# Influence of PI and Dust Ratio on Aggregates in Subbase and Base Course

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# Objective

**Influence of fines content, dust ratio, gradation, material type and plasticity index on the strength of aggregates used for base and subbase applications.**

# DOTs and Standards

| Specification name | Maximum allowable percent passing no. 200 | Dust ratio | Plasticity index (PI) (%) | Liquid limit (LL) (%) | Description |
|---|---|---|---|---|---|
| **Arkansas (2003)** | 15% | <2/3[3] | <6[1] | <25[2] | – |
| **California (2015)** | 19% | – | – | – | R-value, sand equivalent, and durability index |
| **Colorado (2010)** | 20% | – | <6 | <35 | – |
| **Illinois (2016)** | 13% | – | <6 or 4 or 9[4] | – | PI requirement may be waived if the dust ratio is 0.6 or less |
| **Indiana (2014)** | 12% | – | <5 | <25 | For dense graded |
| **Missouri (2016)** | 15% | – | <6 | – | – |
| **North Carolina (2012)** | 12% | – | <6 | <30 | – |
| **Oklahoma (2009)** | 12% | <2/3 | <6 | <25 | – |
| **South Dakota (2015)** | 15% | <0.66 | <6 | <25 | – |
| **Washington (2014)** | 10% | <0.66 | – | – | Sand equivalent |
| **AASHTO M147 (2008)** | 20% | <0.66 | <6 | <25 | – |
| **ASTM D1241-00 (2000)** | 15% | <0.6 | <4 | <25 | – |

[1] There are 8 classes of coarse grading that for class 1 & 2 PI value is acceptable up to 13% & 10% respectively.
[2] For classes 1 and 2 grading, dust ratio should be less than ¾.
[3] For classes 1 and 2 grading, this value can be less than ¾.
[4] Lower plastic material (<6) shall be used if crushed gravel, stone, or slag is used.

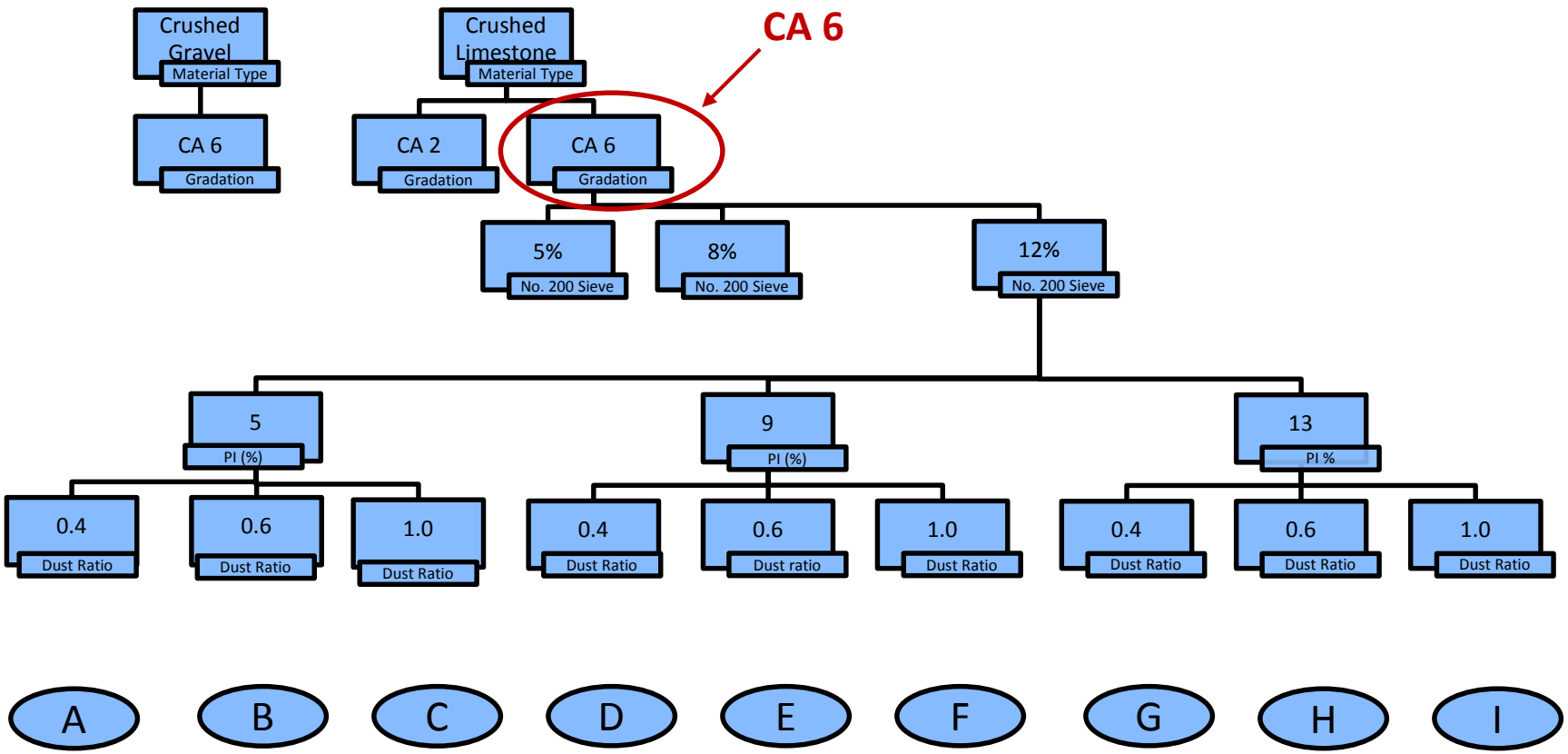
# Strength, Stiffness, and Deformational Behavior

- California Bearing Ratio
  - ❑ Soaked
  - ❑ Unsoaked
- Unconsolidated Undrained Static Triaxial (ASTM D2850)
  - ❑ Confining Pressures (5, 10, 15 psi)
- Resilient Modulus Test (AASHTO T-193)

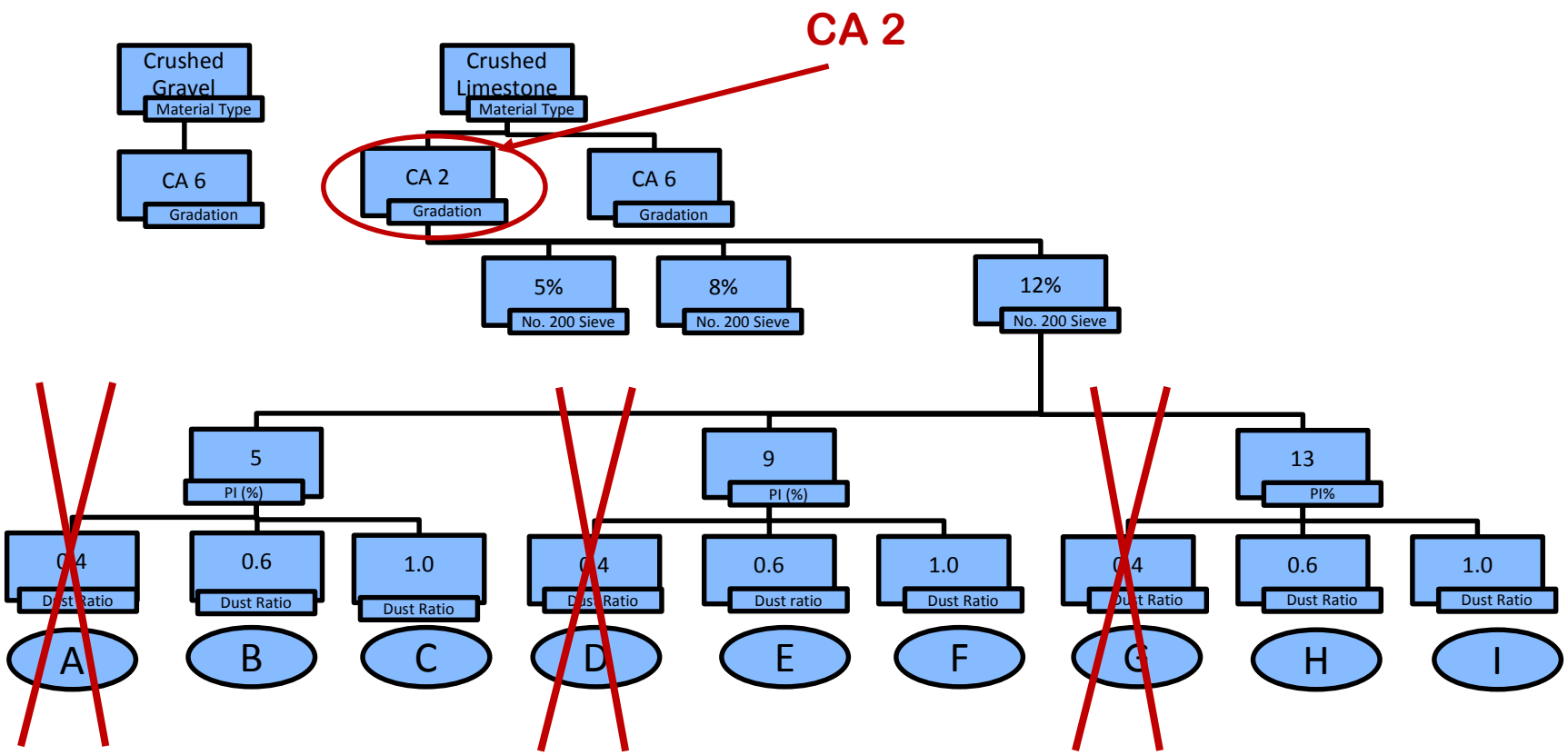
# Materials

- Two types aggregate:
  - ❑ Crushed Limestone
  - ❑ Crushed Gravel
- Two gradations
  - ❑ CA 6
  - ❑ CA 2
- Three fines content
  - ❑ 5%, 8%, 12%
- Three plasticity indices
  - ❑ 5%, 9%, 13%
- Three dust ratios (passing No. 200 to No. 40 sieve)
  - ❑ 0.4, 0.6, 1.0

# Test Matrix of CA 6 Crushed Limestone



# Test Matrix of CA 2 Crushed Limestone



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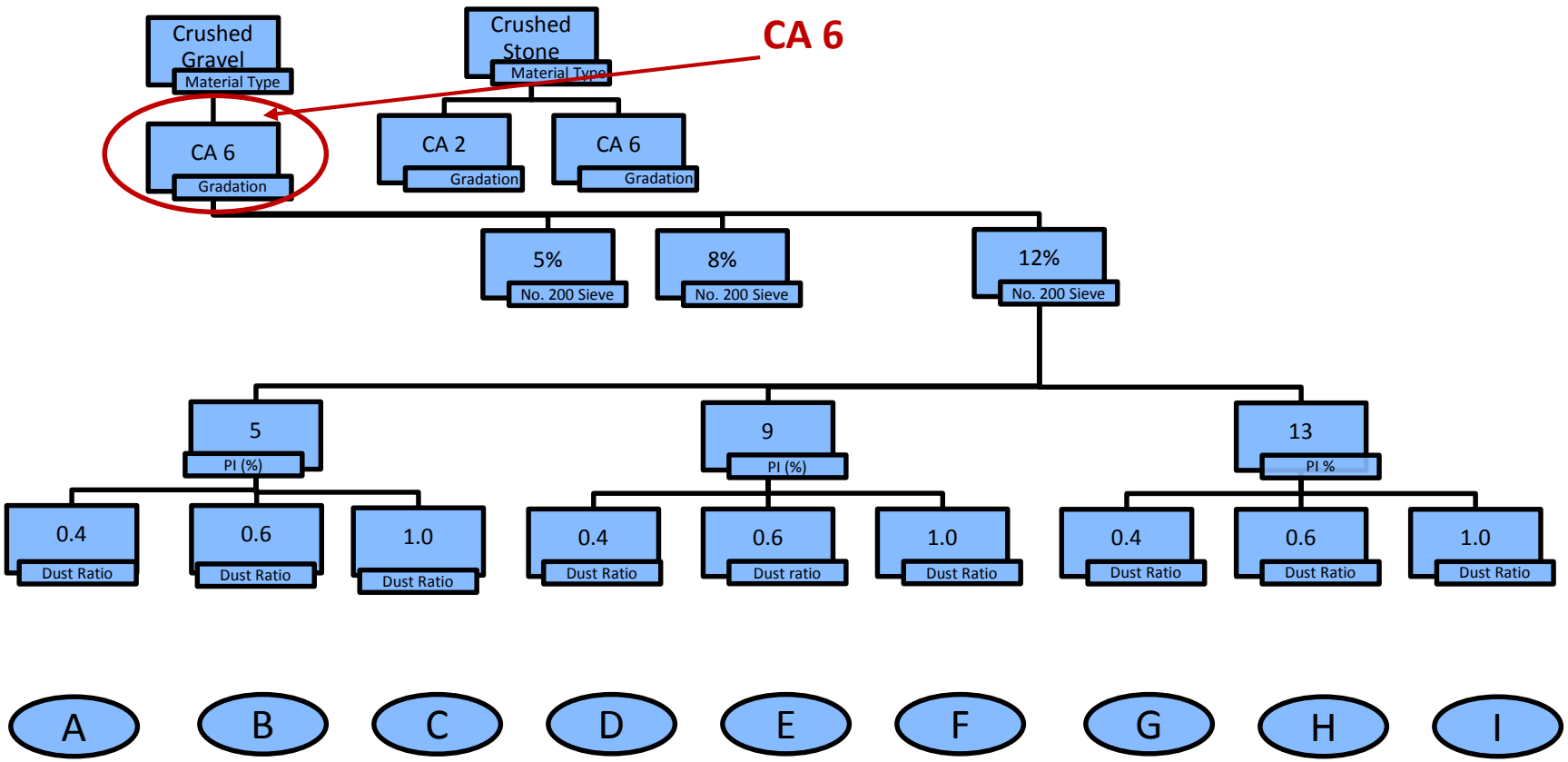
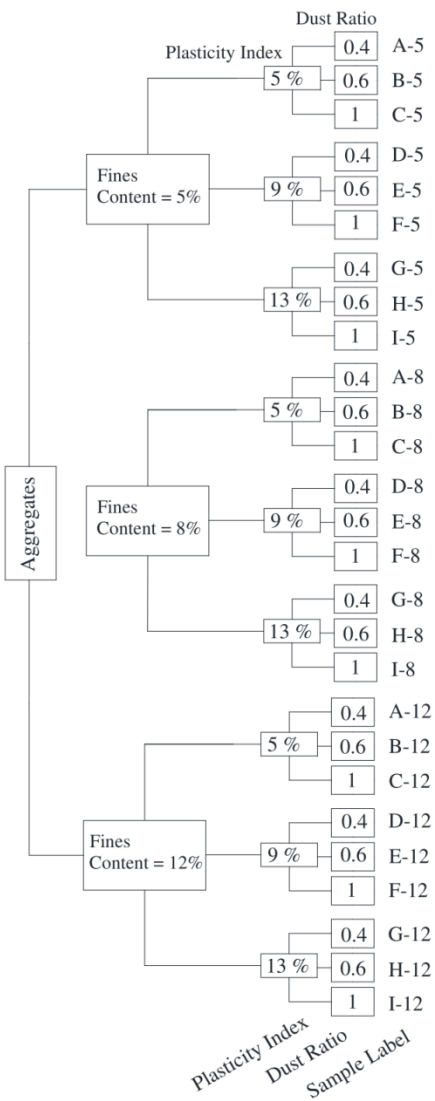
# Test Matrix of CA 6 Crushed Gravel



