we understand how particles fit together, will that help?

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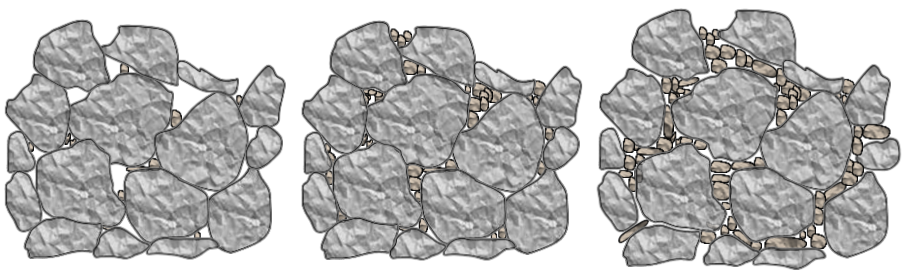
Theory

- In unbound granular materials, load distributes primarily through interactive coarse enough stones supported by a limited amount of fine granular materials which provides stability for the load carrying skeleton



a) Low Fine (Unstable) b) Optimum Fine (Stable) c) Excess Fines (Disrupted)

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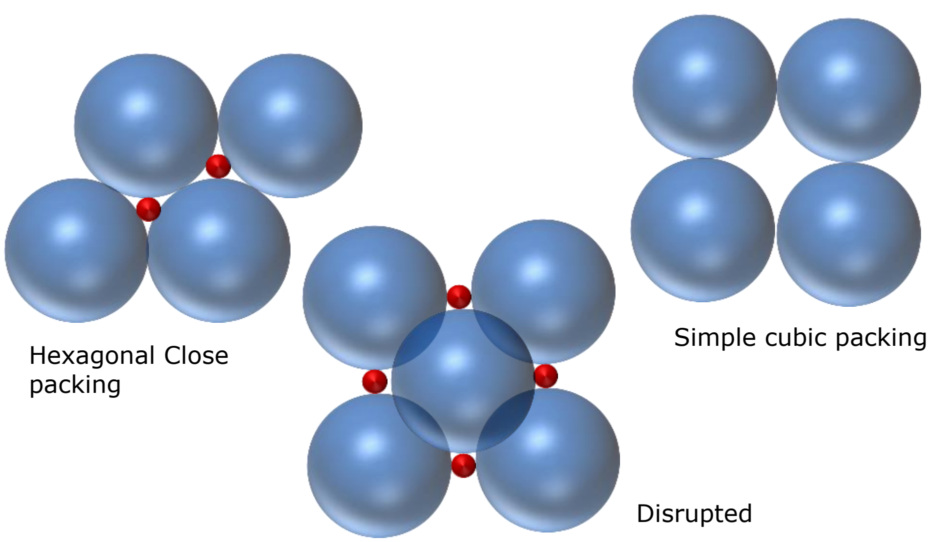
Use basic packing ideas as analogy



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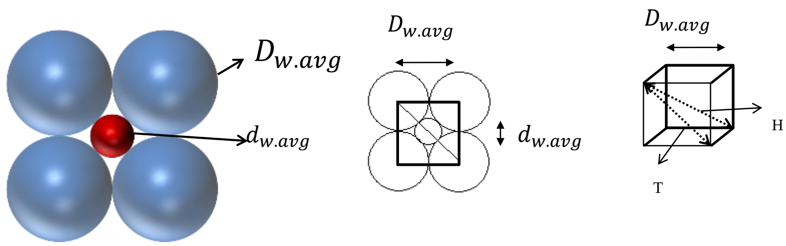
Define an acceptable Primary Structure

Expressing in terms of average weighted void diameter in PS particles



$$d_{w.avg} = H - D_{w.avg} = \sqrt{3}D_{w.avg} - D_{w.avg} = 0.732D_{w.avg}$$

$$\frac{1.1 * D_1 D_2}{\sqrt[3]{D_2^3 + 2.36 * D_1^3}} \leq d_{w,avg} \leq \frac{1.1 * D_1 D_2}{\sqrt[3]{2.36 * D_2^3 + D_1^3}}$$

Yideti, Dawson & Birgisson (2014)

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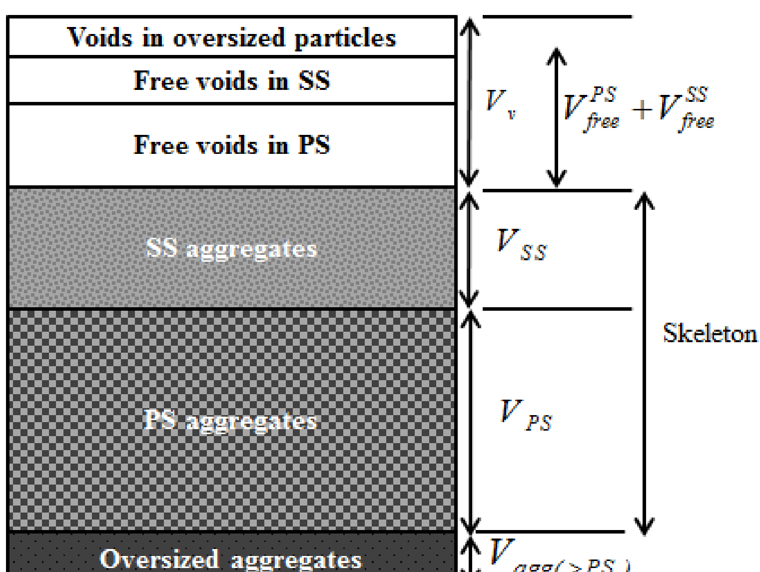
Packing volumetrics

Bitumen goes here



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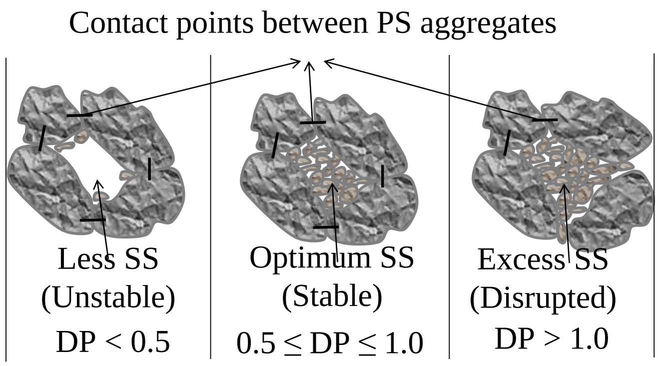
Disruption Potential of PS particles

- Disruption Potential (DP) is defined as the ratio of the volume of potentially disruptive fine material over the free available volume within PS



