Recycled Base Aggregates in Pavement Applications

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The Big Picture

Sustainability

- Nexus of major issues caused by rapidly growing global economy:
  - Global warming
  - Energy constraints
  - Resource availability (metals, cement, oil etc.)
- World population is 6 billion (B) → 12 B projected by 2100. US at 0.5B by 2050.
- US and EU (combined population = 0.75 B) consume most of world resources. China catching up fast.
- Remaining 5.25 B want everything we have. Not enough to go around if we do business as usual.
- **NOT SUSTAINABLE!**

Sustainable Infrastructure

- **How Can We Make Infrastructure Construction More Sustainable?**
- Reduce energy consumed in construction and rehabilitation.
- Reduce emissions emitted in construction and rehabilitation.
- Reduce consumption of natural resources.
- Increase service life and lower cost.

- **Follow the 3 E's:**
- Engineering, Economics and Environment

How Do Recycled Materials Fit In?

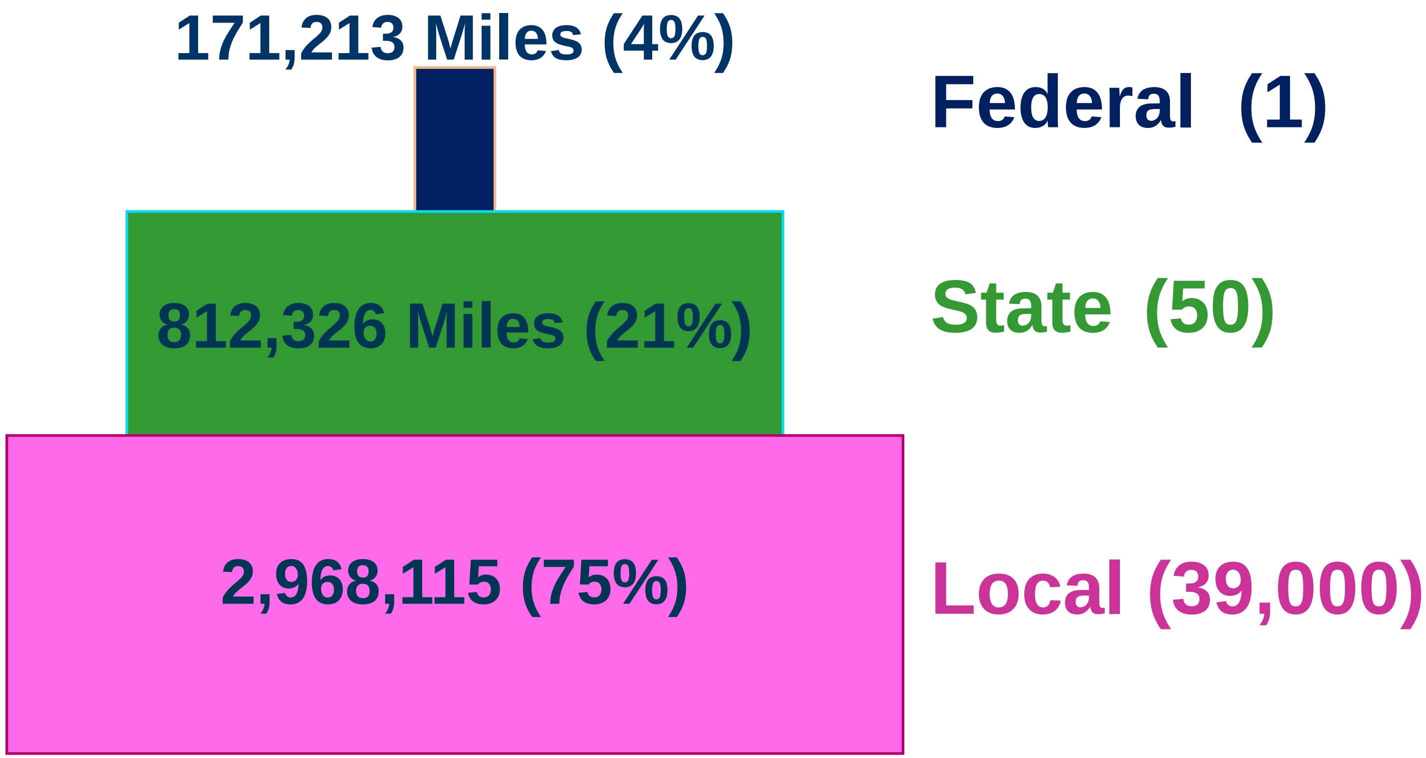
- Avoid energy and emissions associated with mining and processing construction materials. Energy has already been expended in first life of recycled material.
- Avoid use of a natural resources (sand and gravel, limestone, oil), save for more appropriate applications.
- Increase service life. Not a "linear landfill," but comparable or better/longer lasting infrastructure
- Capital and life cycle costs can be lower (economic sustainability).
- **3E's – Good Engineering, Good Economics, Good for the Environment**