# Tested Samples




| Sample Label | Soaked CBR (S) Unsoaked CBR (U) Staged triaxial (T) | | | Resilient modulus (X) | | |
|---|---|---|---|---|---|---|
| | CA 6 Crushed limestone | CA 6 Crushed gravel | CA 2 Crushed limestone | CA 6 Crushed limestone | CA 6 Crushed gravel | CA 2 Crushed limestone |
| A-5 | S, U | S, U | S | X | | X |
| B-5 | S, U, T | S, U, T | S, T | X | X | X |
| C-5 | S, U | S, U | S | X | | X |
| D-5 | S, U | S, U | S | | | |
| E-5 | S, U | S, U | S | X | X | X |
| F-5 | S, U, T | S, U, T | S, T | | | |
| G-5 | S | S | S | | | |
| H-5 | S | S | S | | | |
| I-5 | S | S | S | | | |
| A-8 | S | S | S | | | |
| B-8 | S | S | S | X | | X |
| C-8 | S | S | S | | | |
| D-8 | S | S | S | | | |
| E-8 | S | S | S | | | |
| F-8 | S | S | S | | | |
| G-8 | S | S | S | | | |
| H-8 | S | S | S | | | |
| I-8 | S | S | S | | | |
| A-12 | S, U | S, U | S | X | | |
| B-12 | S, U, T | S, U, T | S, T | X | X | X |
| C-12 | S, U | S, U | S | X | X | |
| D-12 | S, U | S, U | S | | X | |
| E-12 | S, U | S, U | S | X | X | X |
| F-12 | S, U, T | S, U, T | S, T | | | |
| G-12 | S | S | S | | | |
| H-12 | S | S | S | | | |
| I-12 | S | S | S | | | |

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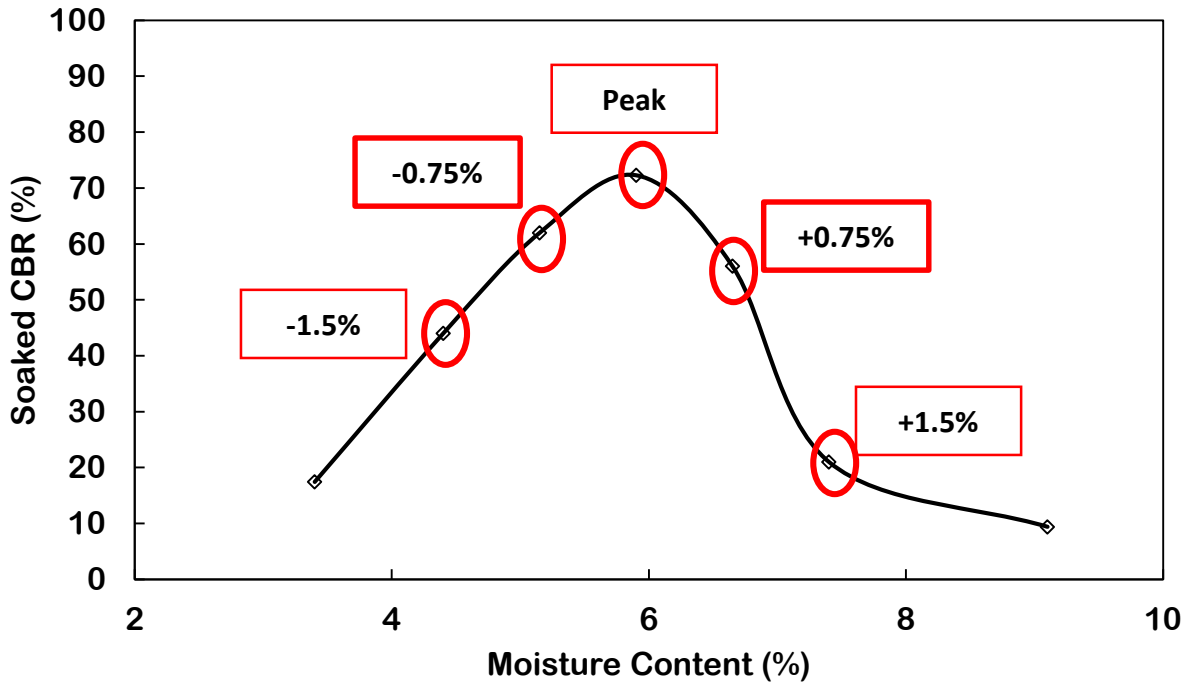
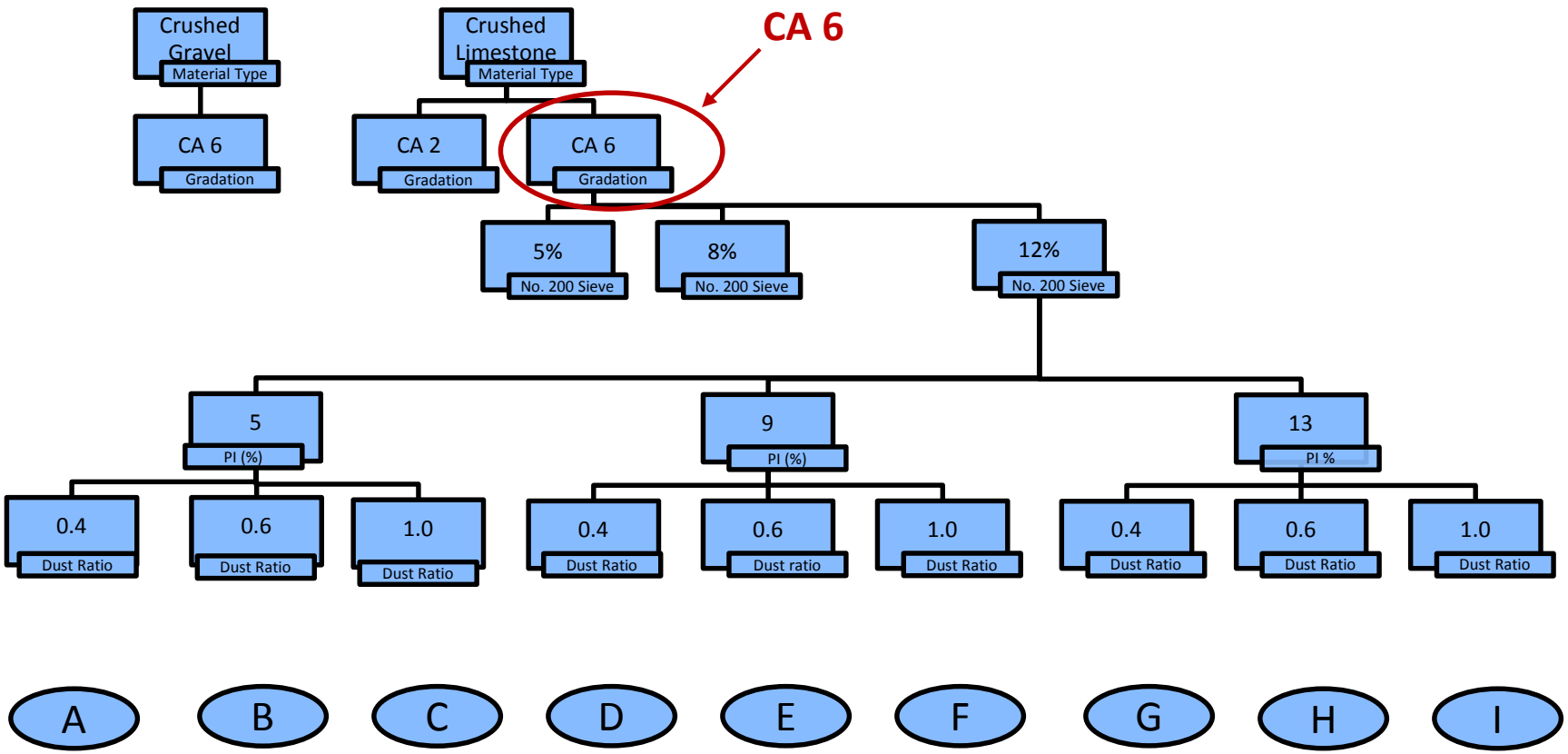
# CBR at Various Moisture Contents

- The strength of the unbound aggregate was evaluated over a range of moisture content.
- Results were plotted based on soaked CBR at OMC, OMC ±0.75% and OMC ±1.5%.