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

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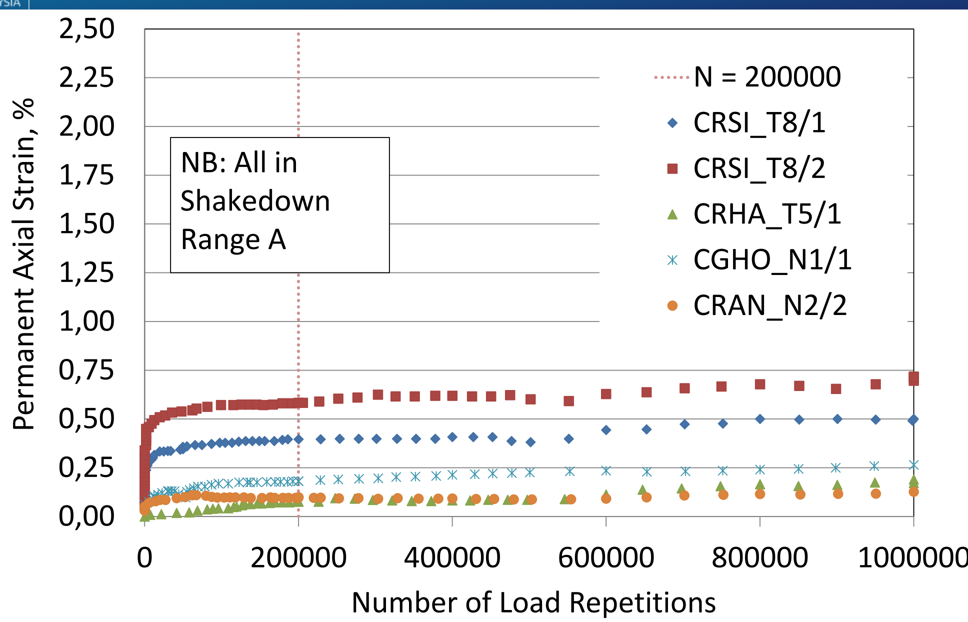
Permanent axial strain and DP



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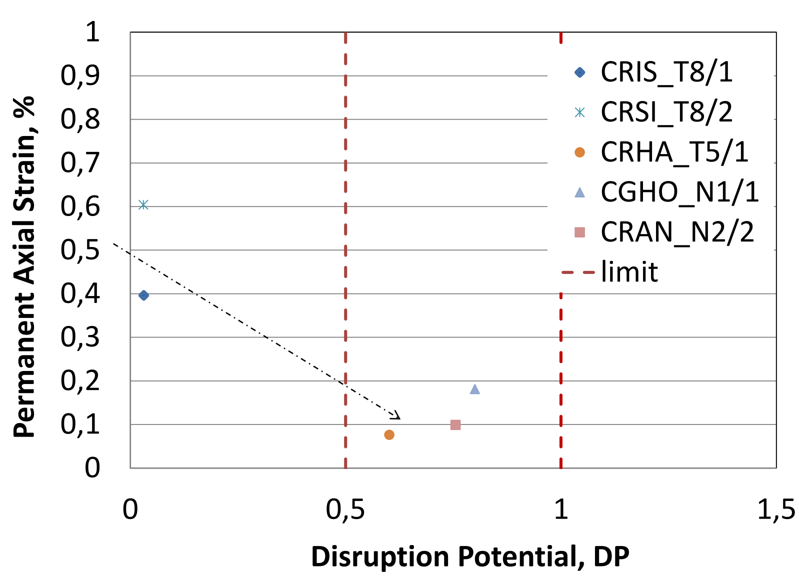
Permanent axial strain and DP



- So, packing can help us to determine HOW we can get low rutting aggregate structures.
- Should work for asphalt, too.

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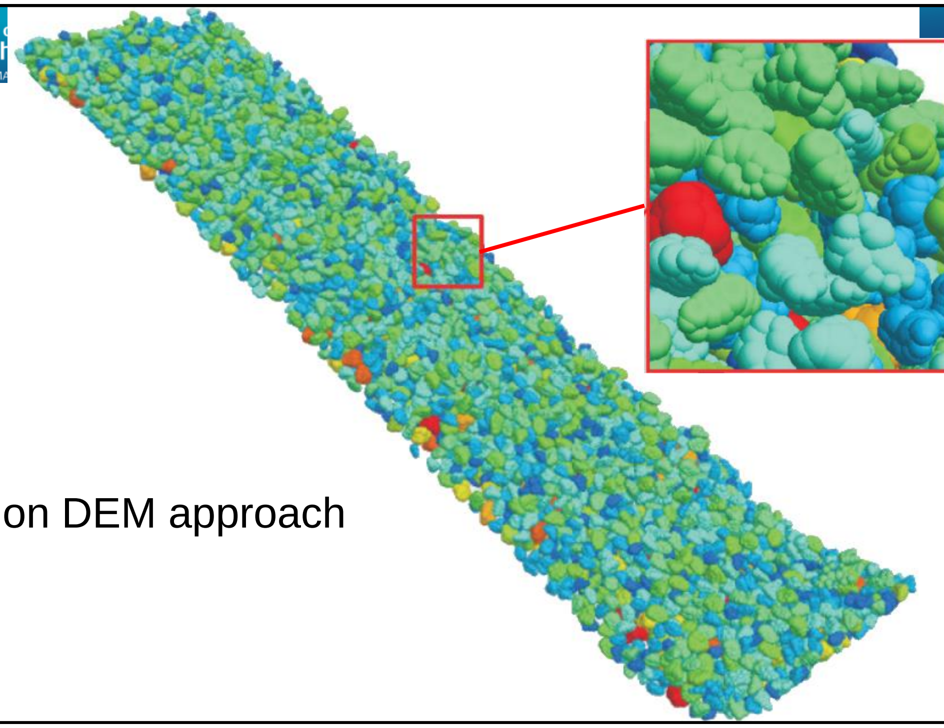
Idea 3

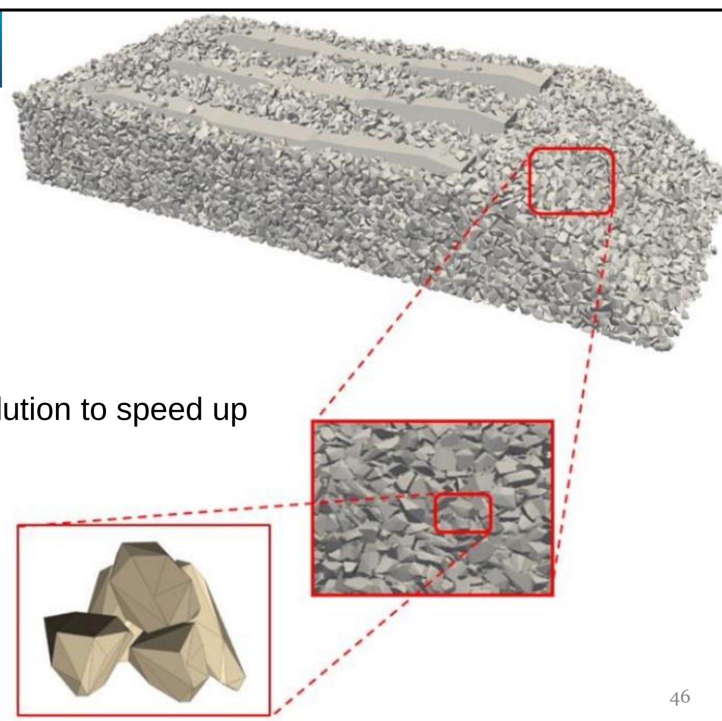
Looking at Particles

Maybe distinct elements (particle-by-particle) is the way forward



Common DEM approach

DEM



Woné (2019)

Using much more realistic stones
Using implicit rather than explicit solution to speed up
Still takes 3 weeks computation!