Objections and Response

- **Objections**
- Global warming and sustainability are pure hooey….
- We tried using material x once in 1983 (197x, 199x) and it didn’t work…
- We have plenty of sand and gravel, we don’t need to recycle….
- We tried to use material x once and the public got mad….
- It costs too much to use recycled materials….

- **Response**
- Recycled Materials **CAN** provide high quality, more environmentally friendly roads that save money. **It has been done. It’s good business!**

The US Highway Pyramid



Roads and Streets Jurisdictional Control

Approximate Annual Highway Materials Use

- 350 million tons of material are used for highway construction each year
  - Aggregates 320 million TPY
  - Asphalt 20 million TPY
  - Portland cement 10 million TPY

- 353 - 859 million tons of recyclable materials are generated each year

- Can we substitute recycled aggregate materials for the natural aggregates in a cost-effective, environmentally sound method that also produces roads that are as good or better than current roads?

- Maybe not for all natural aggregates, but we can replace a large portion.

Most Common Recycled Aggregates

Recycled Concrete Aggregate (RCA)

- RCA is mostly obtained from concrete pavements.
- Stiff and angular material composed of natural aggregates with adhered mortar.
- Generally free of other materials.
- Fines from the mortar fraction can cause “self-cementation” or “re-cementation” when water is added. Individual particles adhere, forming a stiffer layer.

Recycled Asphalt Pavement (RAP)

- Crushed or milled asphalt pavement. Natural aggregate with coating of aged asphalt binder.
- Generally clean, with little deleterious materials.
- Asphalt binder is viscoelasto-plastic material. Can improve stiffness and strength, but may be susceptible to rutting.
- Use as unbound material generally **NOT** the highest value application. Check the 3E's.

Recycled Pavement Material (RPM)

- Generated by grinding up the bound layers and some of unbound base.
- Can be a mixture of RAP and RCA (left), or RAP and base aggregate or RAP, RCA and aggregate.
- Properties depend on the constituents to some degree, may behave more like RAP or more like regular mineral aggregate depending on the proportions.

Building Derived Concrete (BDC)

- Crushed concrete primarily derived from the demolition of industrial buildings and related infrastructure.
- Can contain stone, brick, asphalt pieces, porcelain and decorative concrete. May also have a higher soil fraction.
- Gradation depends on processing, but typically has a higher fines content.
- Currently not accepted by most transportation agencies.

Recycled Road Surface Gravel (RSG)

- Natural mineral aggregate used to surface unpaved roads.
- Actually a blend of gravel (or aggregate), sand and fines that will compact for form a hard crust.
- Mostly used for low volume roads without heavy loads.
- Can be stabilized into a base layer for hot mix asphalt if the road needs to be upgraded.

Attributes of Recycled Aggregates

Attributes of RCA (Part 1)

- **Gradation:** RCA must be crushed and screened to satisfy AASHTO M147 or ASTM D2940 aggregate requirements.
- **Absorption:** Adsorption is higher for RCA than natural aggregates, and ranges between 4 and 8 percent.
- **Specific Gravity:** The specific gravity of RCA aggregates (ranging from 2.0 for fines to 2.5 for coarse particles) is slightly lower than that of natural aggregates due to the mortar fraction.
- **Stability:** RCA has high friction angle, typically in excess of 40°. Good stability and little post-compaction settlement.
- **Strength Characteristics:** Crushed RCA is highly angular in shape. The California Bearing Ratio (CBR) values range from 90 to more than 140, which is comparable to crushed limestone aggregates.