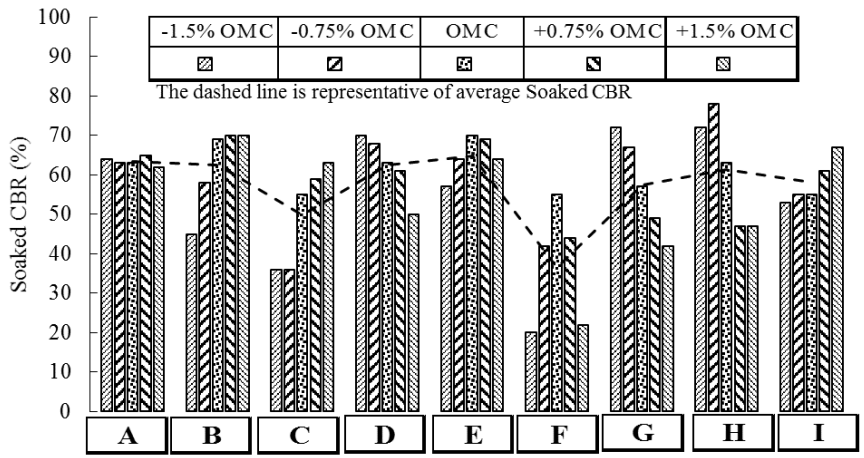


# Test Matrix of CA 6 Crushed Limestone

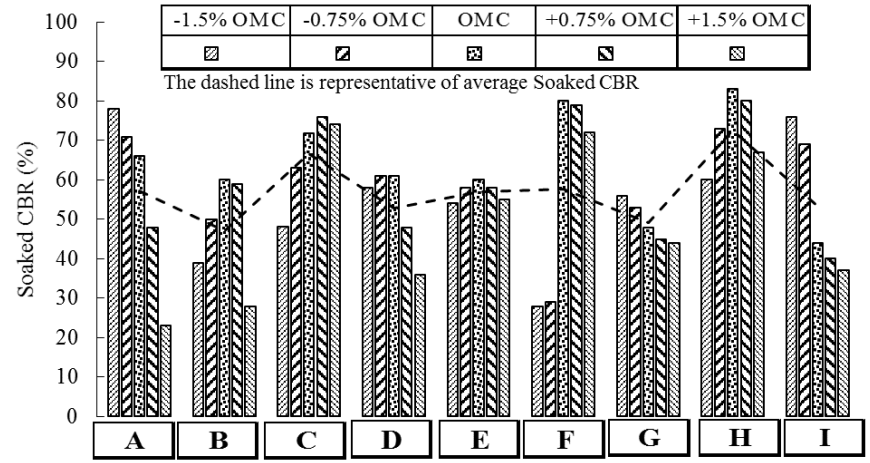


# Soaked CBR - CA 6 Crushed Limestone

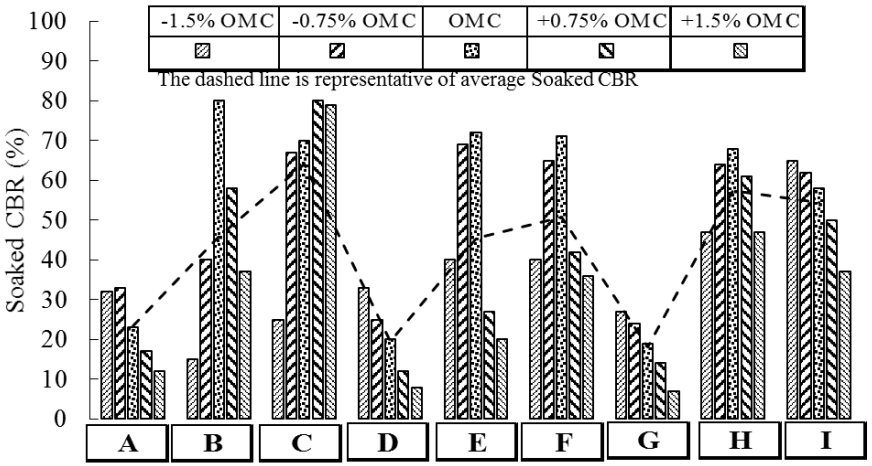
## Fines Content: 5%




## Fines Content: 8%



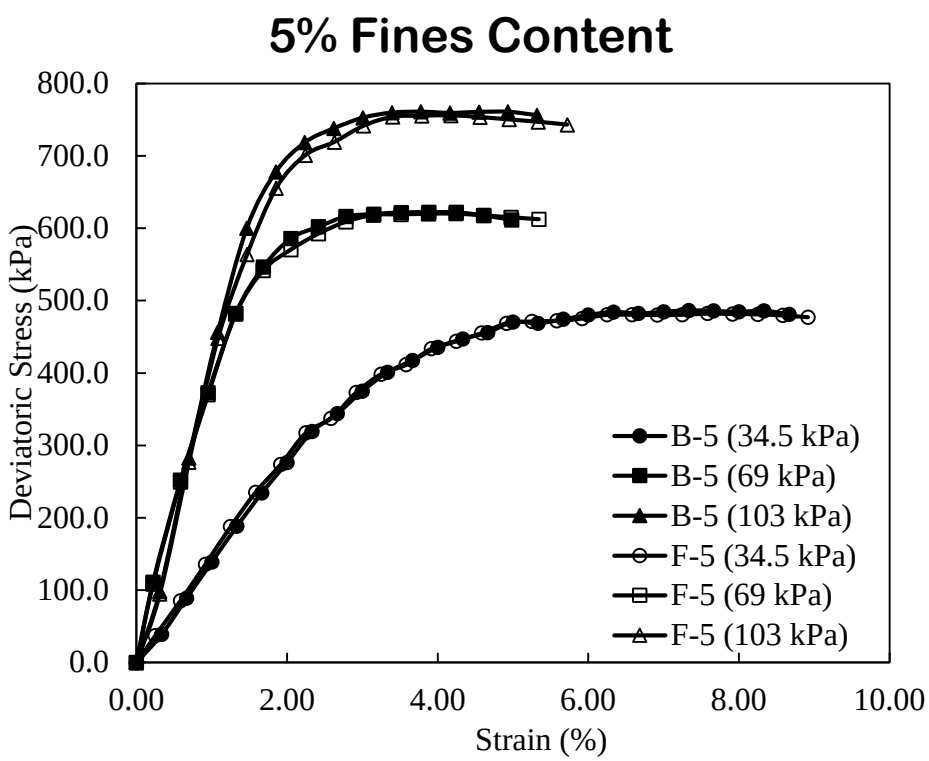

## Fines Content: 12%

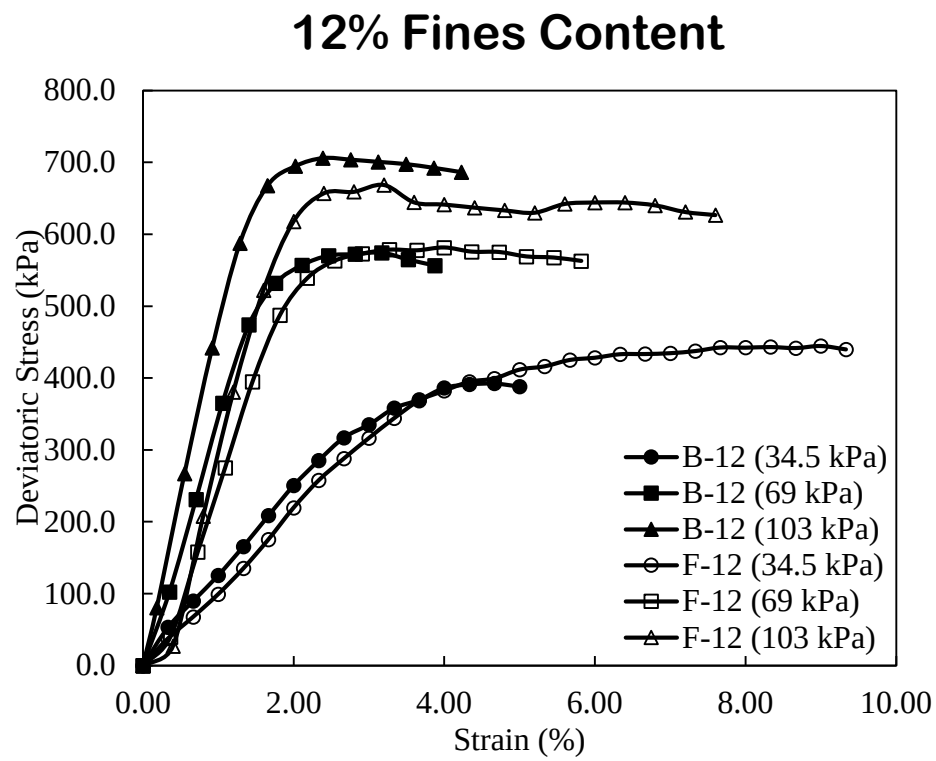


# CBR Conclusions – CA 6 Crushed Limestone

- Among all examined index properties (i.e. Fines Content, Plasticity Index, Dust Ratio, or Liquid Limit), fines content has the dominant effect on strength characteristic of the aggregate.
- For PIs of 5% and 9%, an increase in fines content decreases the strength.
- Increase of PI to 13% and LL to above 30% have limited effect on CBR strength of aggregates.
- Appropriate dust ratio depends on the fines content.
  - Samples engineered with DR of 1.0 had somewhat lower CBRs than other Dr values, when fines content was 5%
  - Samples engineered with DR of 0.4 and 1.0 resulted in lowest and highest average soaked CBR respectively, when fines content was 12%.
- Effect of higher PI was minor at all fines contents.

# Staged Triaxial - CA 6 Crushed Limestone




- ❑Maximum deviatoric stress and strain at failure is almost the same for both B and F samples at the same confining pressure.

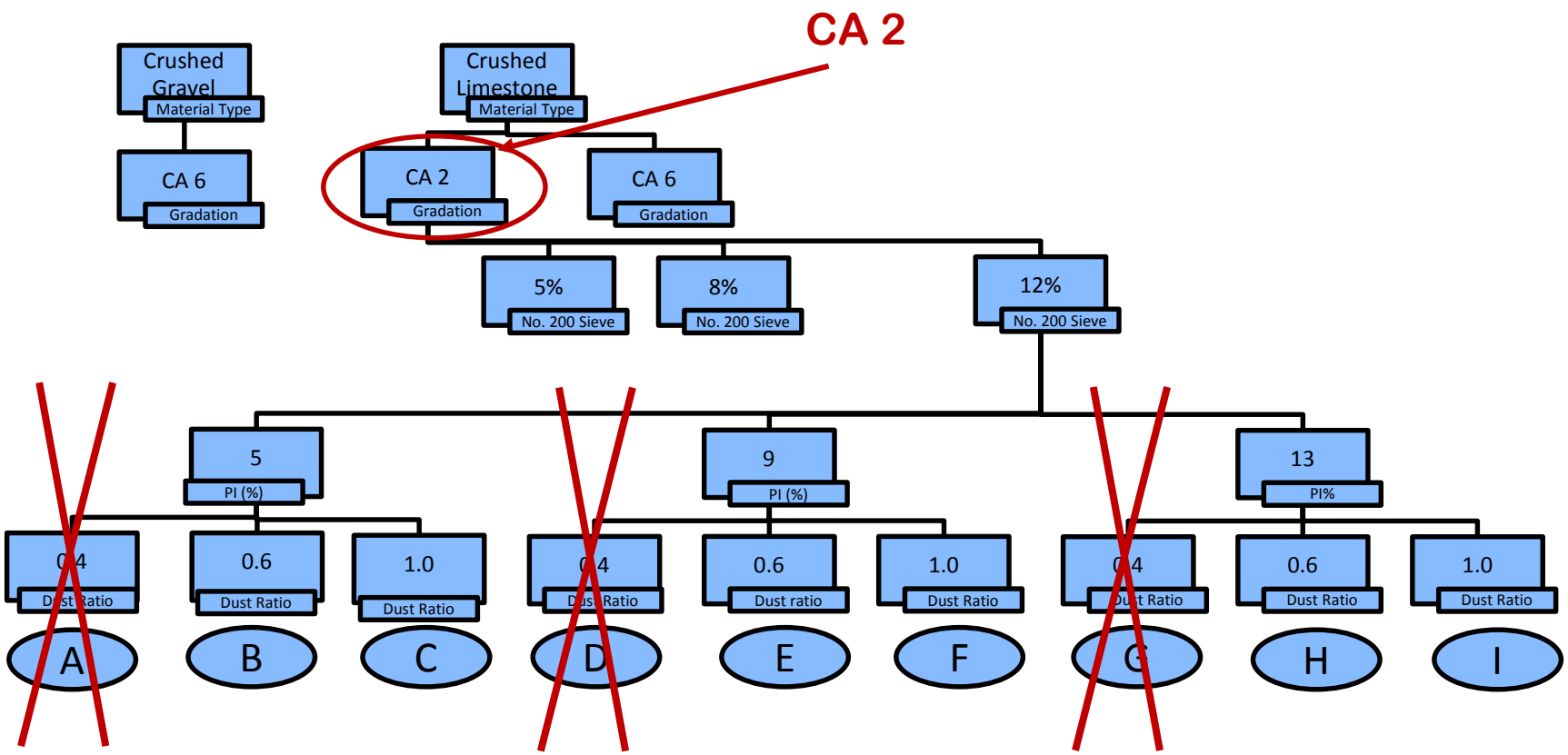
- ❑The difference in maximum deviatoric stress is more noticeable at higher confining pressures.

# Triaxial Conclusions – CA 6 Crushed Limestone

- Overall the differences in CBR test results were greater than the ones for triaxial test results.

- These differences in secant friction angles from triaxial tests and CBR strengths can be attributed to the loading mechanism.
  - CBR is a penetration index test and load is applied only in the center of the sample, while in a triaxial test, the load is applied through a plate of almost the same diameter as sample diameter.
  - In CBR the mold is rigid and in triaxial the confinement pressure is applied

# Updated Matrix – CA 2 Crushed Limestone



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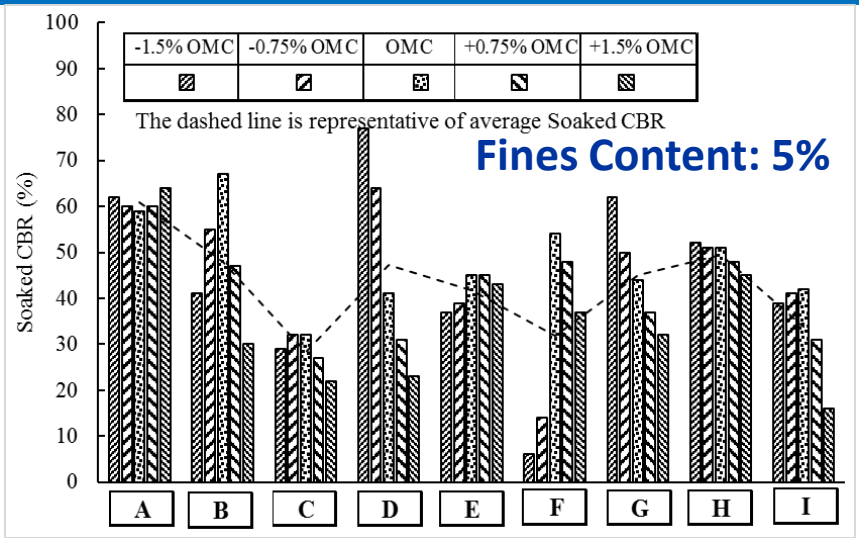
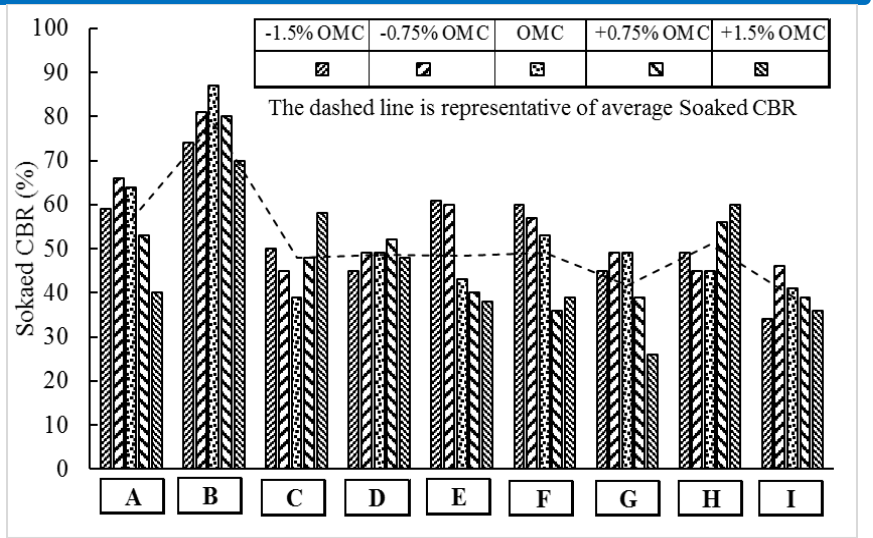
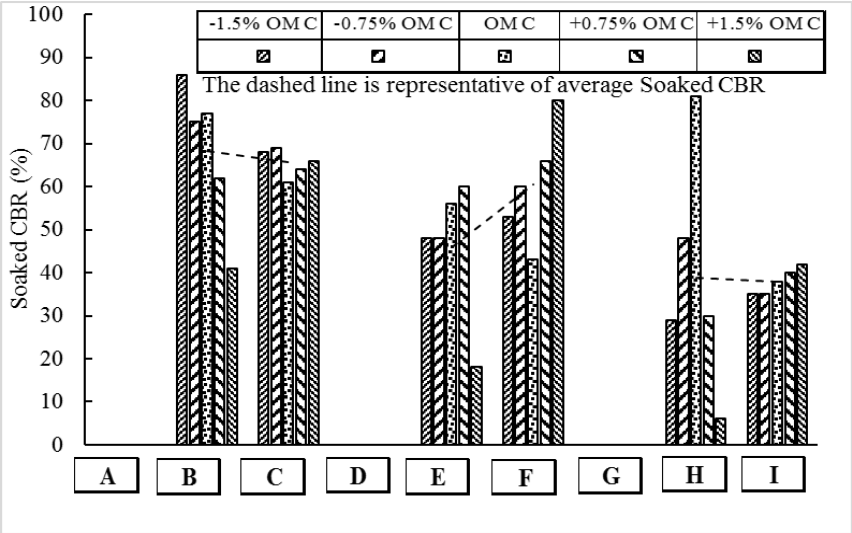
# Soaked CBR - CA 2 Crushed Limestone