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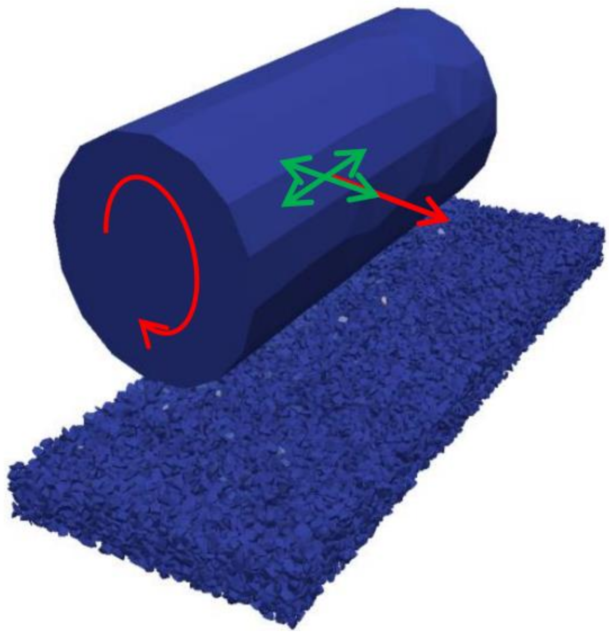
Layer compaction by DEM



Woné (2019)

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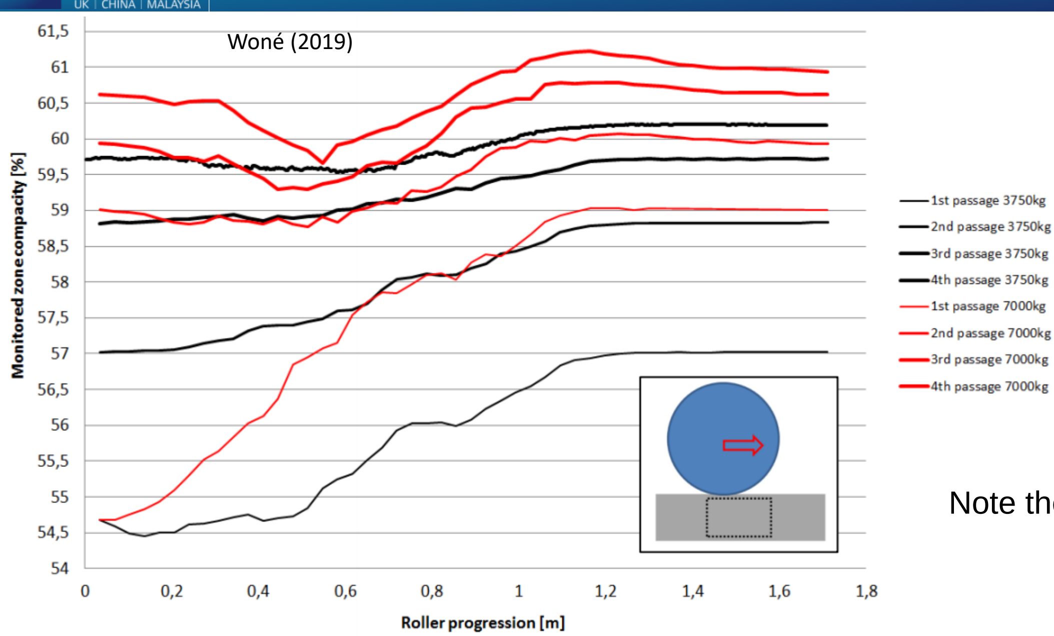
Compaction progress by DEM

Woné (2019)



Note the variability

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DEM – how useful?

- DEM allows us to see things we couldn't before
- It gives us the freedom to investigate inter-particle bond
  - Good/poor, degrading, varying
- Every DEM analysis will give a different answer because the particles are arranged differently
  - We shouldn't be deluded by the 'accuracy' of one arrangement
- Classical DEM is too time-consuming for most practical use

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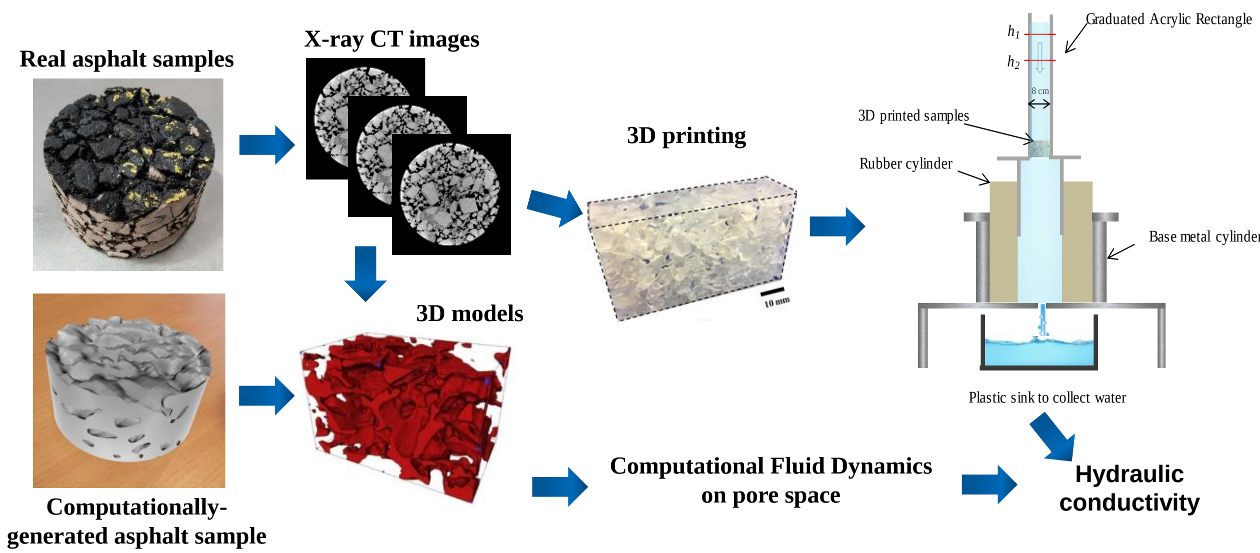
Idea 4

Looking at Particles (2)

