AF2903 Highway Construction and Maintenance

Royal Institute of Technology, Stockholm

Road Aggregates Characterization

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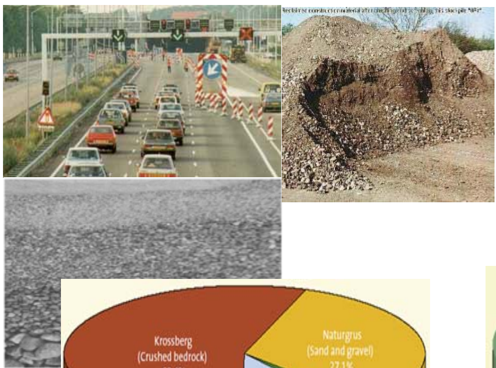
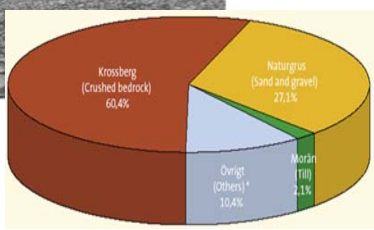
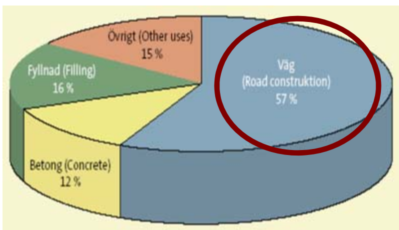
Do you know about...?







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Aggregates

- Aggregate is the major component of all materials used in road construction

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Aggregates

- is a broad category of coarse particulate material used in construction
  - include sand, gravel, crushed stone, slag, recycled concrete and geosynthetic aggregates
  - components of composite materials such as concrete and asphalt concrete
  - serves as reinforcement to add strength to the overall composite material
  - are widely used in drainage applications such as foundation drains, retaining wall drains, and road side edge drains
  - are also used as base material under foundations, roads

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Where do we use Aggregates in Highway Engineering?

- Asphalt – wearing course, base course
  - high fracture resistance
  - good interlocking
  - hardness
  - surface friction
  - light reflective
- Base Material
  - good fracture resistance
  - good interlocking
  - drainage
- Sub-Base Material
  - medium fracture resistance
  - good interlocking
  - drainage

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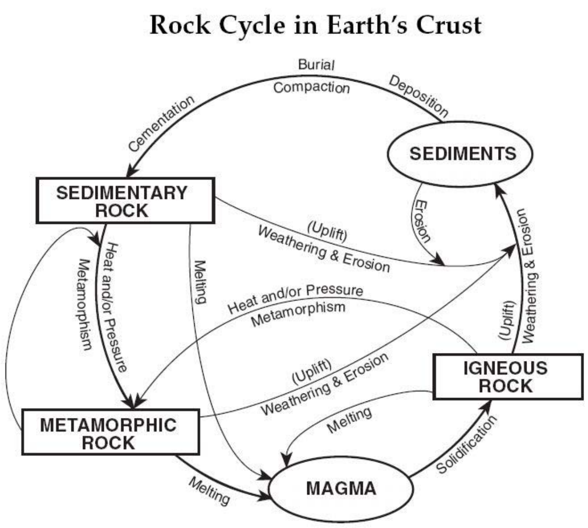
Where do Aggregates come from?



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Classification

1. Igneous rocks

- Origin :- Natural aggregates
- Grain size
  - Coarse grained
  - Medium grained
  - Fine grained
- Composition
  - Acidic > 66% of silica.
  - Intermediate 55 to 66% silica.
  - Basic < 55% silica.

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Classification

2. Sedimentary rocks

- Calcareous
  - Chalk, Lime stone
- Siliceous
  - Sandstone
  - Flint, chert
- Argillaceous
  - Clay, shell etc.

3. Metamorphic rocks

- Artificial aggregate - by product of industrial processes
  eg. Blast furnace slag

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Sources of Aggregates

- **Gravel**
  - Rock quarry
  - On site material
  - Gravel pit
  - Mines
  - Slag from ore processing
- **Sand and Filler**
  - Rock quarry
  - On site material
  - Sand pit
  - Dredging (river and salt water)
  - Processes mine material

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Rock Quarry

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Gravel Pit

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On Land Dredging

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Marine Dredging

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Aggregate Production at Quarries

- Blasting of bedrock
- Primary crushing stage
  - Jaw crusher
- Secondary crushing stage
  - Gyratory or cone crusher
  - Screen
- Tertiary crushing stage
  - Cone crusher
  - Impact crusher (VSI)
  - Screens

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Blasting

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Crushing

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Source Aggregate Characterization

- Gradation
- Toughness and Abrasion Resistance
- Particle Shape and Surface Texture
- Durability and Soundness
- Cleanliness and Deleterious Materials

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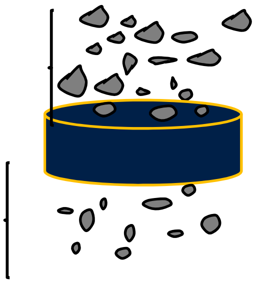
Aggregate Gradation

- In a gradation and size analysis, a sample of dry aggregate of known weight is separated through a series of sieves with progressively smaller openings
- Once separated, the weight of particles retained on each sieve is measured and compared to the total sample weight
- Particle size distribution is then expressed as a percent retained/passing by weight on each sieve size

Percent retained

Percent passing



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Aggregate Gradation

- Aggregate gradation influences almost every important property including:
  - Stiffness
  - Stability
  - Durability
  - Permeability
  - Workability
  - Fatigue resistance
  - Skid resistance and
  - Resistance to moisture damage

(Roberts et al., 1996)