Fines Content: 5%




Fines Content: 8%

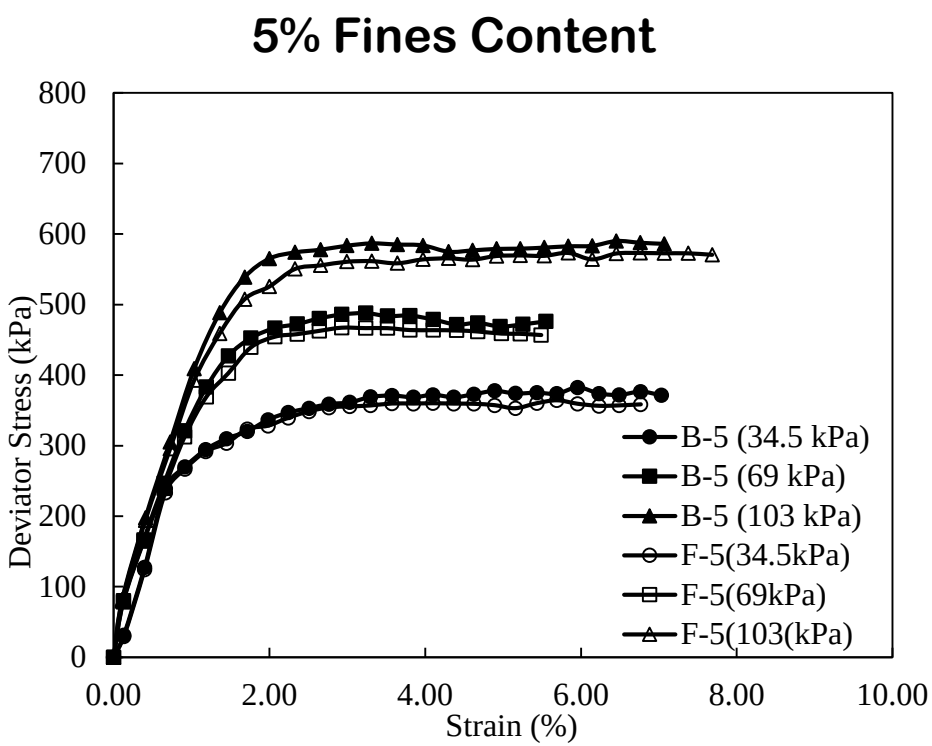


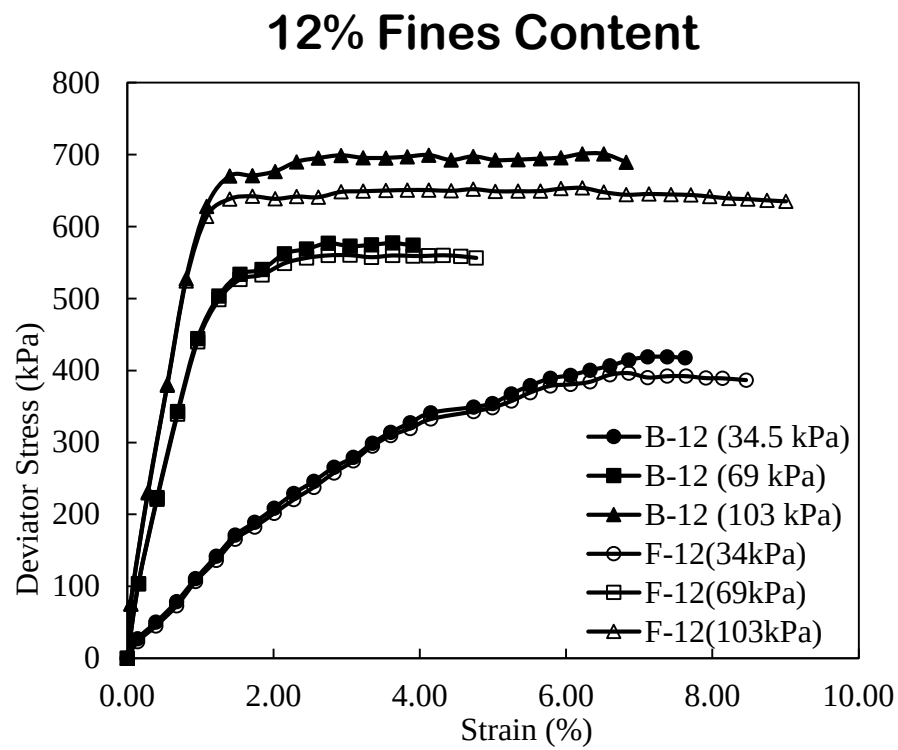

Fines Content: 12%

# Conclusions – CA 2 Crushed Limestone

- Among all examined index properties (i.e. Fines Content, Plasticity Index, Dust Ratio, or Liquid Limit), fines content and dust ratio have the dominant effect on strength characteristic of aggregate.
- For PIs of 5% and 9%, an increase in fines content increases the strength.
- For PI of 13% the increase of fines content does not show any effect on strength.
- Appropriate dust ratio depends on the fines content.
  - Samples engineered with DR of 1.0 had somewhat lower CBRs than other Dr values, when fines content was 5%
  - Samples engineered with DR of 1.0 resulted in high average soaked CBR, when fines content was 12%.
- Effect of higher PI was trivial at fines content of 5% and 8% while it is significant in samples with 12% fines content.

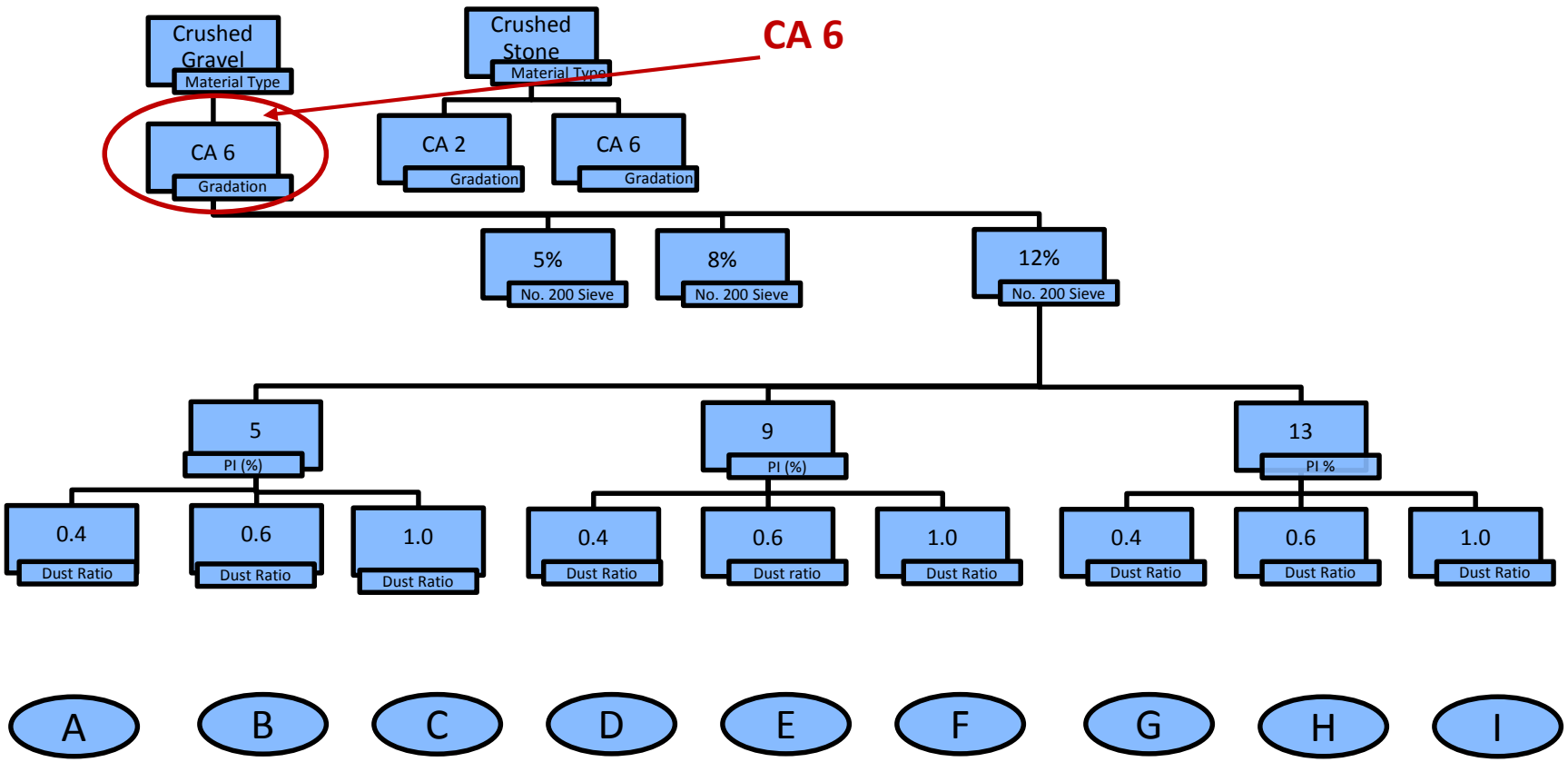
# Staged Triaxial - CA 2 Crushed Limestone



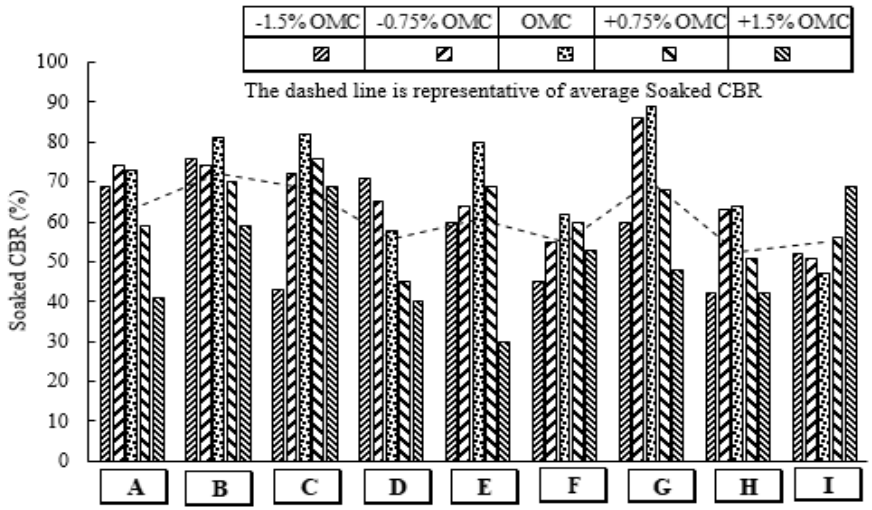




- **Similar to CA 6 crushed limestone, triaxial strength were less sensitive to different indices compared to CBR.**