Attributes of RCA (Part 2)

- **Durability:** RCA aggregates generally exhibit good durability with resistance to weathering and erosion. RCA is non-plastic, and is not susceptible to frost.

- **Drainage Characteristics:** RCA (mainly coarse fraction) is free draining and is more permeable than conventional granular material because of lower fines content.

- **pH and Tufa**: The initial pH of pore water in the can be 11 or greater, but decreases with time. The release of calcium compounds has sometimes caused creation of “tufa”, a form of calcium carbonate. However, removing the fine fraction (#4 mesh) greatly reduces pH problems.

Attributes of RAP (Part 1)

- **Gradation:** RAP can be and should be processed to meet AASHTO M147 or ASTM D2940 aggregate requirements.
- **Strength:** RAP is blended with other aggregates to form the base. The bearing capacity of the blend is strongly dependent on the proportion of RAP to conventional aggregate. The bearing capacity decreases with increasing RAP content. The California Bearing Ratio (CBR) is reduced below that expected for conventional granular base when the amount of RAP exceeds 20 to 25 percent.
- **Compacted Density:** Due to the coating of asphalt cement on RAP aggregate, which inhibits compaction, the compacted density of blended granular material tends to decrease with increasing RAP content.

Attributes of RAP (Part 2)

- **Moisture Content:** The optimum moisture content for RAP blended aggregates is reported to be higher than for conventional granular material, particularly for RAP from pulverizing operations, due to higher fines content and the absorptive capacity of these fines.

- **Permeability:** The permeability of blended granular material containing RAP is similar to conventional granular base course material.

- **Durability:** Since the quality of virgin aggregates used in asphalt concrete usually exceeds the requirements for granular aggregates, there are generally no durability concerns regarding the use of RAP in granular base, especially if the RAP is less than 20 to 25 percent of the base.

Attributes of RPM (Part 1)

- **Gradation:** RPM can be pulverized in-place or using traditional methods. It can be difficult to specify a in-place gradation because the original aggregate, depth of cut and pulverizing methods all affect gradation. Often maximum limit on size, for example 97% passing 50 mm (2 in) mesh. If done ex situ, then can follow AASHTO M147 or ASTM D2940 aggregate requirements.

- **Strength:** The bearing strength depends on the proportion of RAP to other aggregates, and the fraction of fine material. There seems to be a trend of lower CBR for material pulverized in place, due to the fines, compared to materials that are mixed pulverized and screened off-site. RPM is often stabilized with a binder to improve the strength.

- **Compacted Density:** The compacted density will generally be lower due to the inclusion of RAP and possibly RCA.

Attributes of RPM (Part 2)

- **Moisture Content:** Like RAP mixtures, the optimum moisture content for RPM is generally higher than for conventional granular material, particularly for in place material tends to have more fines.
- **Permeability:** The permeability of compacted RPM depends on the constituents and the addition of stabilizers. However, the permeability through the compacted layer is generally decreased, which reduces moisture issues.
- **Durability:** Again, the durability depends on the original aggregate, and the proportions of the RAP and other aggregates, and stabilizers. A durable base can be made from compacted RPM, though stabilizers are often added to improve durability.

Attributes of BDC (Part 1)

- **Gradation:** BDC must be crushed and screened to satisfy AASHTO M147 or ASTM D2940 aggregate requirements.
- **Absorption:** Adsorption is higher for BDC than natural aggregates. Depends on proportions of concrete, rock, RAP, etc.
- **Specific Gravity:** The specific gravity of BDC aggregates (ranging from 2.0 for fines to 2.5 for coarse particles) is slightly lower than that of natural aggregates due to the mortar fraction and RAP.
- **Stability:** Generally has a medium to high friction angle due to the crushed aggregate.
- **Strength Characteristics:** The CBR values are similar to RCA (>90), but decrease with the addition of RAP. Also, brick tends to lower CBR, especially wet CBR.