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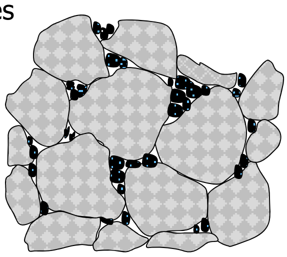
Aggregate Gradation

- It is often expressed in graphical form
  - Using concepts of **Maximum density gradation**
  - A special graph referred to as the FHWA (Federal Highway Administration) 0.45 power graph.
- This gradation would involve a particle arrangement where successively smaller particles are packed within the voids between larger particles



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Fuller and Thompson's Equation (Interactive Equation)

- A widely used equation to describe a maximum density gradation for a given maximum aggregate size. It is developed by **Fuller and Thompson in 1907.**

$$p = \left(\frac{d}{D}\right)^{n} * 100$$

Where:

- P = percent passing (%)
- d = aggregate size being considered
- D = maximum aggregate size
- n = parameter which adjusts curve for fineness or coarseness (for maximum particle density n ≈ 0.5 according to Fuller and Thompson)

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The 0.45 Power Maximum Density Graph

- In the early 1960s, the FHWA introduced the standard gradation graph used in the HMA industry today
- This graph uses Fuller and Thompson's equation with n = 0.45 and is convenient for determining the maximum density line and adjusting gradation (Roberts et al., 1996)
- This graph is slightly different than other gradation graphs because it uses the sieve size raised to the nth power (usually 0.45) as the x-axis units. Thus, a plot of Fuller and Thompson's maximum density equation with n = 0.45 appears as a straight diagonal line

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Calculations for a 0.45 Power Gradation Curve

Particle Size (mm)	% Passing
19.0	$P = \left(\frac{19.0}{19.0}\right)^{0.45} = 1.000\ (100.0\%)$
12.5	$P = \left(\frac{12.5}{19.0}\right)^{0.45} = 0.833\ (83.3\%)$
9.5	$P = \left(\frac{9.5}{19.0}\right)^{0.45} = 0.732\ (73.2\%)$
2.00	$P = \left(\frac{2.00}{19.0}\right)^{0.45} = 0.363\ (36.3\%)$
0.300	$P = \left(\frac{0.300}{19.0}\right)^{0.45} = 0.154\ (15.4\%)$
0.075	$P = \left(\frac{0.075}{19.0}\right)^{0.45} = 0.082\ (8.2\%)$

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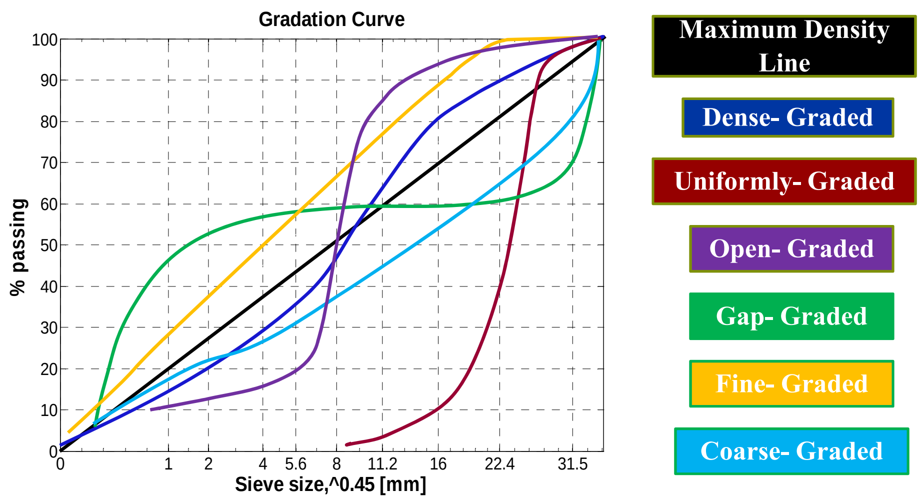
The 0.45 Power Maximum Density Graph



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Coarse Aggregate and their Sieve Sizes

Sieve Designation	Opening (in)	Openeing (mm)
3 in	3.00	75.0
2 in	2.00	50.0
1½ in	1.50	37.5
1 in	1.00	25.0
3/4 in	0.75	19.0
½ in	0.50	12.5
3/8 in	0.375	9.50

- Retained on 4.75 mm (No.4) ASTM D692
- Retained on 2.36 mm (No.8) Asphalt Institute
- Retained on 2.00 mm (No.10) HMA Book

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Fine Aggregate and their Sieve Sizes

Sieve Designation	Opening (in)	Opening (mm)
No. 4	0.187	4.75
No. 8	0.0937	2.36
No. 16	0.0469	1.18
No. 30	0.0234	0.60
No. 50	0.0117	0.30
No. 100	0.0059	0.15
No. 200	0.0030	0.075

Passing 4.75 mm (No.4) ASTM D1073

Passing 2.36 mm (No.8) Asphalt Institute

- **Mineral filler**
  - At least 70% pass 0.075 mm ASTM D242

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Maximum and Nominal Aggregate Sizes

%P	%R
100	0
100	0
92	8
72	20
65	7
48	17
36	12
22	14
15	7
9	6
4	5
0	4

Nominal maximum size

One size larger than the first sieve to retain more than 10 %

Maximum size

One size larger than nominal maximum size

%P	%R
100	0
99	1
88	11
72	16
65	7
48	17
36	12
22	14
15	7
9	6
4	5
0	4

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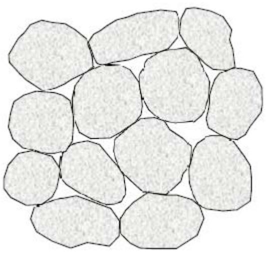
Uniformly Graded Aggregate

- **Uniformly graded refers to a gradation that contains most of the particles in a very narrow size range. The curve is steep and only occupies the narrow size range specified. All the particles are the same size.**