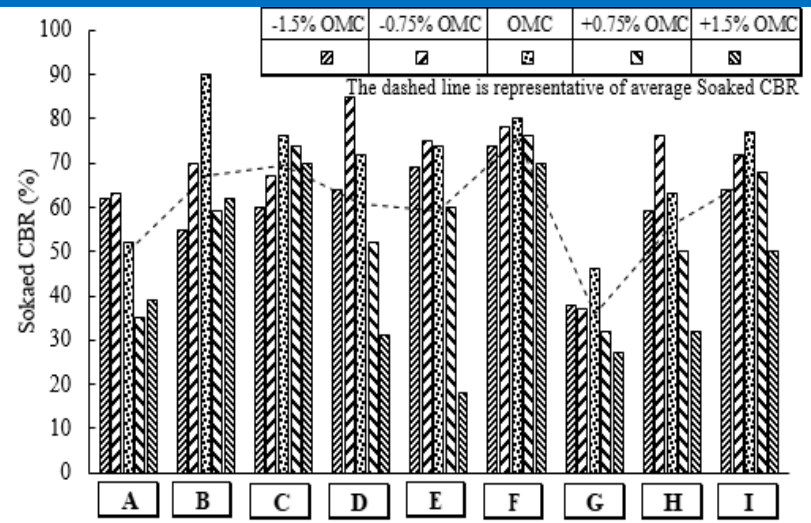
# Test Matrix of CA 6 Crushed Gravel



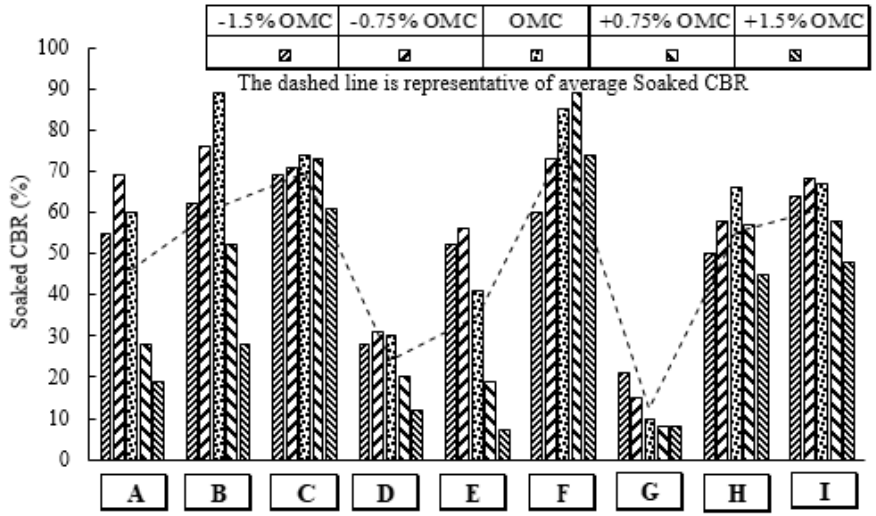
# Soaked CBR - CA 6 Crushed Gravel




**Fines Content: 5%**




**Fines Content: 8%**

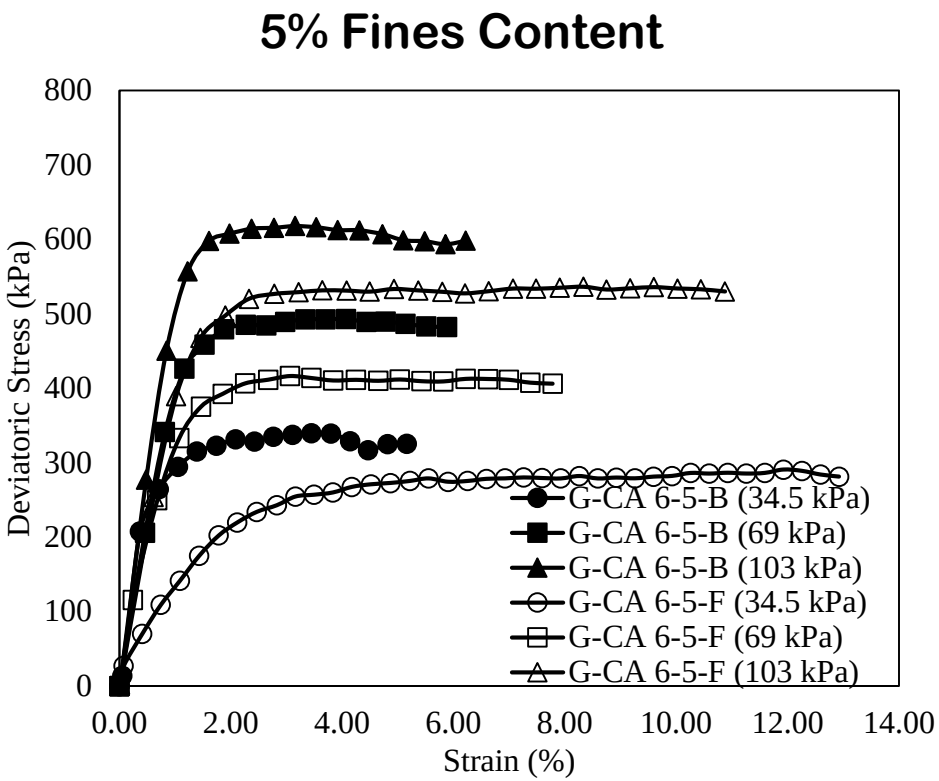


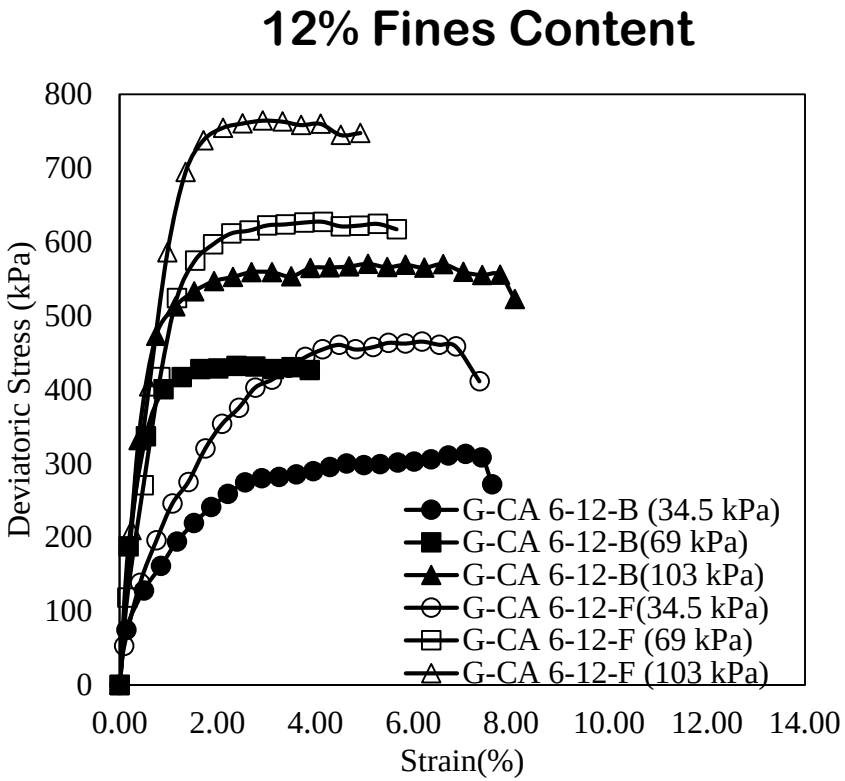

**Fines Content: 12%**

# Conclusions – CA 6 Crushed Gravel

- Fines content is the dominant index property influencing the strength of crushed gravel
- For PIs of 5% and 9%, an increase in fines content decreases the strength.
- Increase of PI to 13% and LL to above 30% have limited effect on strength of aggregates.
- Effect of dust ratio depends on fines content:
  - At 5% FC, increase in dust ratio to 1.0 have almost negligible effect on the strength
  - At 8% and 12% FC, soaked CBR increases with the increase in dust ratio.
- Effect of higher PI was trivial at fines content 5% and 8% while it is significant in samples with 12% fines content.

# Staged Triaxial - CA 6 Crushed Gravel



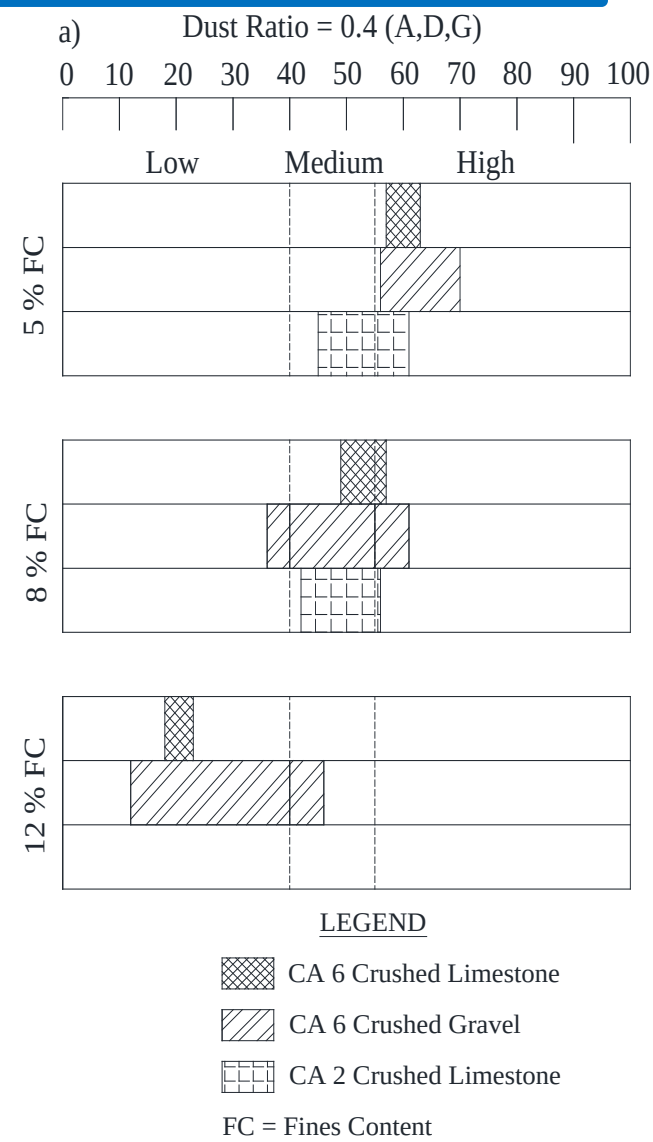

- Similar to CA 6 and CA 2 crushed limestone, triaxial were less sensitive to indices compared to CBR.
- Crushed gravel triaxial results were more sensitive compared to crushed limestone.

# Strength Zones for CA 6 Crushed Gravel, CA 6 Crushed Limestone and CA 2 Crushed Limestone Based on Soaked CBR Tests

# DR 0.4

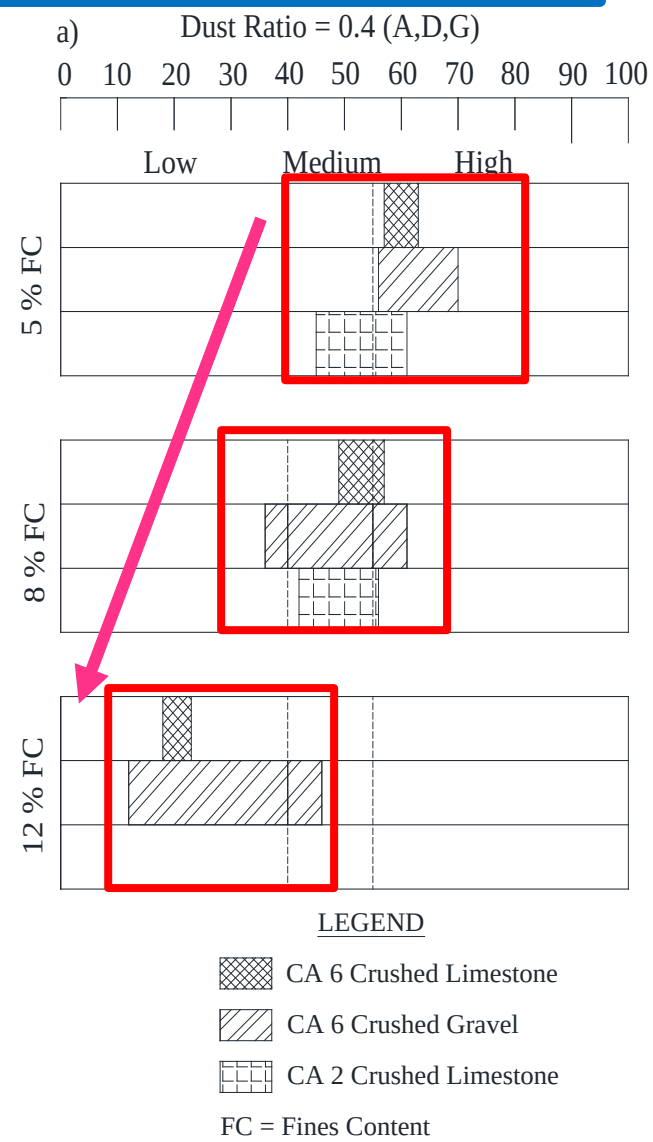
- Three strength zones were proposed:
  - High: 55% < $CBR_{soaked}$
  - Medium: 40% < $CBR_{soaked}$ < 55%
  - Low: $CBR_{soaked}$ < 40%

**The lower and upper CBR boundaries show the minimum and maximum soaked CBR values within OMC+/-1.5%.**



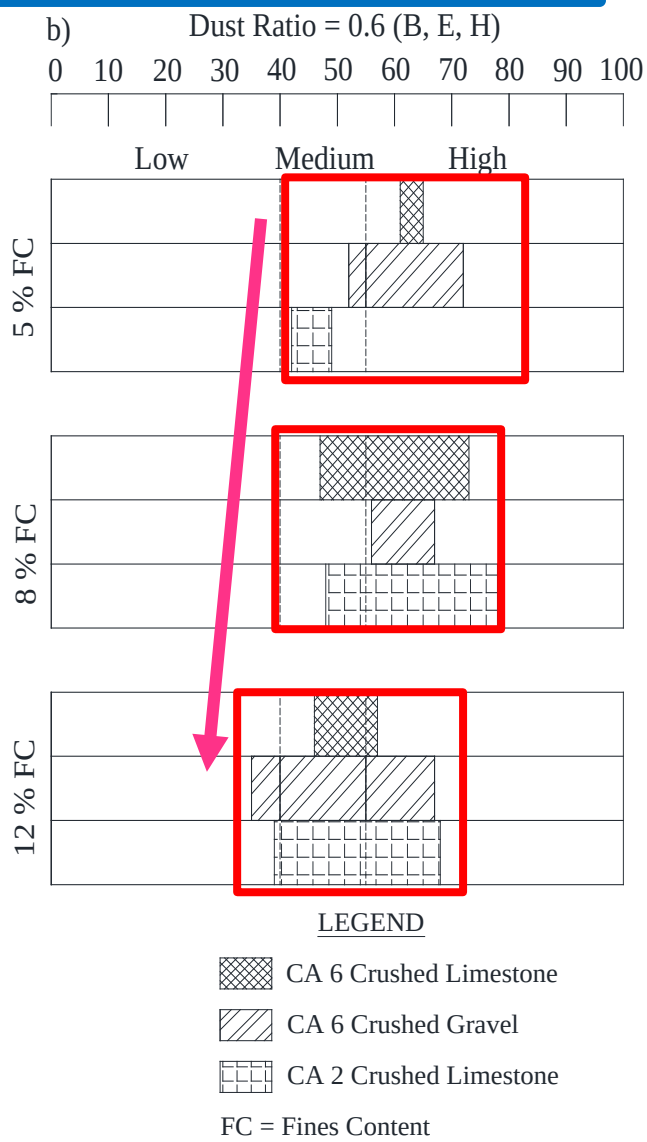
# DR 0.4

- Average soaked CBR of G-CA 6, C-CA 6 and C-CA 2 had a decreasing trend with increasing FC.
- Soaked CBR of CA 6 gradation samples with lower DR and higher FC were limited to low and medium strength zones.
- Regardless of material type, for aggregate gradations with DR of 0.4, the use of FC of 12% may not be appropriate in construction of base and subbase layer.



# DR 0.6

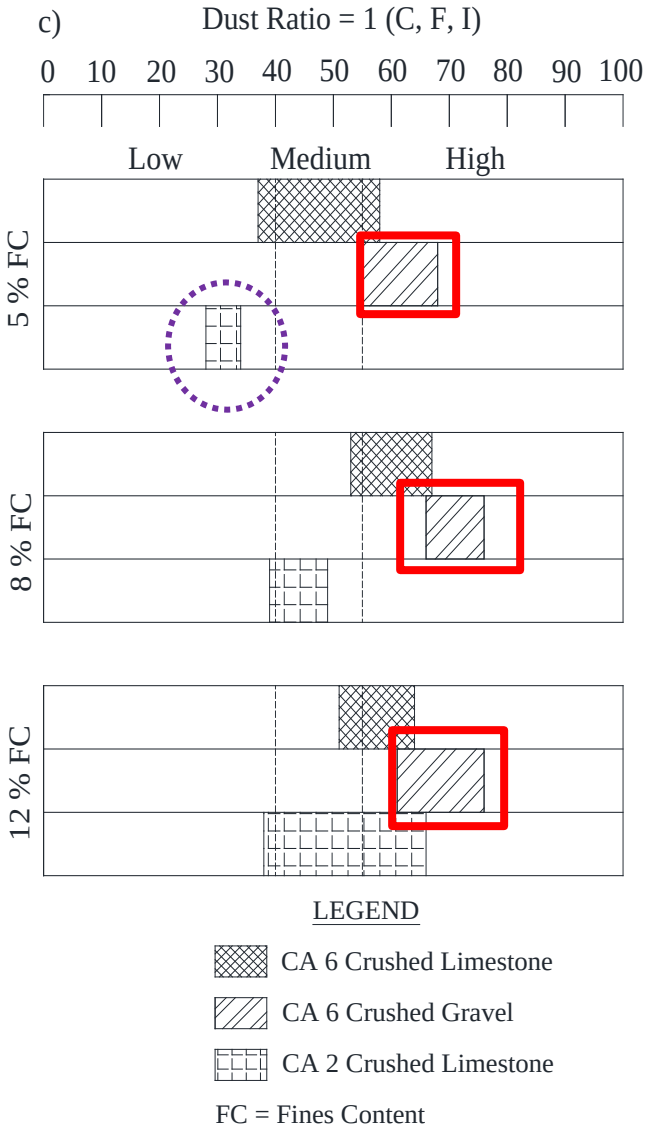
- Except for a few samples from crushed gravel group, average soaked CBR of all C-CA 6 and G-CA 6 samples were in the medium and high strength zone.