Attributes of BDC (Part 2)

- **Durability:** BDC aggregates generally exhibit good durability with resistance to weathering and erosion. Presence of clay-based aggregates may increase moisture sensitivity and weathering.
- **Drainage Characteristics:** BDC is generally free draining because the fines are usually screened off.
- **pH and Tufa**: Like RCA, the initial pH of pore water in the can elevated, but decreases with time. Since BDC contains a much higher fractions of non-concrete material, pH issues are not as significant.

Attributes of RSG

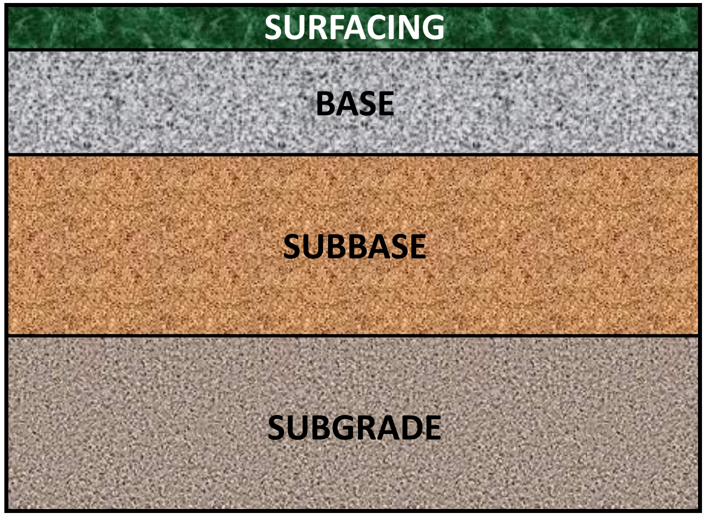
- **Gradation:** RSG generally has a finer gradation than other road aggregates, with more than 50% passing the 6.3 mm (0.25”) mesh. This material would not be recycled for use as unbound base, but would be stabilized. Coarser aggregates may be added to improve the base performance.

- **Strength Characteristics:** CBR values are lower than for coarse aggregates, on the order of 50, depending on the fines content. In order to create a strong base, coarser material can be added to RSG, and binders are mixed in to increase the strength and stiffness.

- **Durability:** Somewhat limited data, but durability is expected to be good based on experience with stabilized subbase and base layers.