- **Particle-to-particle contact**
- **High void content**
- **Low but variable density**
- **High stability if confined**
- **Low stability when unconfined**
- **Difficult to compact**

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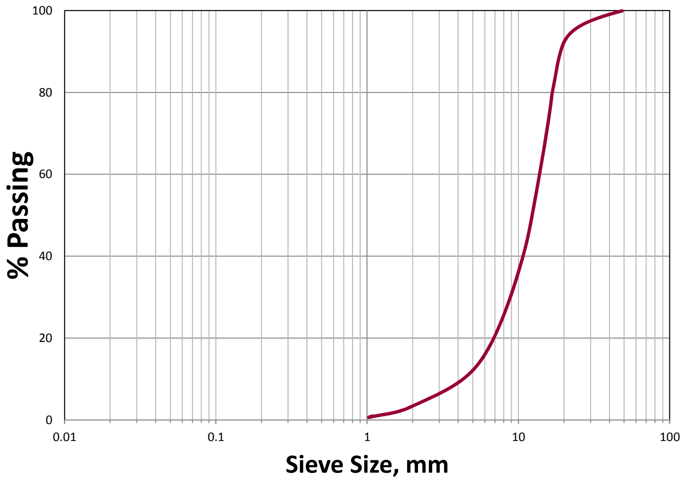
Uniformly Graded Aggregate



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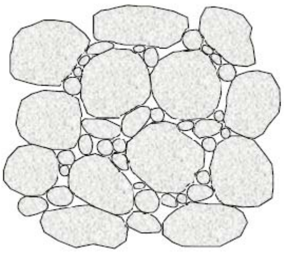
Open-Graded Aggregate

- Open graded refers to a gradation that contains only a small percentage of aggregate particles in the small range



- Few particle-to-particle contact
- High void content
- Low but variable density
- High stability if confined
- Low stability when unconfined
- Difficult to compact

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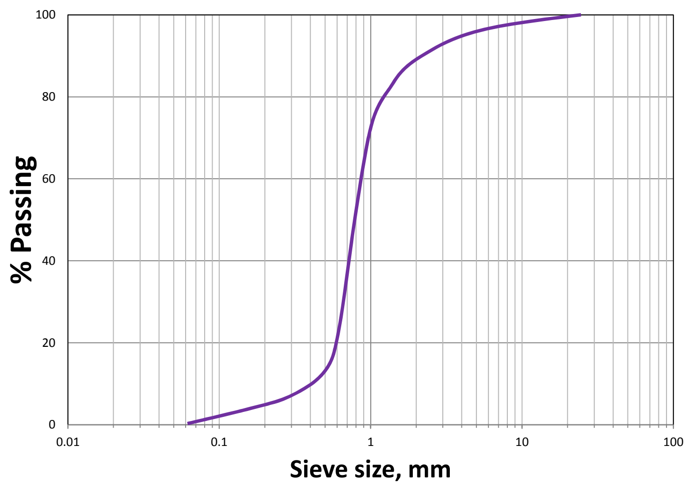
Open-Graded Aggregate



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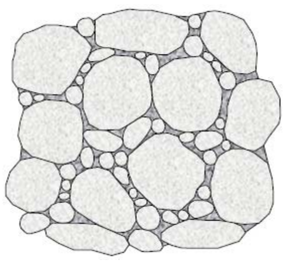
Dense-Graded Aggregate

- Dense or well-graded refers to a gradation that is near the 0,45 power curve for maximum density and contains optimum amount of aggregates from all ranges.



- Particle-to-particle contact
- Low void content
- High density
- High stability if confined
- High stability when unconfined
- Difficult to compact

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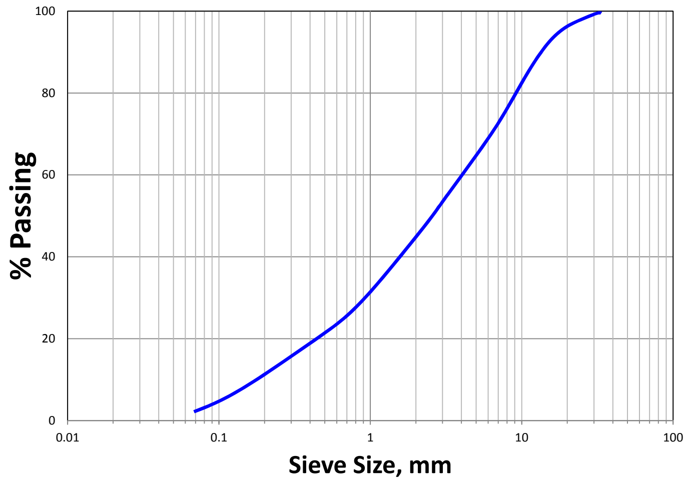
Dense-Graded Aggregate



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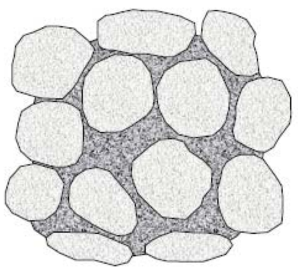
Gap-Graded Aggregate

- Gap graded refers to a gradation that contains only a small percentage of aggregate particles in the mid-size range. The curve is flat in the mid-size range



- No particle-to-particle contact
- High void content
- Lower density
- Low stability if confined
- Low stability when unconfined
- Easy to compact