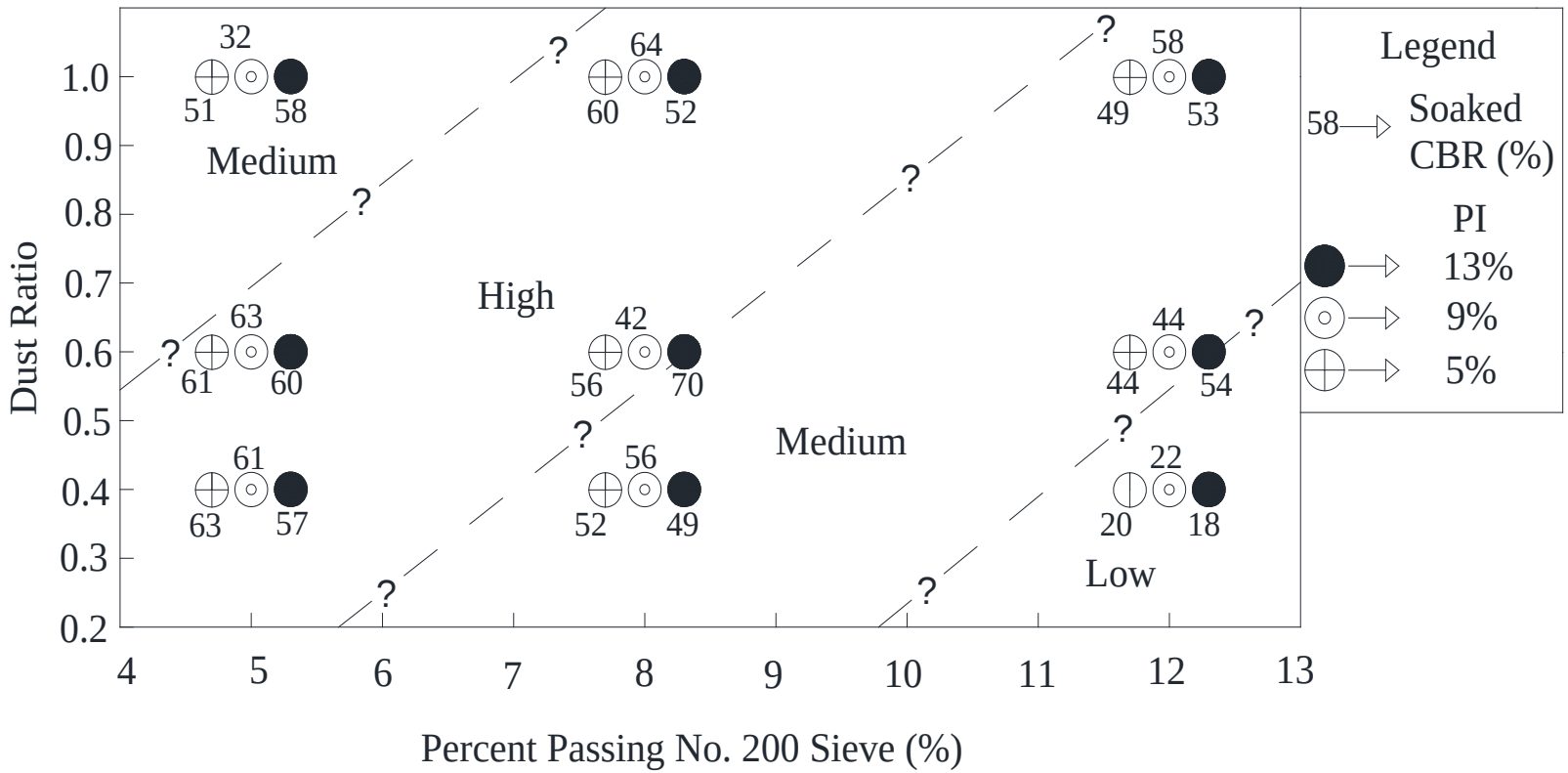
# DR 1.0

- Average soaked CBR of all G-CA 6 samples were in high strength zone.

- Generally, all crushed limestone samples showed medium to high strength except crushed limestone samples with DR 1.0 and FC of 5%.

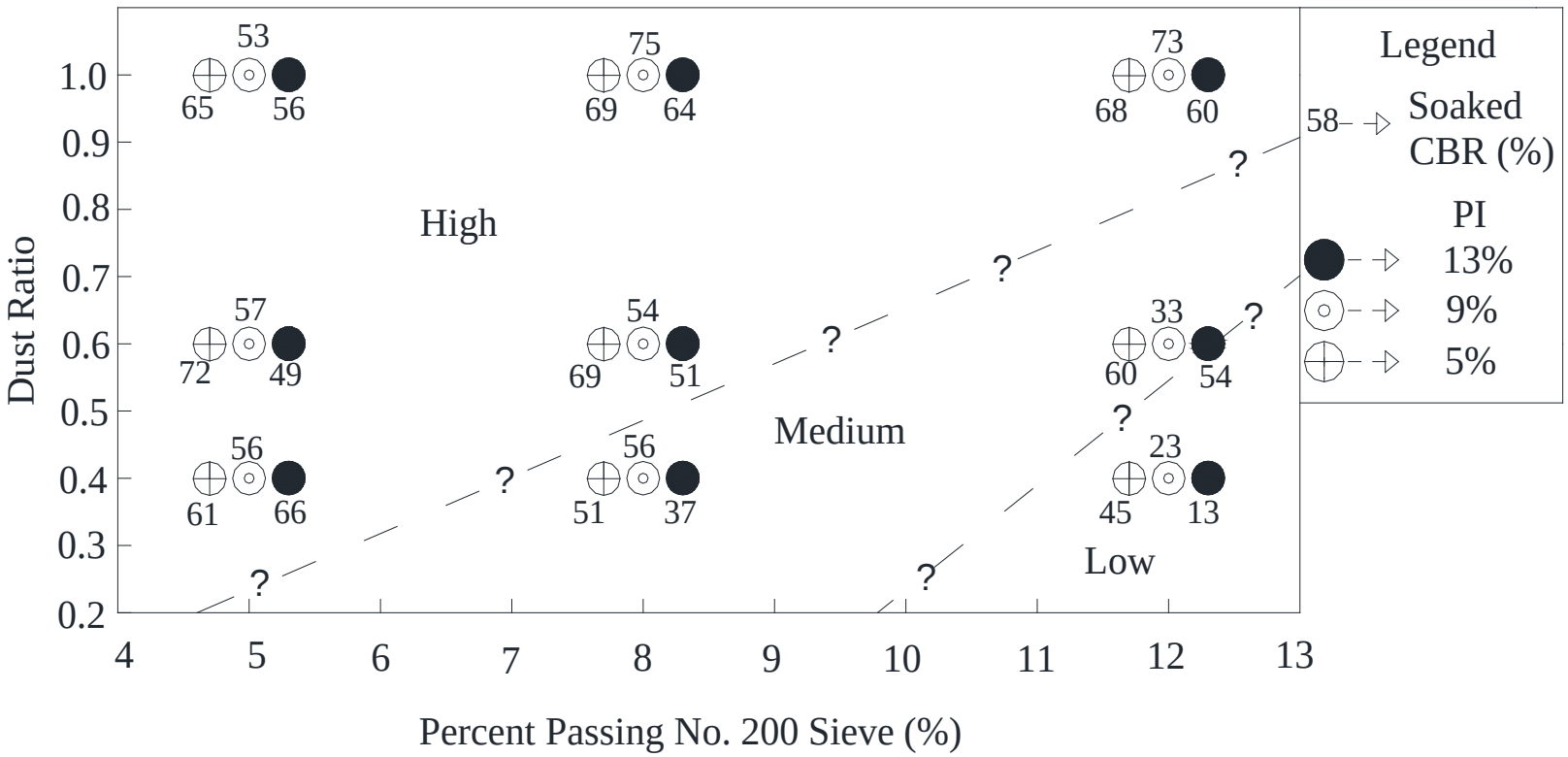


# Strength Zones for CA 6 Crushed Limestone



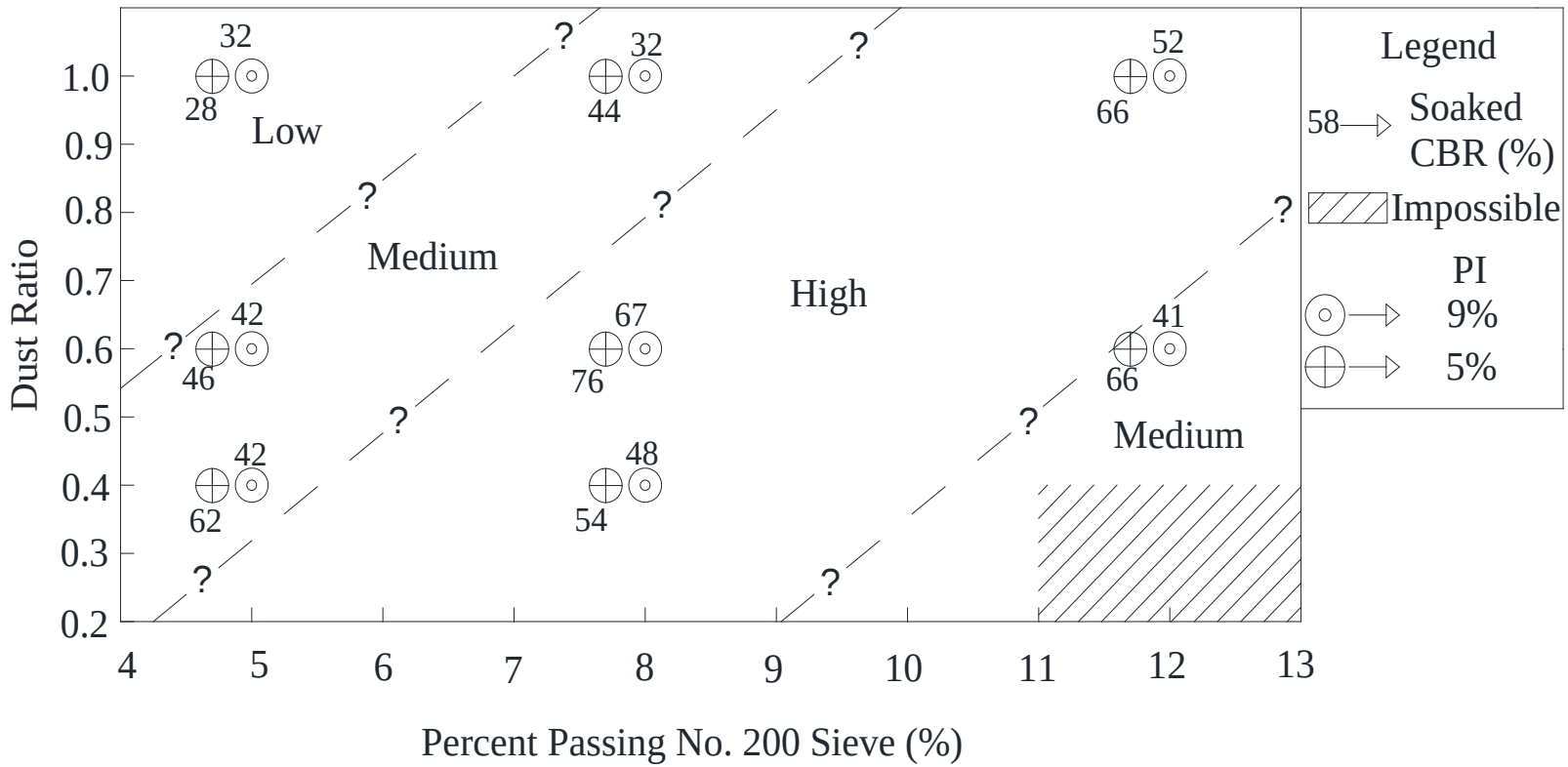

- **In CA 6 crushed limestone, the low strength zone is associated with high FC and low DRs.**

# Strength Zones for CA 6 Crushed Gravel




- Similar to CA 6 crushed limestone, the low strength zone is associated with high FC and low DR.
- In low fines content, there is low sensitivity to DR.

# Strength Zones for CA 2 Crushed Limestone



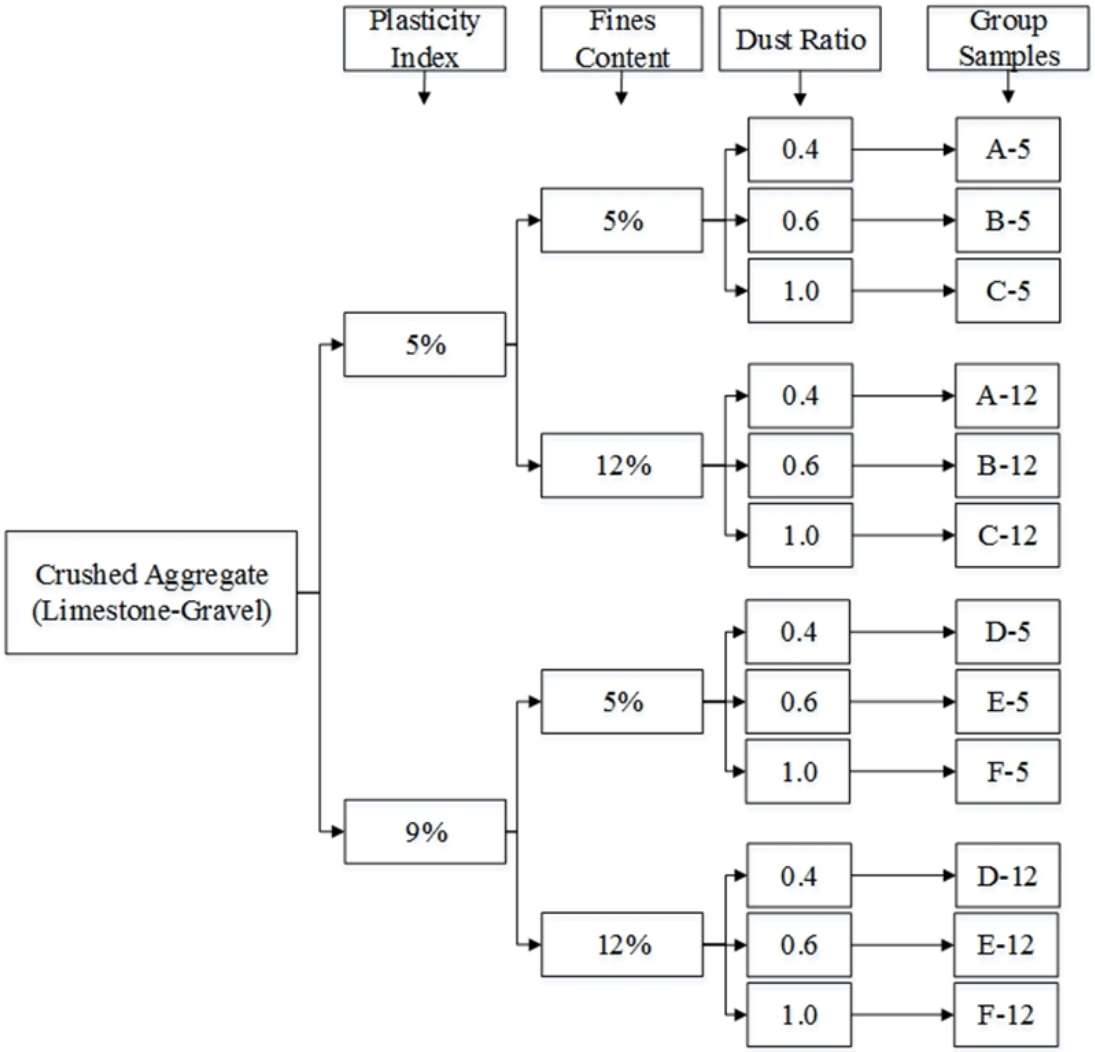

- The combination of low FC and high DR results in low strength zones.
- The area of high strength zone shifted towards right of the figure compared to CA 6 gradation.