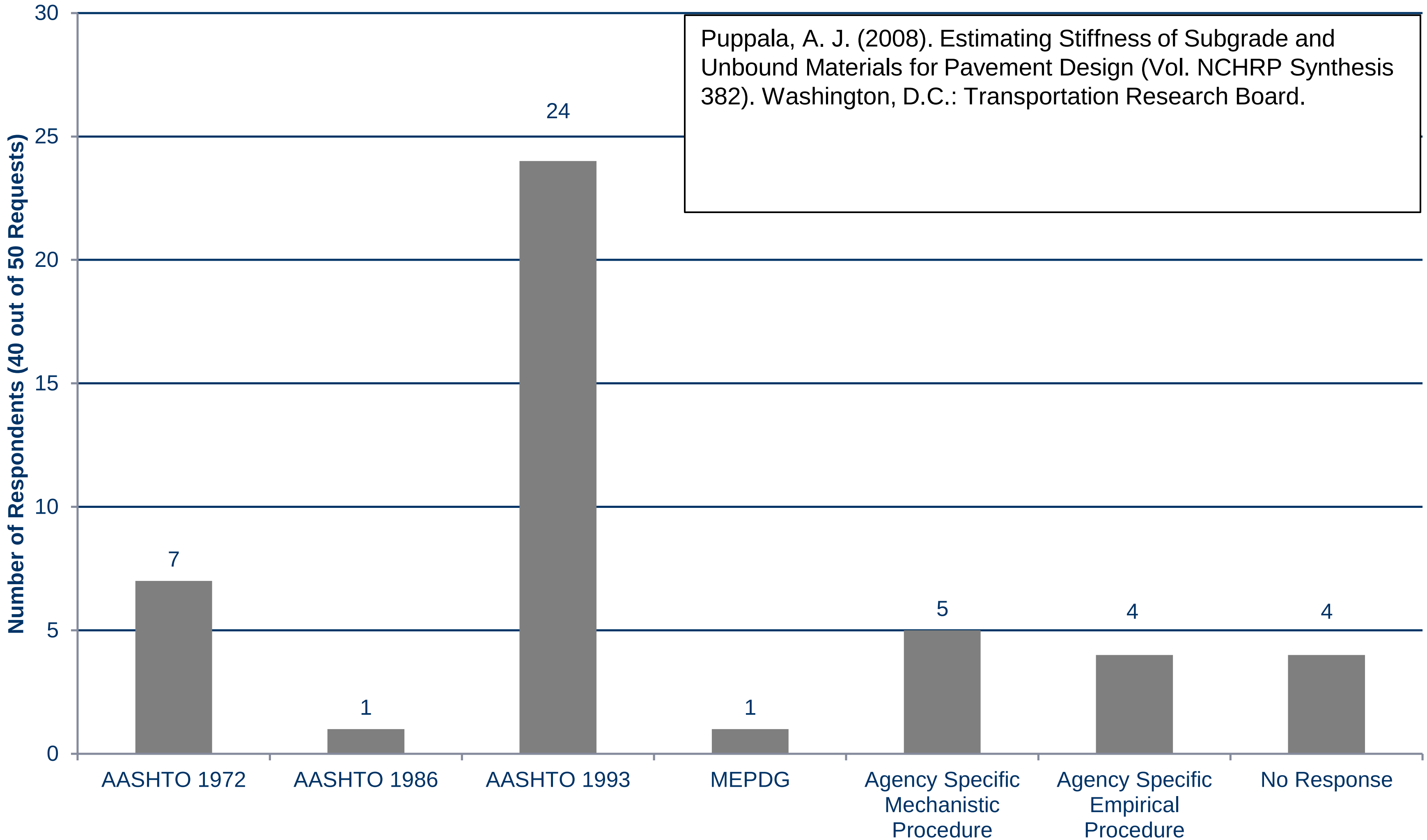
Design Considerations

Flexible Pavement Design



- For this webinar, considering only flexible pavement design.
- There are empirical and mechanistic-empirical pavement design.
- Will focus on mechanistic-empirical design for unbound applications.
- Will consider stabilization at the end.

Pavement Design Methods in Use



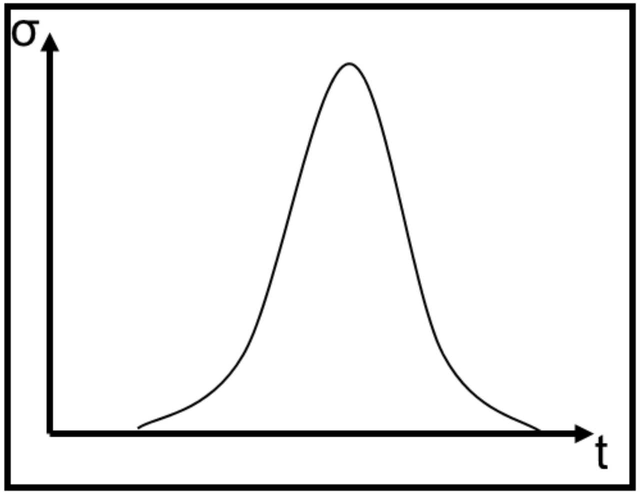
Puppala, A. J. (2008). Estimating Stiffness of Subgrade and Unbound Materials for Pavement Design (Vol. NCHRP Synthesis 382). Washington, D.C.: Transportation Research Board.