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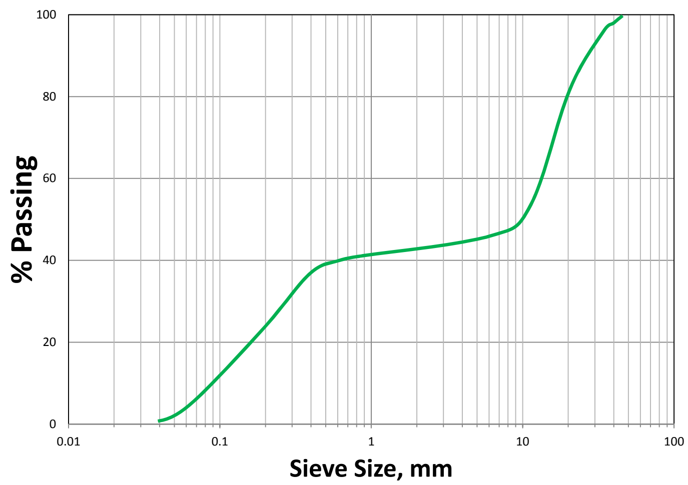
Gap-Graded Aggregate



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Example
Percentage Passing Calculation

Sieve Designation	Aggregate weight retained (g)	Aggregate percent retained (%)	Cumulative weight retained (g)	Cumulative percent retained (%)	Cumulative percent passing (%)
12.5	0	**0**	**0**	**0**	**100**
9.5	480	**4.8**	**480**	**4.8**	**95.2**
4.75	1540	**15.4**	**2020**	**20.2**	**79.8**
2.36	2240	**22.4**	**4260**	**42.6**	**57.4**
1.18	1300	**13**	**5560**	**55.6**	**44.4**
0.6	1650	**16.5**	**7210**	**72.1**	**27.9**
0.3	740	**7.4**	**7950**	**79.5**	**20.5**
0.15	720	**7.2**	**8670**	**86.7**	**13.3**
0.075	930	**9.3**	**9600**	**96**	**4**
0	400	**4**	**10000**	**100**	**0**
Total	10000				

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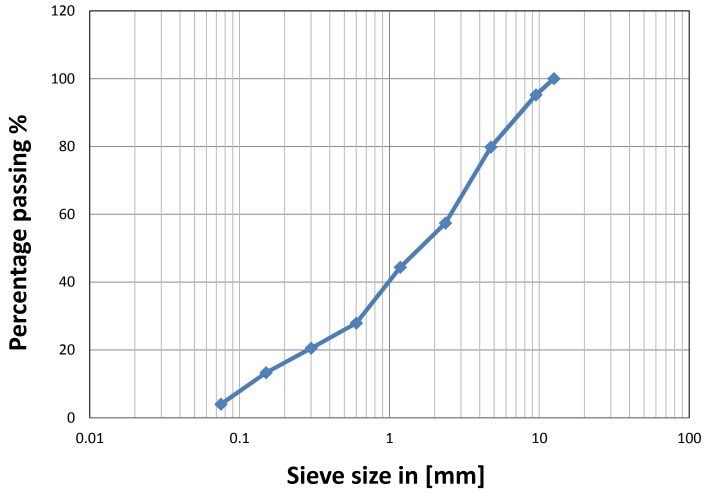
Example
Percentage Passing Calculation



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Toughness/Abrasion Resistance

- Common test methods for characterizing aggregate toughness/abrasion resistance
  - Los Angeles Abrasion (AASHTO T96, ASTM C131)
  - Aggregate Impact Value (British)
  - Aggregate Crushing Value (British)
  - Micro-Deval Abrasion (French/Canadian)
  - Degradation in the SHRP Gyratory Compactor

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Los Angeles Abrasion test

- **The Los Angeles (L.A.) abrasion test** is a common test method used to indicate aggregate toughness and abrasion characteristics **(AASTO T96, ASTM C131)**
- Resistance of coarse aggregate abrasion and mechanical degradation during handling, construction and use
- For the L.A. abrasion test, the portion of an aggregate sample retained on the 1.70 mm sieve is placed in a large rotating drum that contains a shelf plate attached to the outer wall
- A specified number of steel spheres are then placed in the machine and the drum is rotated for 500 revolutions at a speed of 30 - 33 revolutions per minute (RPM)

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Los Angeles Abrasion test

- The material is then extracted and separated into material passing and retained on the 1.70 mm sieve
- The retained material is then weighed and compared to the original sample weight. The difference in weight is reported as a percent of the original weight and called the "percent loss"

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Los Angeles Abrasion test

Aggregate Type	L.A Abrasion value
General Values	
Hard, igneous rocks	10
Soft limestone's and sandstones	60
Ranges for Specific Rocks	
Basalt	10 - 17
Dolomite	18 – 30
Gneiss	33 – 57
Granite	27 - 49
Limestone	19 – 30
Quartzite	20 - 35

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Aggregate Crushing Value

- The aggregate crushing value indicates the ability of an aggregate to resist crushing
- The lower the figure the stronger the aggregate, i.e. the greater its ability to resist crushing
- The aggregate passing 12.5 mm sieve and retained on 10 mm sieve is selected for standard test
- Compression testing machine with a load of 40 tonnes is applied for 10 minutes

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Aggregate Crushing Value

- The aggregate crushing value is defined as a ratio of the weight, of fines passing the specified sieve (2.36 mm) to the total weight of the sample expressed as a percentage.
  - Aggregate crushing value > 35 weak for pavement
  - Aggregate crushing value < 10 exceptionally strong

Rock group	Crushing value
Basalt	14
Granite	20
Lime stone	24
Quartzite	16

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Aggregate Impact Value

- Toughness of an aggregate is its resistance to failure by impact

Rock group	Impact value
Basalt	15
Granite	19
Lime stone	23
Quartzite	21

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Durability/Soundness

- AASHTO T 104 and ASTM C 88
- Estimates resistance of aggregate to breakdown or disintegration when subjected to weathering action
- Successively wetting and drying aggregate in saturated solutions of either **sodium sulfate or magnesium sulfate solution**
- Result is total percent loss over various sieve intervals for a prescribed number of cycles
  - Maximum loss values typically range from 10 to 20 % per 5 cycles