An alternative – and more practical? - strategy

Virtual porosity of asphalt



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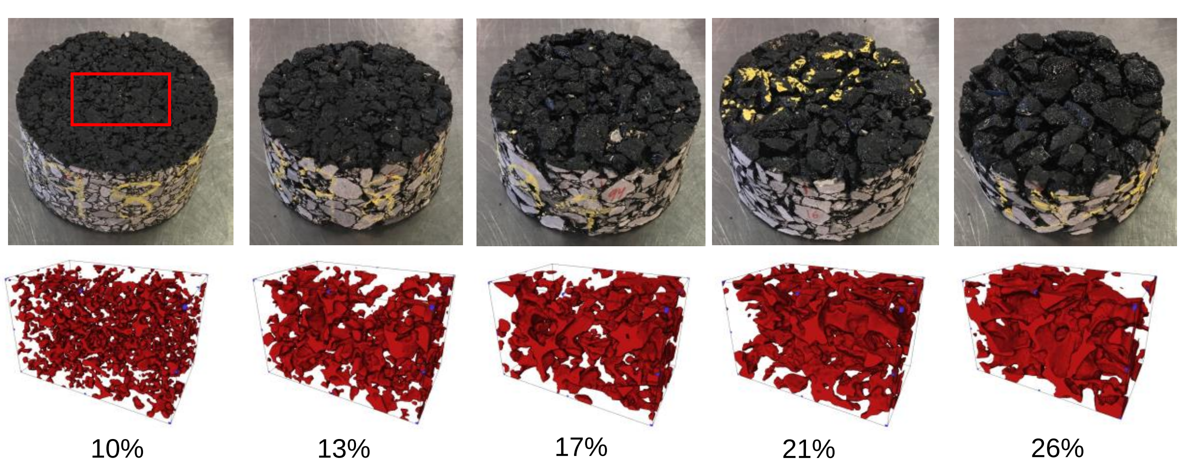
Choose your porometry!

HMA specimens, aggregate 6-20mm, air voids 13.6-31.3%.



- Examples of reconstruction of macropores from X-ray CT images.

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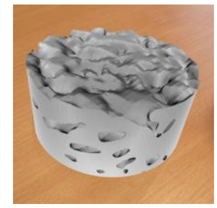
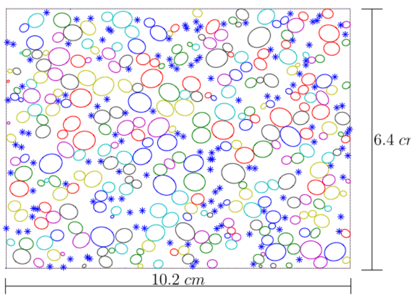
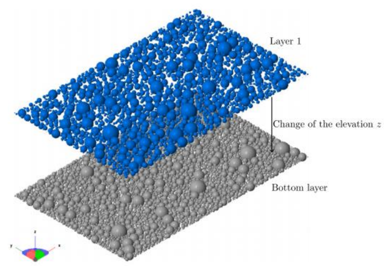
Simple 'squashed ovoid' method

A simple way to make a virtual asphalt porometry

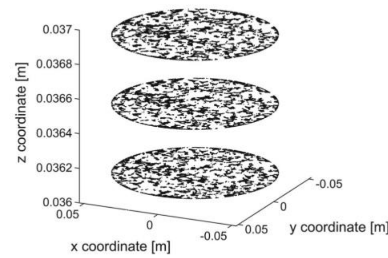




2D model generated from packing algorithm.



3D multi-layered samples generated with 3D layers converted from 2D packed domains.



Sample layers generated from the sampling algorithm

4

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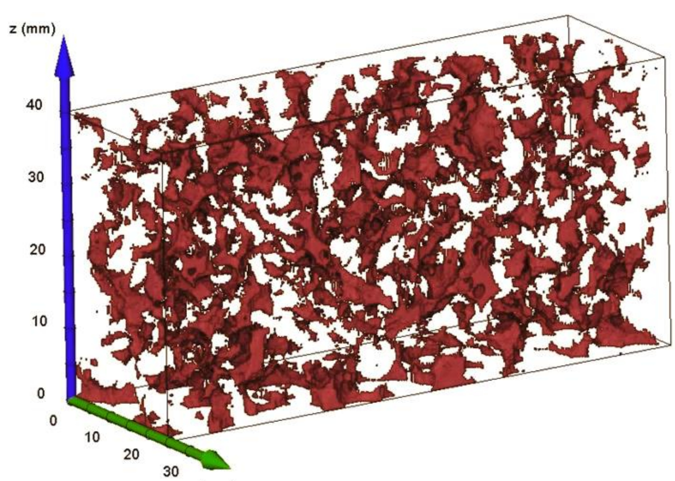
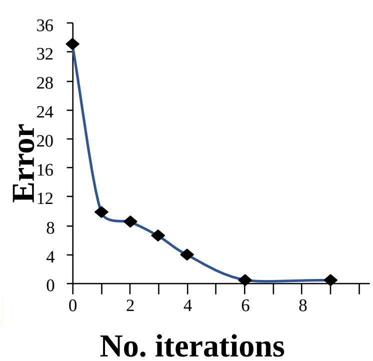
Target Pore Space	: 26.8 % (AVC) & 2.5 mm (Avd)
Iteration NO. 1	: 4.7 % (AVC) & 1.8 mm (Avd)

Error: 33.05

Differential Evolution algorithm





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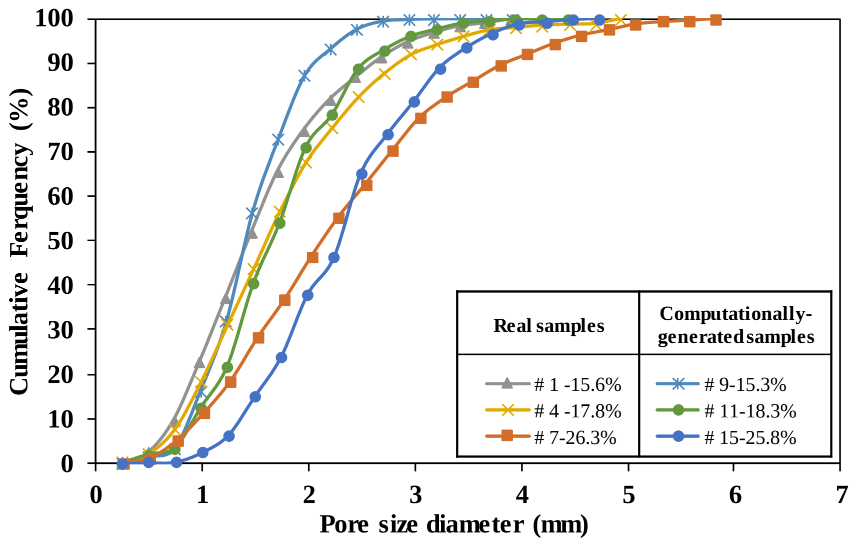
Real & Virtual *Pore* Gradings