# Soaked and Unsoaked CBR Comparison of CA 6 Crushed Limestone and CA 6 Crushed Gravel

# Purpose

1. Identify the effect of soaking on strength
2. Develop a correlation between soaked and unsoaked CBR for CA6 crushed limestone and crushed gravel

# Test Matrix for Unsoaked CBR




- **Samples with 5% and 12% fines content were tested**

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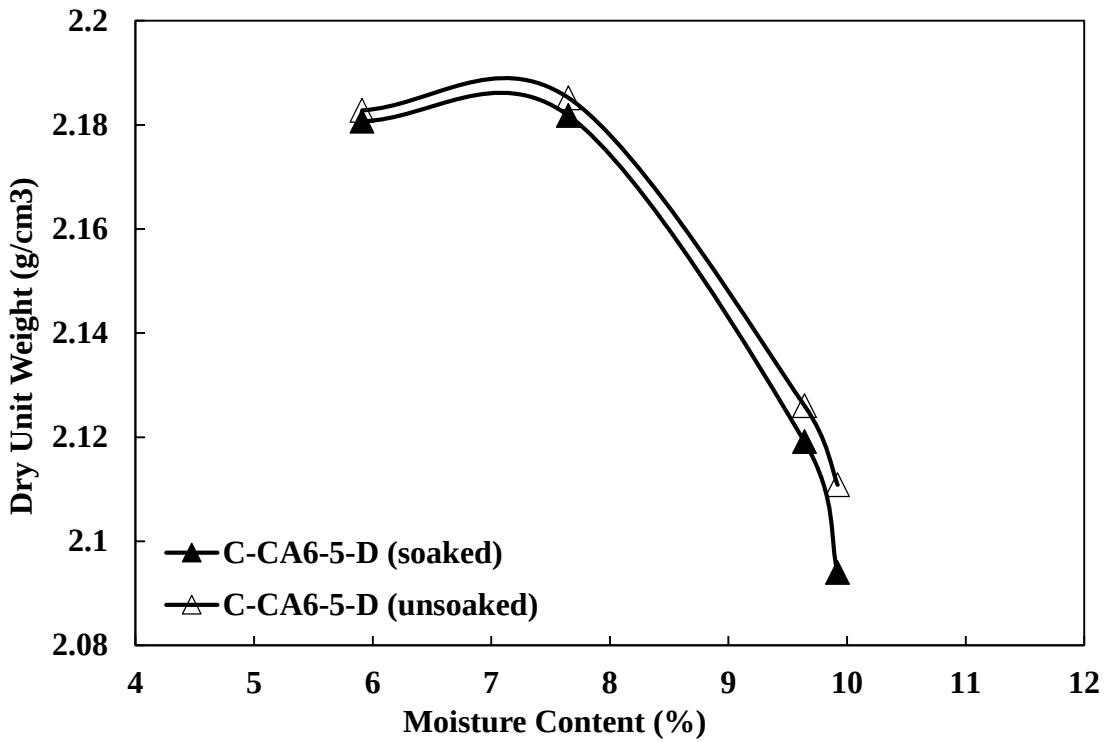
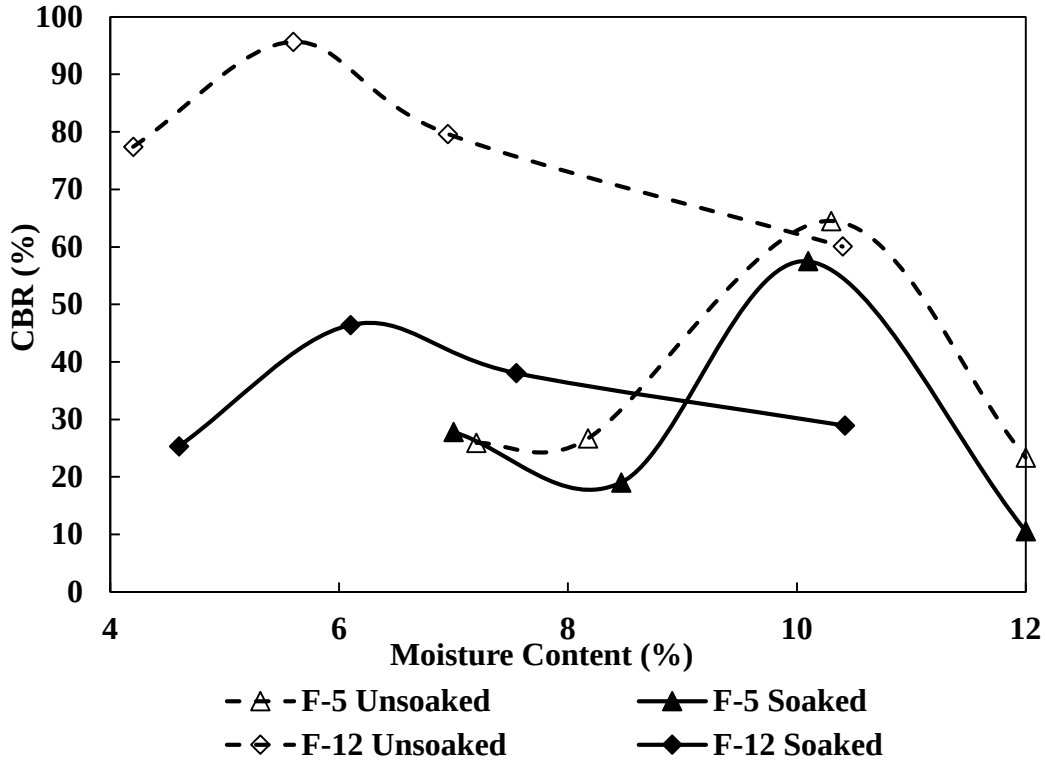
# Dry Density – An Example

- Dry density of unsoaked samples were almost same as soaked samples.



# Soaked and Unsoaked CBR

- Similar trend of soaked and unsoaked CBR were observed for all group samples.
- Soaked and unsoaked CBR values were very close for majority of the samples with 5% fines content.



# Soaked and Unsoaked CBR Summary

- The difference of soaked and unsoaked CBR values for each material was more pronounced when FC is 12% compared to 5%.

- The unsoaked CBR for both materials were higher than their soaked CBR values – more pronounced for samples with 12% FC.

# Prediction Model - Estimate Soaked CBR from Unsoaked CBR

$$\text{Soaked CBR}_{(\text{Predicted})} = \alpha_p \times \alpha_f \times \alpha_d \times \alpha_m \text{ Unsoaked CBR}$$

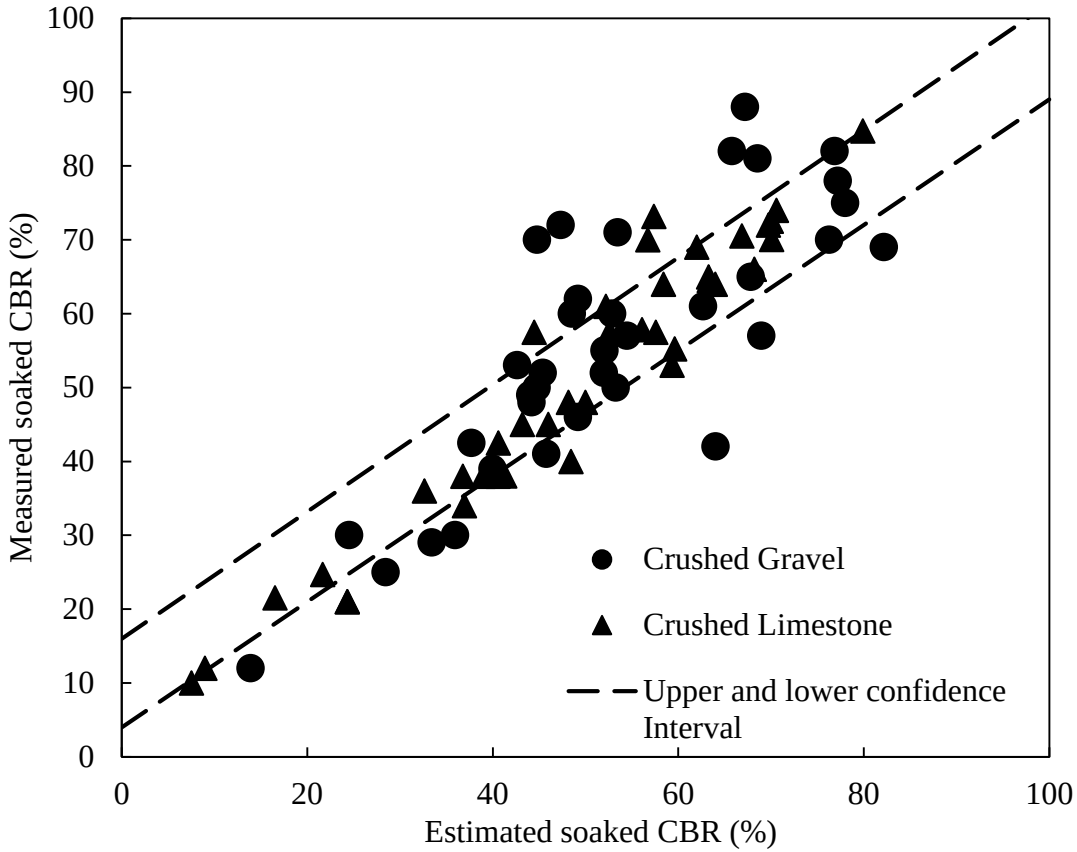
$\alpha_p$ : Plasticity index correction factor.
$\alpha_f$ : Fines content correction factor.
$\alpha_d$ : Dust ratio correction factor.
$\alpha_m$: Material type correction factor.

| Plasticity Index (%) | $\alpha_p$ | Fines Content (%) | $\alpha_s$ | Dust Ratio | $\alpha_d$ | Material | $\alpha_m$ |
|---|---|---|---|---|---|---|---|
| **5** | 0.793 | 5 | 1.079 | 0.4 | 1.096 | Gravel | 1.018 |
| **9** | 0.797 | 12 | 0.844 | 0.6 | 0.953 | Limestone | 1.108 |
| **-** | - | - | - | 1 | 0.794 | - | - |

- Regression analysis was conducted using 72 pair of CBR test results at OMC and OMC+/-1.5%.

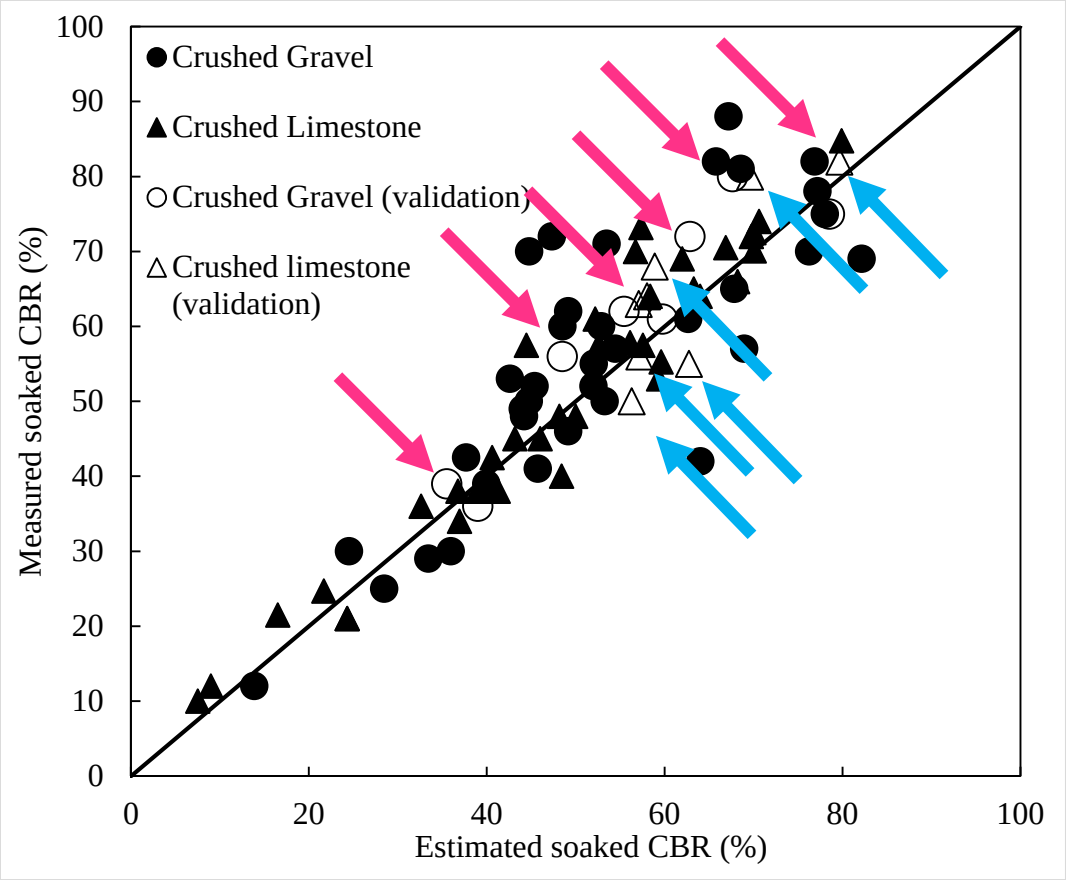
# Prediction Model - Estimate Soaked CBR from Unsoaked CBR