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Soundness

Before

After

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Cleanliness and Deleterious Materials

- Deleterious material is the mass percent of contaminants such as clay limps, shale, wood, mica, and coal in the blended aggregate
- Aggregates must be relatively clean when used in HMA or PCC
- **To test for clay lumps or friable particles**
  - A sample is first washed and dried to remove material passing the 0.075-mm (No. 200) sieve. The remaining sample is separated into different sizes and each size is weighed and soaked in water for 24 hours
  - Particles that can be broken down into fines with fingers are classified as clay lumps or friable material. The amount of this material is calculated by percentage of total sample weight
  - The test can be performed for both fine and coarse aggregates

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Volumetric relationships of Aggregate Materials

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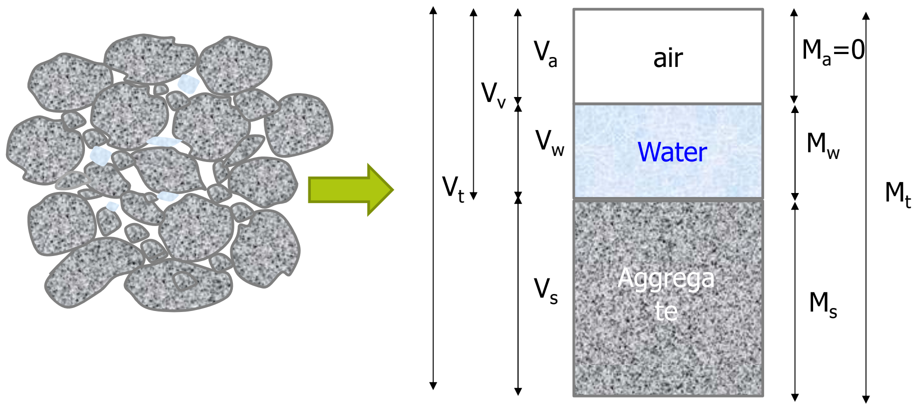
Phase Diagram

To compute mass (or weight) and volume of the three different phases



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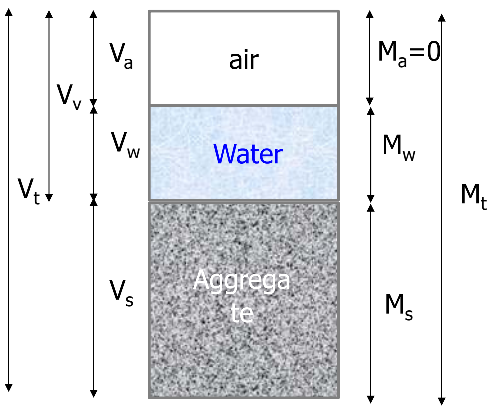
Phase Diagram

- M= mass of unbound materials
- V = volume
- s= solid solids
- w= water
- a= air
- v = voids
- t = total



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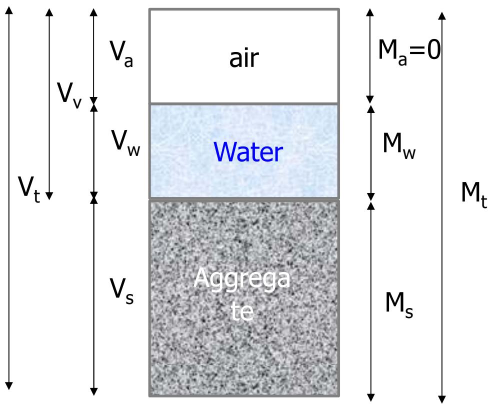
Gravimetric water content (w)

- Gravimetric water content (w) is a measure of the water present in the granular mix by weight . It is defined as the ratio of the mass of water, M_W to the mass of the solids,

$$w = \frac{M_W}{M_S} * 100\%$$



- Expressed as percentage
- Range from 0 to 100 %

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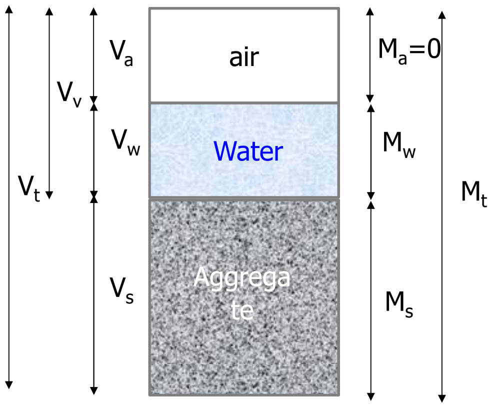
Volumetric water content (θ_v)

- Volumetric water content (θ_v) is defined as the ratio of the volume of water, V_w to the total volume of the aggregate, V_t

$$\theta_v = \frac{V_w}{V_t} * 100\%$$



- Expressed as percentage
- Range from 0 to 100 %

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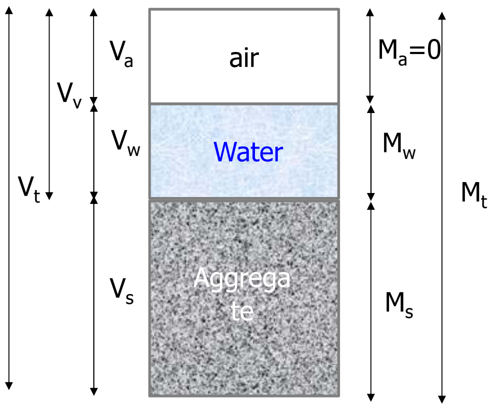
Porosity (n)