Example of correlation between virtual and real materials

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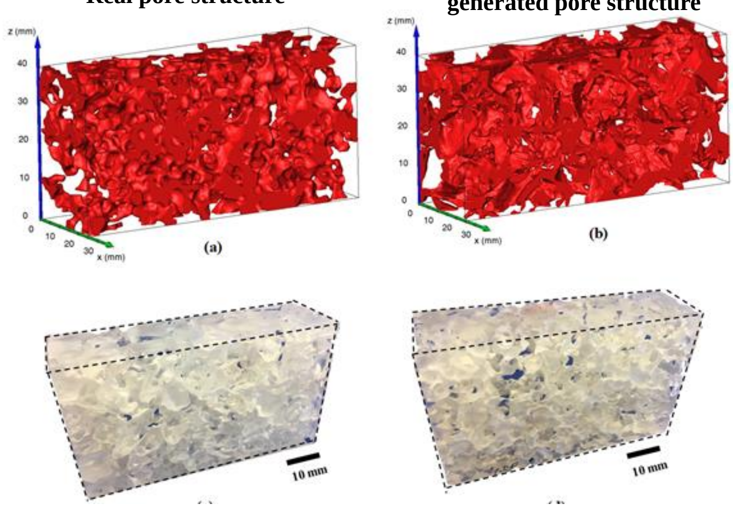
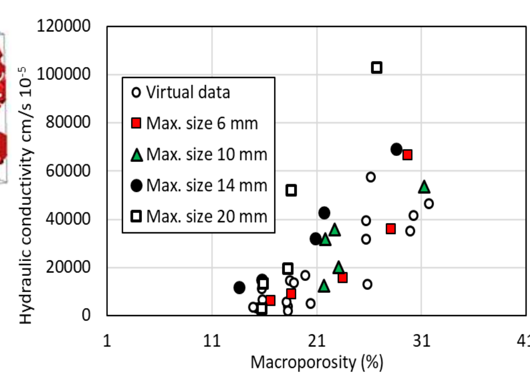
Validating pore similarity

Real pore structure

Computationally-generated pore structure





Hydraulic conductivity (3D printed samples)

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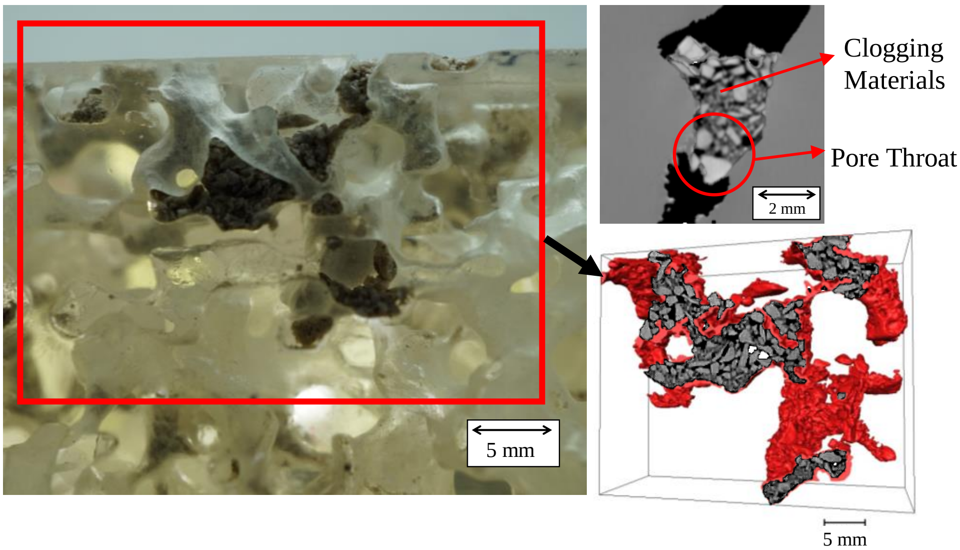
Studying clogging of porous asphalt



Transparent 3D printed materials allow us to characterize the clogged areas without the need for X-ray CT-Scans

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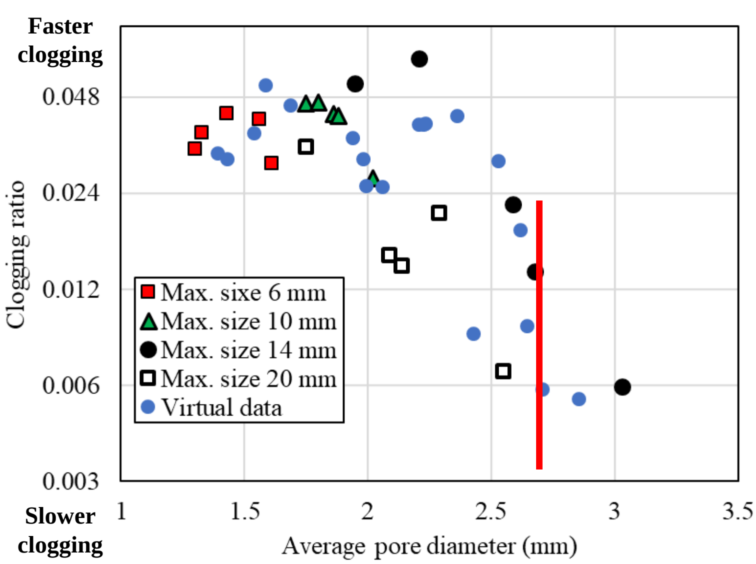
Studying clogging of porous asphalt



- When pores are < max. size of clogging material (~2.7mm in this example) the mixture clogs faster.
- And all without a real specimen!

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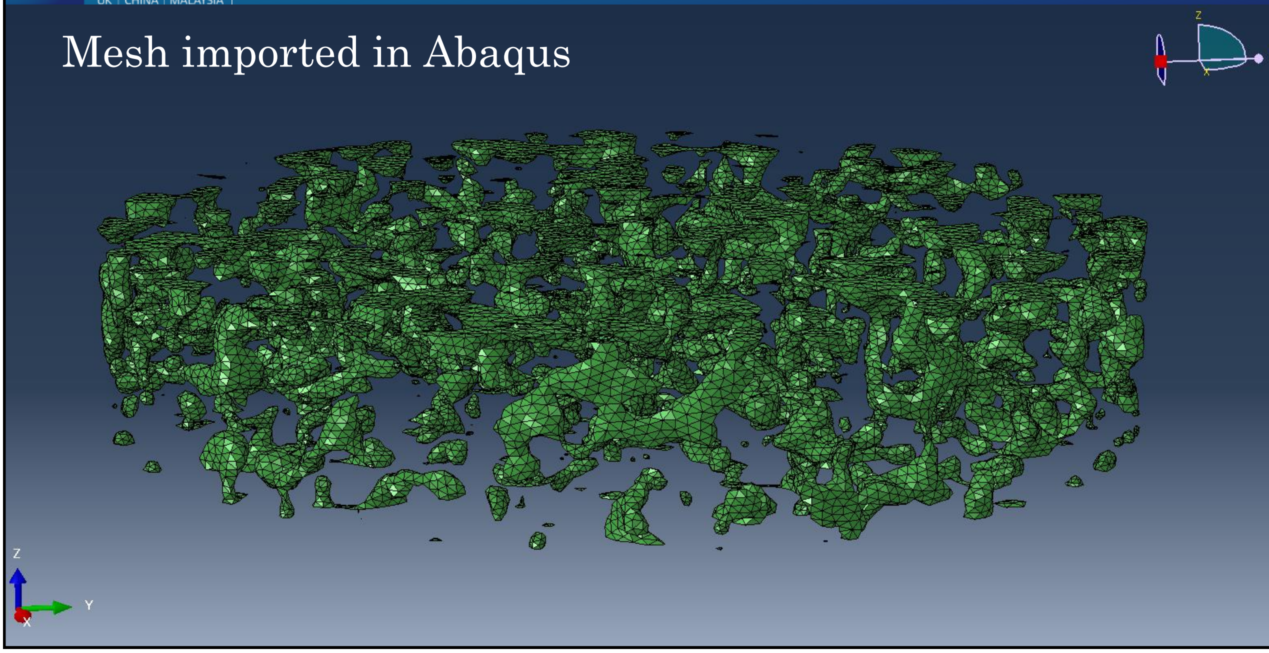
Convert pores to a CFD mesh