- The prediction model provides a reasonable agreement between measured and predicted soaked CBR
- 12% Mean Absolute Percentage Error (MAPE) was observed in the prediction model



# Verification of the Prediction Model

- Samples with following index properties were engineered and tested for soaked and unsoaked CBR:
  - DR= 0.4 and 0.6
  - PI= 5% and 9%
  - Fines = 8%
- These tests results were not used in developing the prediction model
- The results of measured and predicted soaked CBR are in reasonable agreement

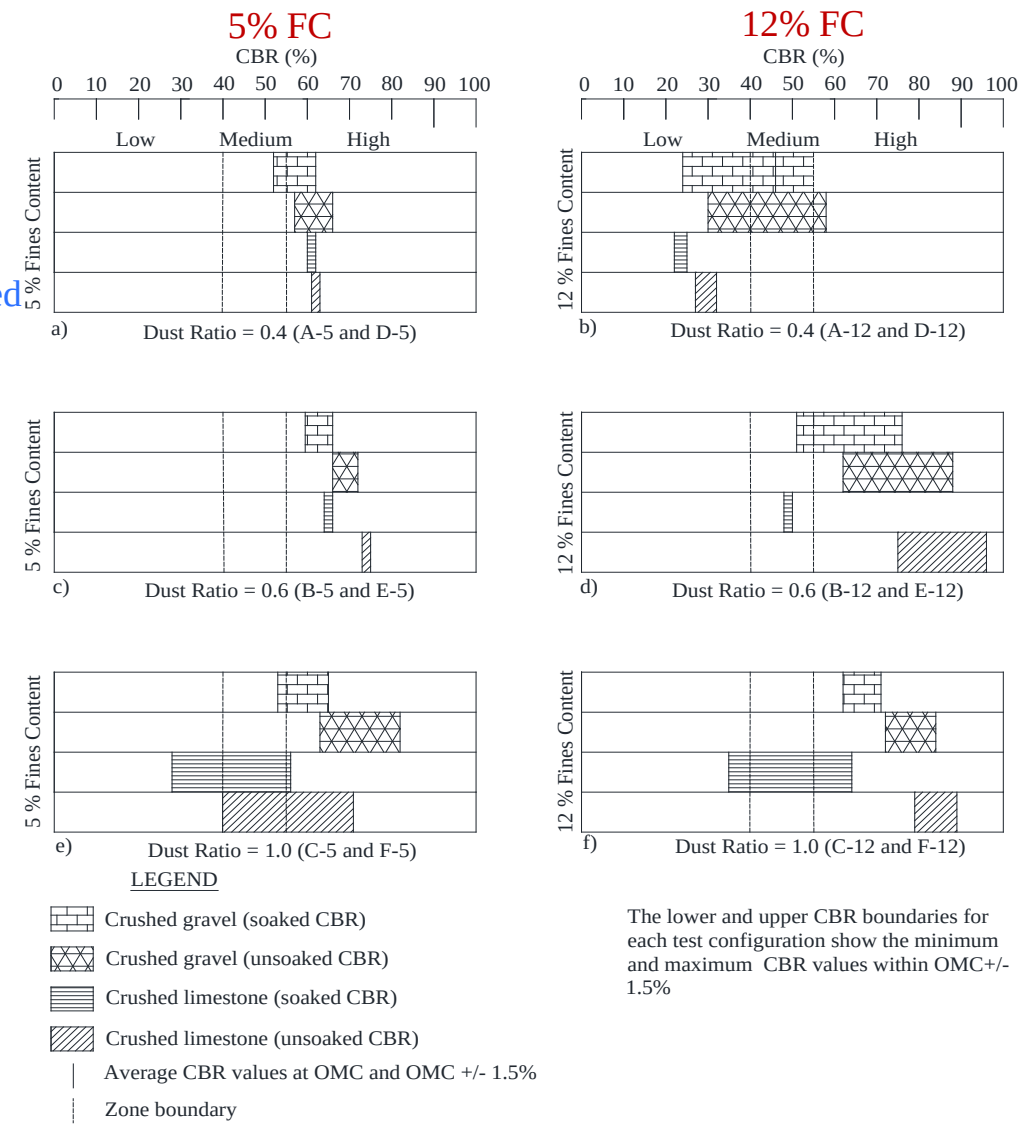


# Strength Zones Comparisons for Soaked and Unsoaked CBR

- Average soaked CBR at OMC and +/- 1.5% OMC results were used to develop the strength zones

Crushed gravel - soaked
Crushed gravel – unsoaked
Crushed limestone – soaked
Crushed limestone - unsoaked

- Three strength zones were proposed:
  - High: 55% < $CBR_{soaked}$
  - Medium: 40% < $CBR_{soaked}$ < 55%
  - Low: $CBR_{soaked}$ < 40%



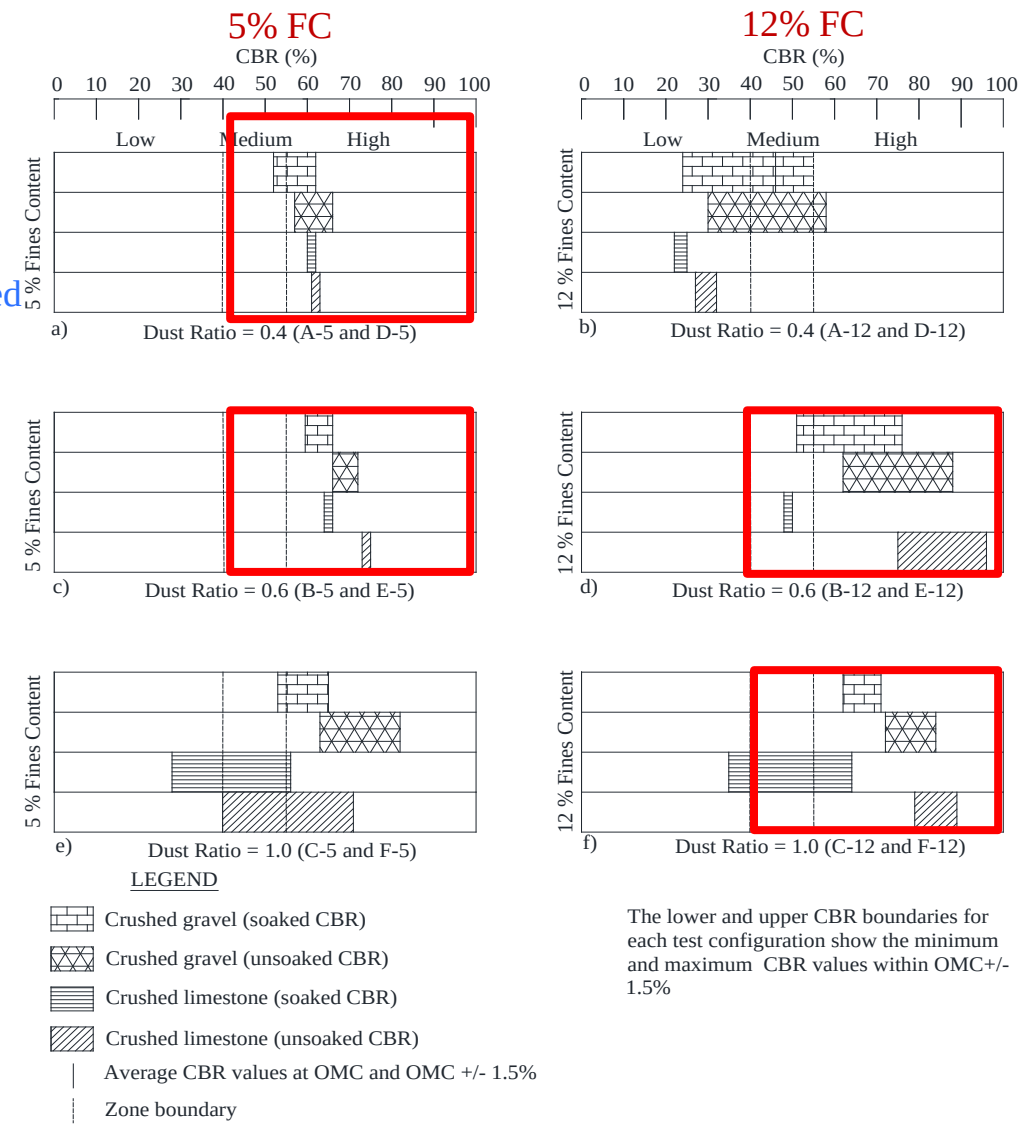

The lower and upper CBR boundaries for each test configuration show the minimum and maximum CBR values within OMC+/- 1.5%

# Strength Zones Comparisons for Soaked and Unsoaked CBR

**Medium and High zones:**

- **DR of 0.4 or 0.6 and FC of 5%.**
- **DR of 0.6 or 1.0 and FC of 12%**

Crushed gravel - soaked
Crushed gravel – unsoaked
Crushed limestone – soaked
Crushed limestone - unsoaked




The lower and upper CBR boundaries for each test configuration show the minimum and maximum CBR values within OMC+/- 1.5%

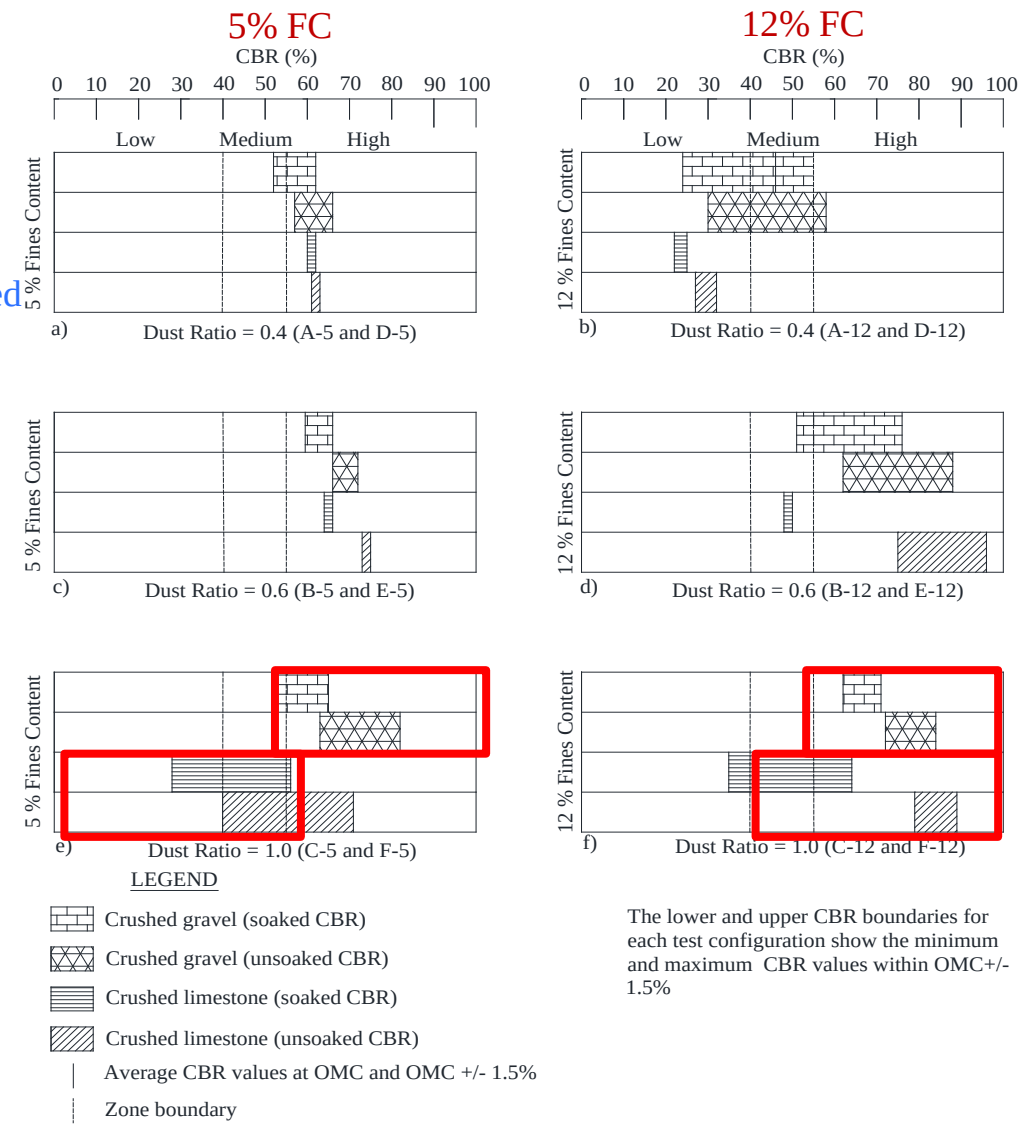
- **For both materials with DR of 0.6, the increase in FC from 5% to 12% resulted in an increase in the soaked and unsoaked CBRs, except for soaked crushed limestone samples.**

# Strength Zones Comparisons for Soaked and Unsoaked CBR

- Both soaked and unsoaked CBR ranges for crushed gravel samples with DR of 1.0 were in high strength zone regardless of FC

Crushed gravel - soaked
Crushed gravel – unsoaked
Crushed limestone – soaked
Crushed limestone - unsoaked

- For crushed limestone samples, the soaked CBRs were in the low to medium range and the unsoaked CBRs were in the medium to high range.



# CBR Strength Zones and Cyclic Performance

**In CA 6 crushed limestone**

- **Samples in high and medium CBR strength zones generally showed good performance under cyclic loading.**

- **High fines content (i.e., 12%) and low DR (i.e., 0.4) show poor performance both in CBR and under cyclic loading.**

- **Sample with FC of 12% and DR 0.6 showed medium to high strength in CBR while it performed poor under cyclic loading.**

# CBR Strength Zones and Cyclic Performance

**In CA 6 crushed gravel**

- **High fines content (12%) and high DR (1) show high CBR and good performance under cyclic loading test.**
- **High fines content (12%) and low DR (0.4) show weak performance in CBR and under cyclic loading.**
- **At high FC (12%) and DR of 0.6, CBR shows good performance, however, cyclic performance is poor.**

# CBR Strength Zones and Cyclic Performance

**In CA 2 crushed limestone**

- Samples that are in high and medium strength zone in CBR also show good performance under cyclic loading.

- Sample with 8% FC at DR of 0.6 showed good performance both in CBR and under cyclic loading.

- Sample with FC of 12% and DR 0.6 showed medium to high strength in CBR while it showed poor performance under cyclic loading.

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