- Porosity (n) is defined as the ratio of the volume of voids over the total volume of aggregate mix

$$n = \frac{V_V}{V_t} * 100\%$$

- Theoretical range : 0 to 100 %

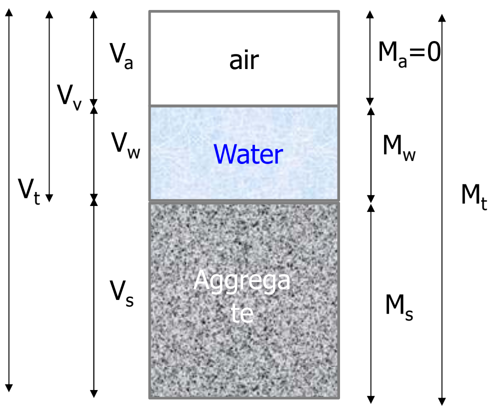


Void ratio (e)

- Void ratio (e) is defined as the ratio of the volume of voids over the volume of aggregate

$$e = \frac{V_V}{V_S}$$

$$n = \frac{e}{1 + e}$$



Degree of saturation (S)

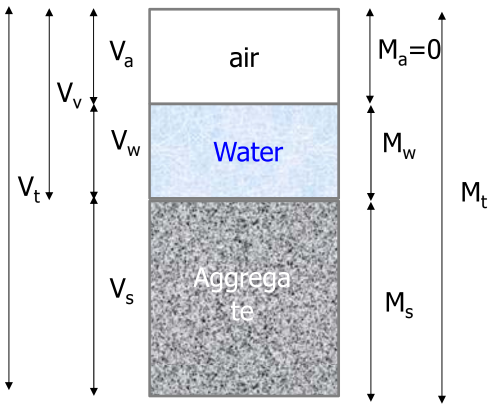
- Degree of saturation (S) is the percentage of the void volume filled by water

$$S = \frac{V_w}{V_v} * 100\%$$

- Dry aggregate materials S = 0%
- Fully saturated S = 100 %
- Unsaturated (0% <S<100%)

Note:

$$Gw = Se$$



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Densities (ρ)

- Densities is the unit mass of a material
  - Units : g/cm³, kg/m³, lb/ft³, t/m³, g/ml,
  - Density of water (ρ_w = 1.0 g/cm³ =1000 kg/m³ =62.4 lb/ft³)
  - Bulk density (ρ_m) is the density of the aggregate materials in the current state.

$$\rho_m = \frac{M_T}{V_T}$$

  - Dry density (ρ_d) is the density of the aggregate materials in dry state

$$\rho_d = \frac{M_S}{V_T}$$

  - Solid density (ρ_s) is the density of the aggregate materials in solid state

$$\rho_S = \frac{M_S}{V_S}$$

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Specific Gravity (G)

- Specific gravity is the ratio of density of aggregate mix to the density of water

$$G_S = \frac{\rho_S}{\rho_w} \quad G_S = \frac{M_S}{V_S \rho_w}$$

$$\rho_S = \frac{M_S}{V_S}$$

$$G_S = \frac{\rho_d V_t}{V_S \rho_w}$$

$$\rho_d = \frac{M_S}{V_t} = \frac{G_S}{1+e}\rho_W$$

$$\frac{V_S}{V_t} = \frac{\rho_d}{G_S \rho_w}$$

- Unit volume of aggregate

$$\frac{V_V}{V_t} = 1 - \frac{\rho_d}{G_S \rho_w}$$

- Unit volume of voids

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Example

1. A cubic meter of aggregate in its natural state weighs 17.75kN, after being dried it weighs 15.08kN. The specific gravity of the aggregate is 2.70. Determine the degree of saturation (S), void ratio (e), porosity (n), and gravimetric water content (w) the aggregate as its natural state.

Given

Total volume of aggregate V_t =1m^3
Total weight of aggregate W_t = 17.75kN
Dry weight of aggregate Ws = 15.08kN
Specific gravity of aggregate G_s = 2.70

Solution (on white board)

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Mechanical Properties of Aggregates

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California Bearing ratio (CBR) Value

- Basically a penetration test
- Piston penetrates soil at constant rate 0.05 in/min
- Pressure is recorded
- Take the ratio to the bearing capacity of a standard rock
- Range: 0 (worst) –100 (best) Type equation here.

$$\text{CBR} = \frac{\text{Pressure to cause } 0.1'' \text{ penetration to the sample}}{\text{Pressure to cause } 0.1'' \text{ penetration for standard rock}}$$

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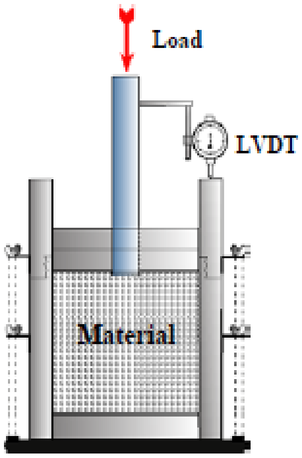
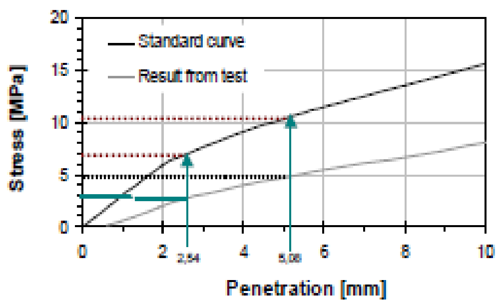
California Bearing ratio (CBR) Value





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California Bearing ratio (CBR) Value

General Soil Type	USC Soil Type	CBR Range
Coarse-grained soils	GW	40 - 80
	GP	30 - 60
	GM	20 - 60
	GC	20 - 40
	SW	20 - 40
	SP	10 - 40
	SM	10 - 40
	SC	5 - 20
Fine-grained soils	ML	15 or less
	CL LL < 50%	15 or less
	OL	5 or less
	MH	10 or less
	CH LL > 50%	15 or less
	OH	5 or less