Mesh imported in Abaqus



Virtual aggregate

- Possible to create virtual assemblages
  - Similar particles
  - Similar pore sizes
  - Similar packing
- Assemblies can be made in various ways
  - Drop & roll (+ vibration ?); fluid bed; other
- Easy to make virtual assemblies for CFD analyses for fluid flow studies … **no need for permeability testing!**
- Reliable virtual assemblies for mechanical analyses a bit more challenging … DEM approaches

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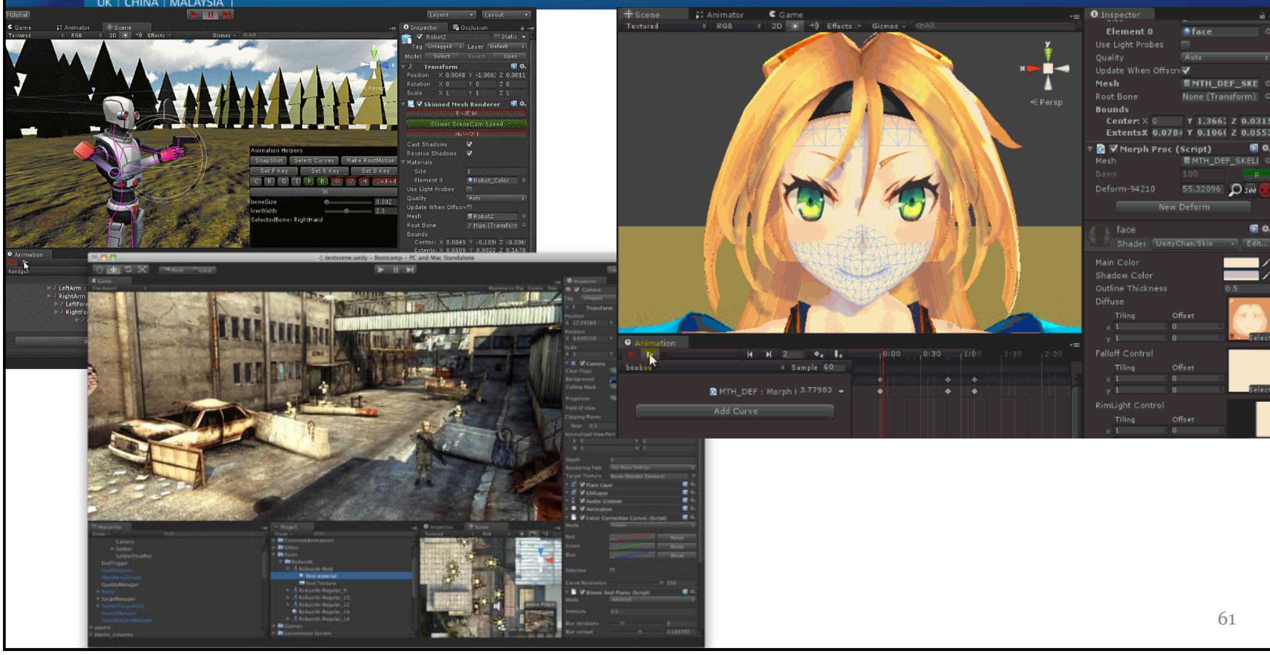
Another approach – Grand Theft Auto for Stones!



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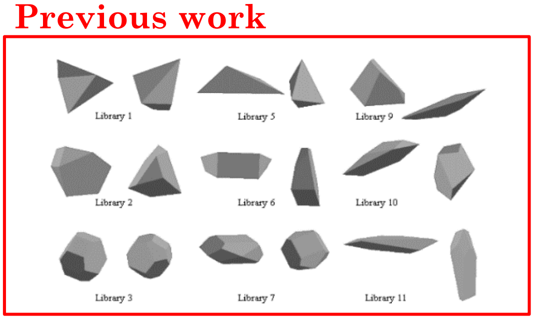
Introduction to DEM by Physics engine

- Changes in the aggregate size distribution and particle shapes affects materials behaviour
- Previous work used spherically-based or a ‘library’ of standard shapes

Previous work | **Our work**



Library of representative particle shapes using DEM simulation

Random virtual aggregates created in *Unity 3D software.*

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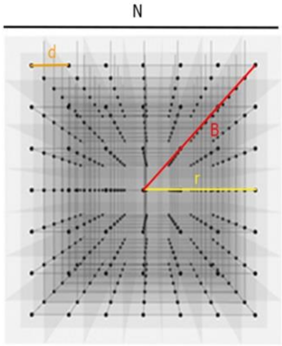
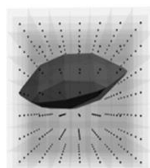
Physics engine can create realistic aggregates quickly