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Stress and Strain

- Stress

$$Stress = \frac{Load}{Area}$$

- Strain

$$Strain = \frac{Deformation}{Original\_length}$$

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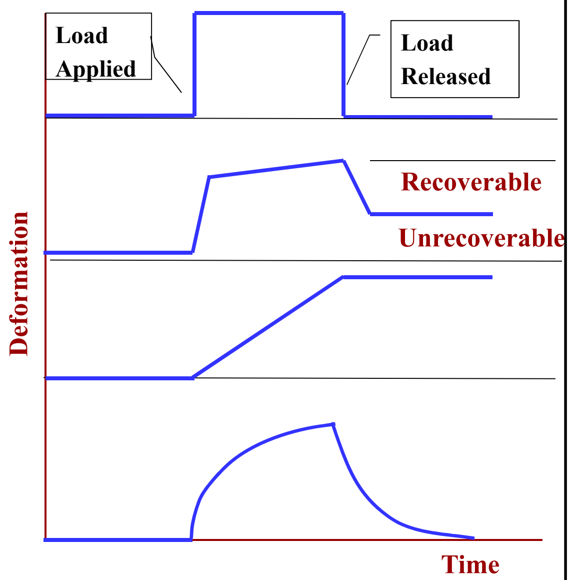
Types of materials responses

- Elastic
- Elasto-Plastic
- Viscous
- Visco-elastic



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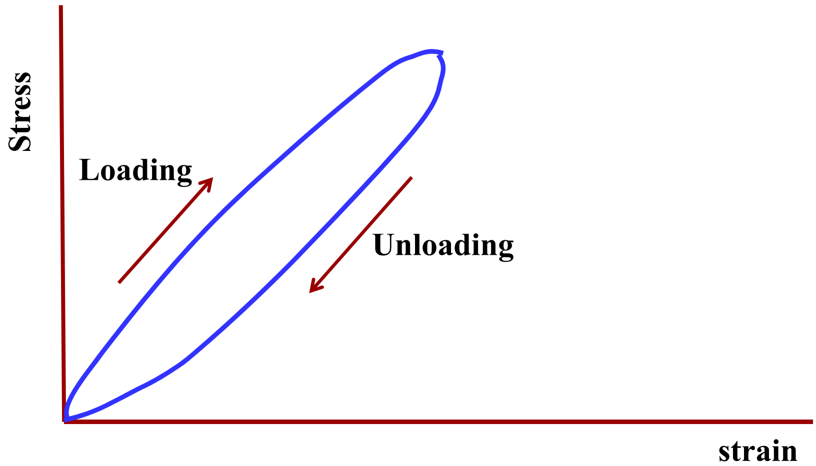
Elastic Stress – strain behavior



Fully recovered Strain

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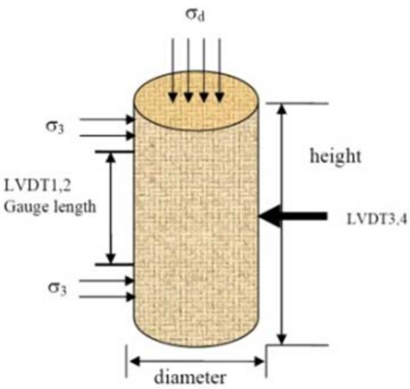
Cyclic Loading Behavior



- Triaxial loading cell is used to test the cyclic loading behavior

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Cyclic Loading Behavior

- The response of the materials is elasto-plastic
- Under cyclic load application the aggregates experience:-
  - recoverable (resilient) strain
  - non-recoverable (permanent) strain
- The stable resilient behavior obtained after a large number of load cycles.
- The accumulation of permanent strains, which is more complex to describe

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Stresses

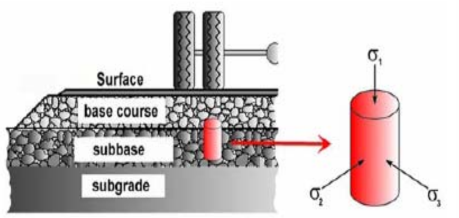
- Deviator Stress

$$q = \sigma_d = \sigma_1 - \sigma_3$$

- Mean principal stress

$$p = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} = \frac{\sigma_1 + 2\sigma_3}{3}$$

$$\sigma_2 = \sigma_3$$



- Bulk stress

$$\theta = \sigma_1 + 2\sigma_3$$

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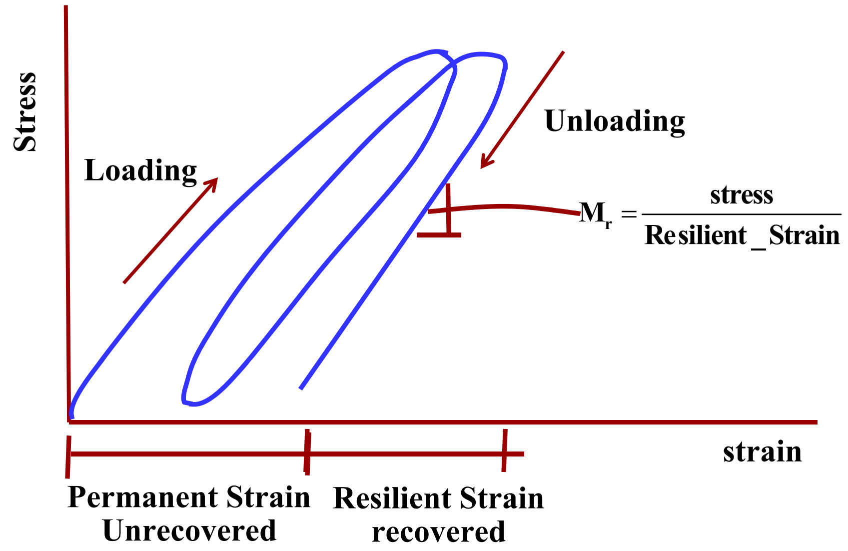
Elasto-Plastic Stress – strain behavior