Modelling process

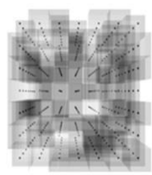


Lattice where Marching Cube Algorithm acts

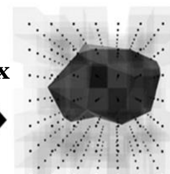


Spherical density matrix

➡ + ➡

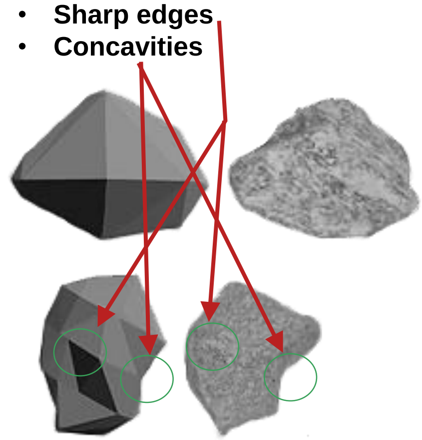


Noise density matrix



Deformed particles

- Realistic shapes
- Sharp edges
- Concavities



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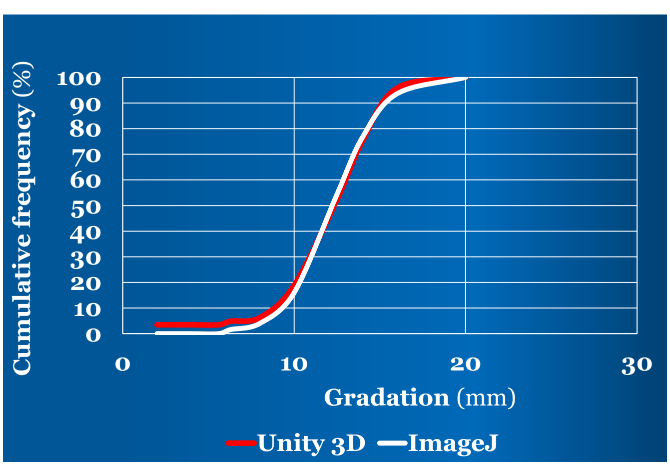
Comparison of morphology of real & virtual stones

Cumulative frequency distribution curves of the geometrical parameters



Reliability index

$$\text{Reliability index} = \frac{P_{50\ real}}{P_{50\ virtual}}$$

If Reliability Index = 1

⬇

Perfect adjustment

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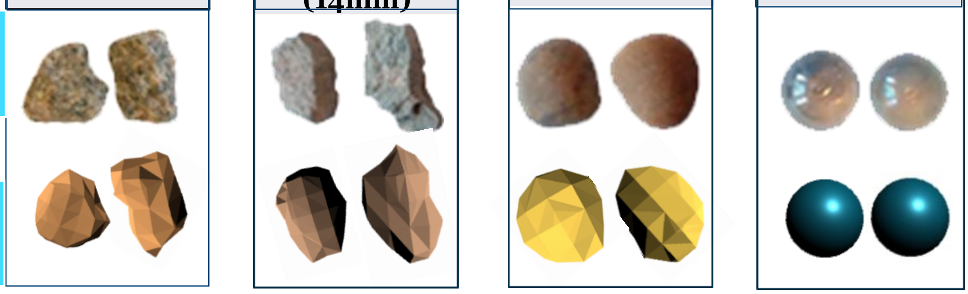
Comparison methods of real and virtual stones

	Bardon Hill (14 mm)	Tarmac Granite (14mm)	Round gravel (20mm)	Sphere glass (15mm)
Real				
Virtual				



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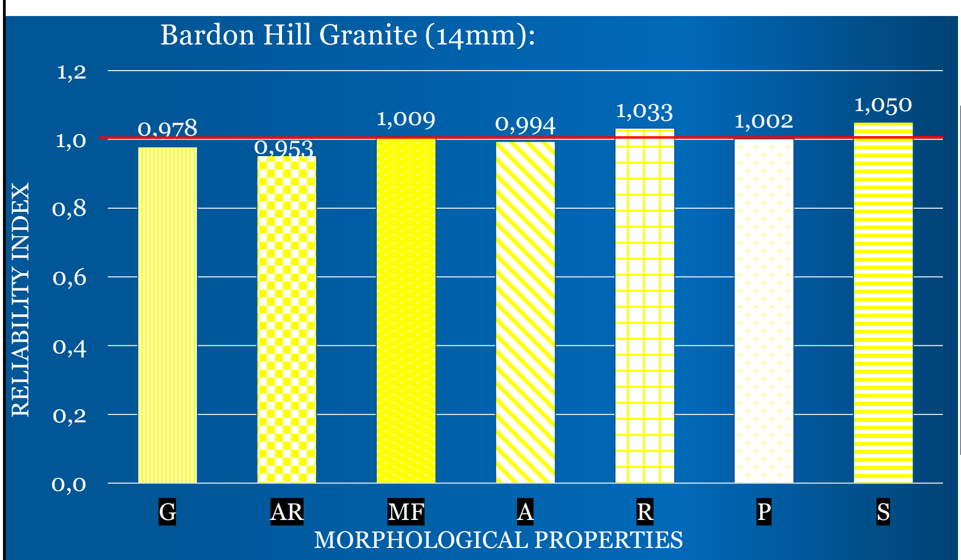
Comparison of morphological of real and virtual stones



G	Gradation
AR	Aspect Ratio
MF	Major Feret
A	Area
R	Roundness
P	Perimeter
S	Sphericity

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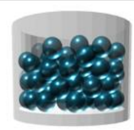
Virtual aggregates assembly under pressure model

	Bardon Hill Granite (14mm)		Sphere Glass (15mm)	
	Real sample	*Virtual sample*	*Real sample*	*Virtual Sample*
Particles number	170	194	102	104
				
	Round Gravel (20mm)		**Tarmac Granite (14 mm)**	
	Real Sample	*Virtual Sample*	*Real Sample*	*Virtual Sample*
Particles number	83	89	104	110
				

Virtual recreation of maximum compaction

Adjust virtual vibration to achieve realistics particles movements and porosity of virtual assemblies samples.

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Compacting virtual stones

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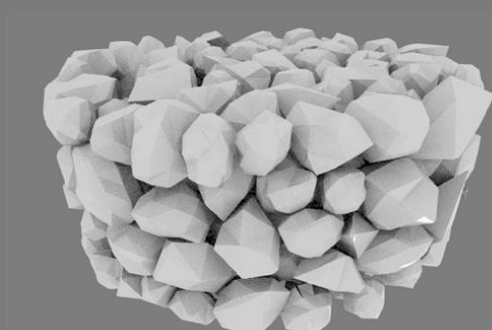
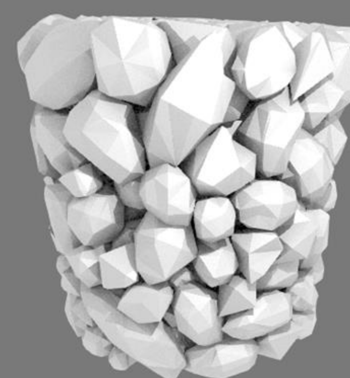
Other Cylindrical Specimens

	Samples 1. Max aggregate size: 6,3mm		Sample 2. Max aggregate size: 10mm	
	Real sample	Virtual sample	Real sample	Virtual Sample
VMA (%)	50.6	52.3	42	40
V_{sample} (cm^3)	46,9	50.63	99.4	104.4
V_{stones} (cm^3)	23,32	24.09	57.4	62.17
Height (cm)	2.4	2,56	5.06	5.32