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Resilient Modulus (M_r)

- Important mechanical property for pavement design
- is the elastic properties of aggregate recognizing certain non-linear characteristics (AASHTO T 307)
- Defined as applied stress divided by recoverable strain

$$M_r = \frac{\sigma_d}{\varepsilon_r}$$

- Deviator stress σ_d
- Resilient strain ε_r
- Resilient modulus ≠ Strength

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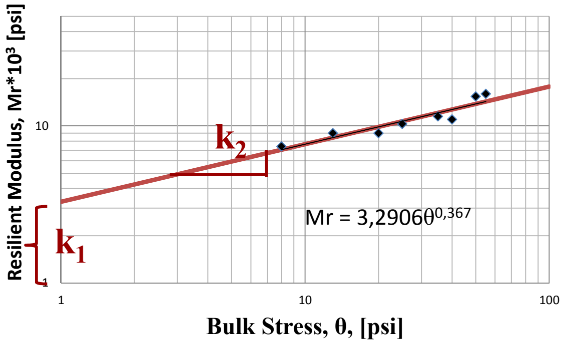
K-θ Model for Resilient Modulus (M_r)

- k_1 and k_2 are constants that represent the intercept and slope of resilient modulus against the bulk stress on logarithmic scales.
- Psi (Pounds per square inch)

$$M_r = k_1 \theta^{k_2}$$



k_1= 3290.6 psi (22.68Mpa)

k_2=0.367

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Example

- The Table below shows the result of resilient modulus tests on an aggregate materials. Determine the nonlinear coefficient k_1 and k_2.

Confining Pressure (psi)	Deviatoric Stress (psi)	Recoverable Strain (x 10E-3)	Resilient Modulus (x 10E3)	Bulk Stress θ, (psi)
2	6	0,58	10,34	12
5	15	0,74	20,27	30
10	30	0,95	31,58	60
15	45	1,14	39,47	90
20	50	1,2	41,67	110

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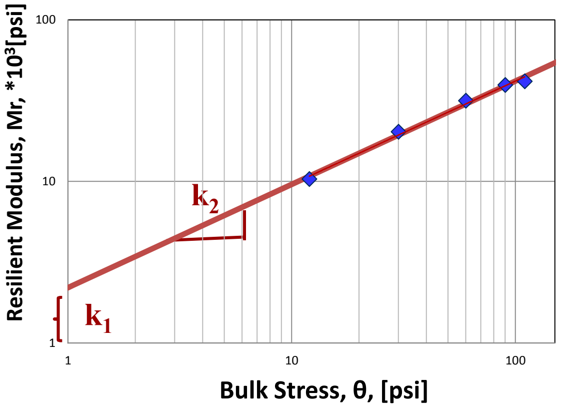
Example

$$Mr = 2{,}2015\theta^{0{,}639}$$



k_1= 2201,5 psi (15,2 Mpa)

k_2=0.639

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Deformation of Unbound Aggregate Materials

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Factors that influence the deformation and shear behavior

- Particle shape
- Particle size
- Angularity
- Grain size distribution
- Surface texture
- Packing (i.e. degree of compaction)
- Density
- Mineralogy

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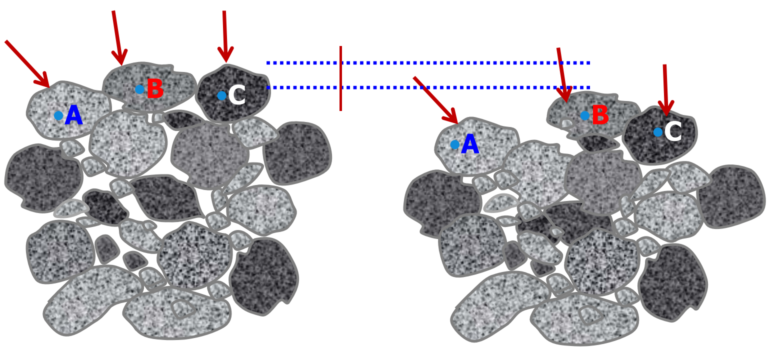
Mechanisms that contribute to deformation

- Relative motion of particles due to sliding or rolling
- Distortion and crushing of particles



Before Loading **After Loading**

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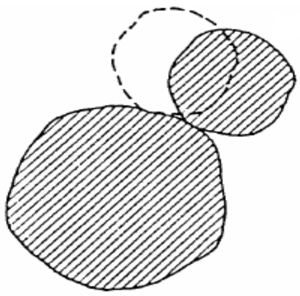
Mechanisms that contribute to deformation

- When the shear force becomes larger than the shear resistance at the contact:
  - Relative sliding between particles
- The overall deformation is partly from:
  - Individual particles, and
  - Relative sliding between particles

Position before loading

Position after loading



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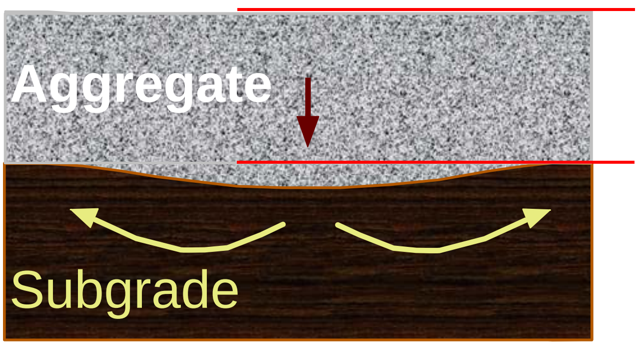
Unbound Base layer Deformation



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Unbound Base layer Deformation

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Present Approach

- Use a high quality aggregate for surface and base layers
  - Scandinavian countries

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END

Questions?