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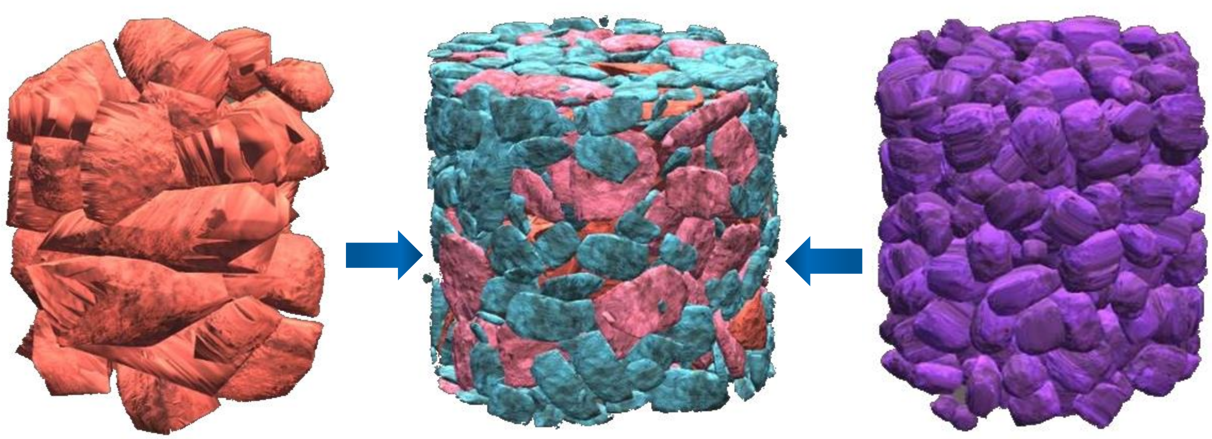
Virtual samples, by physics engine



Single size, large | Graded aggregate | Single size, small

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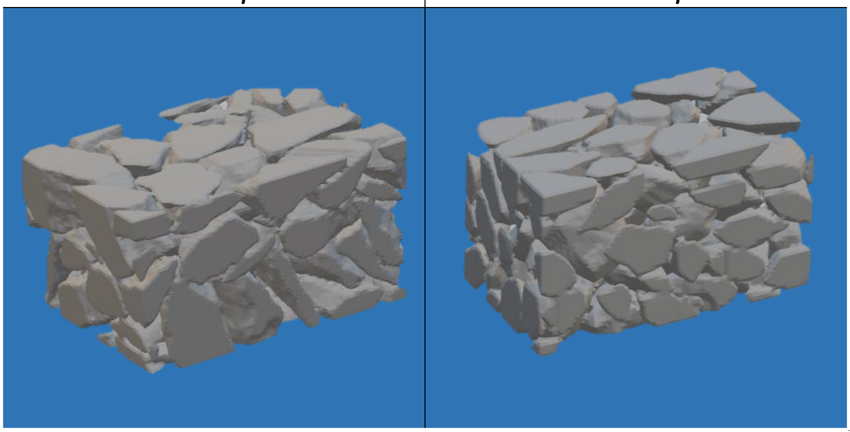
Virtual assembly

Bardon Hill Granite (14mm)

Real sample	*Virtual Sample*



Measures			
Parameters	**Unit**	**Real**	**Virtual**
Porosity (p)	-	0.37	0.38
Average pore size (Φv)	cm	0.32	0.29
Maximum pore size	cm	0.72	0.77
Average aggregate size (ϕ_P)	cm	0.57	0.53
Maximum particle size	cm	1.18	0.90
Euler Characteristic (χ)	-	-390	-387
Tortuosity (τ)	-	1.20	1.19

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n....

… with (Deep Convolutional) Generative Adversarial Networks (GANs) coming very soon!

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Future benefits of virtual particles approach

Mechanical assessment still to come. But when it's available:

- Can test variability
  - Run several times – none will be identical
  - Statistical approaches become possible (like real-life!)
- Laboratory work reduced (or even stopped!)
- Can design material blends
- Can design new materials
- Can anticipate in-service behaviour under real stresses

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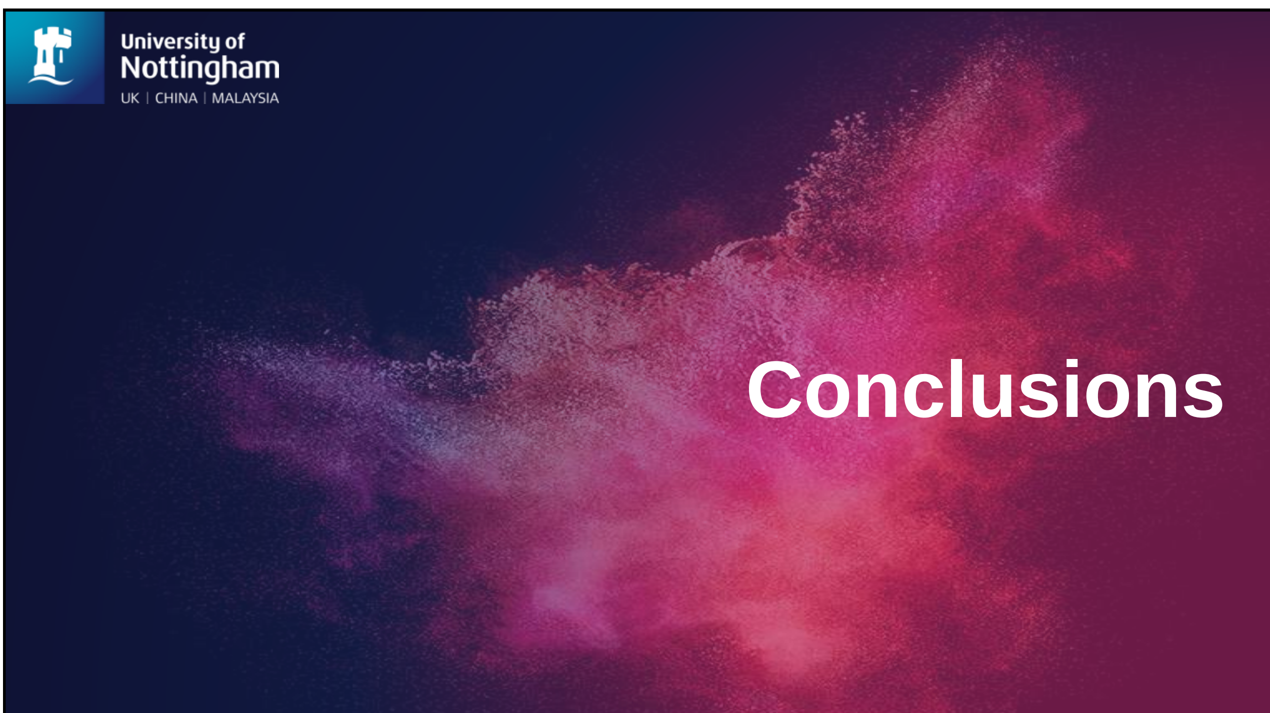

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Conclusions

- History shows us that good developments work for a while but developments eventually put them under challenge
- Maybe the time for the resilient modulus / mechanistic approach is reaching its retirement?
- Other *particle-based* stress analyses and particle/packing approaches have great potential
- But they need unifying, testing and putting into practice
- And I haven't had time to address uncertainty, moisture, deterioration/damage …..

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Thanks for listening!

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