Early Pavement Design

http://www.fhwa.dot.gov/pavement/recycling/98042/01.cfm

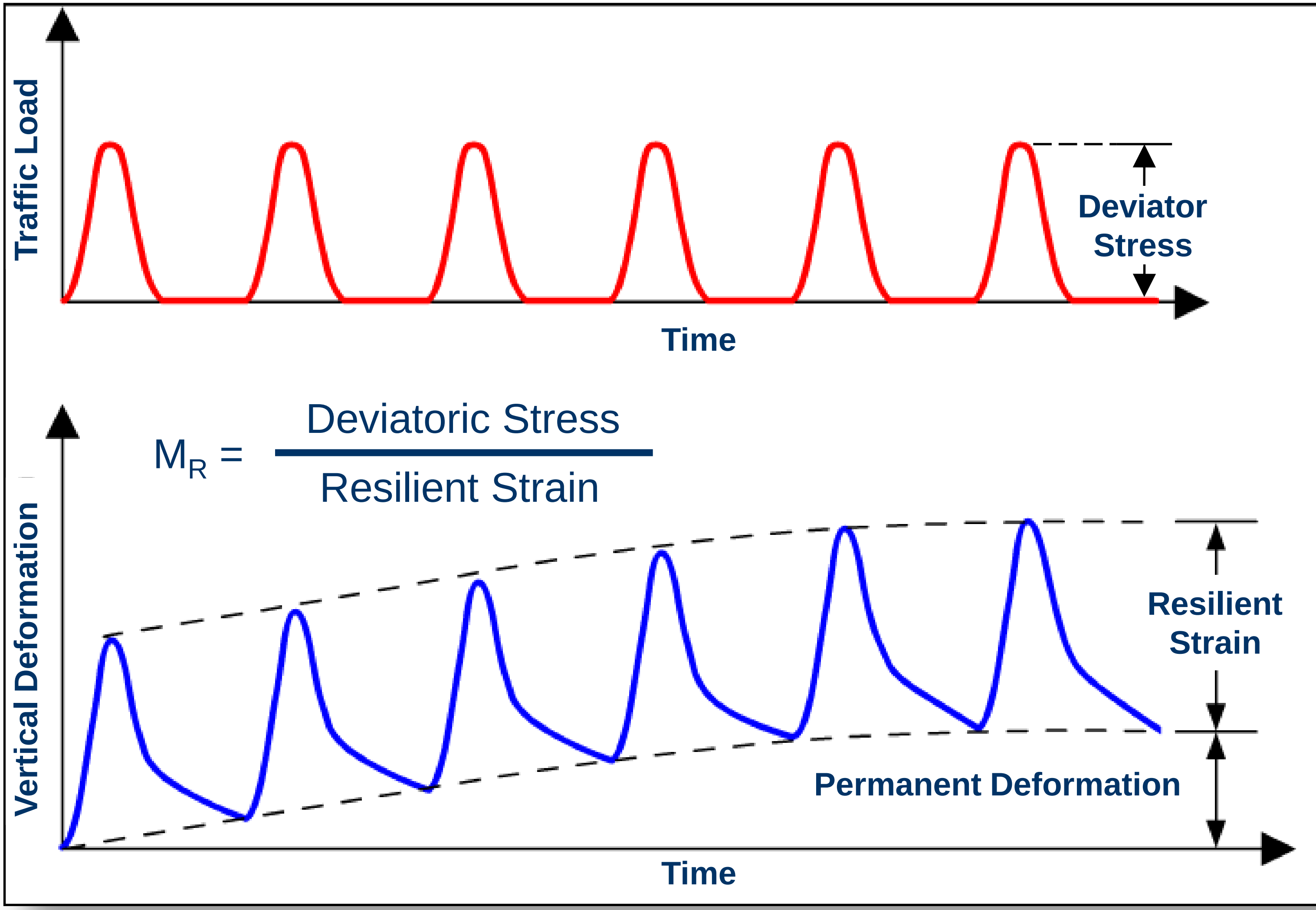
- Early pavement design was based on soil strength. The California Bearing Ratio (CBR) test and other tests were used to characterize the bearing capacity of pavement layers.
- However, flexible pavement layers very rarely fail due to soil strength failure.
- Pavement layers are more likely to fail due to rutting and cracking from fatigue.

Stiffness and Plastic Strain

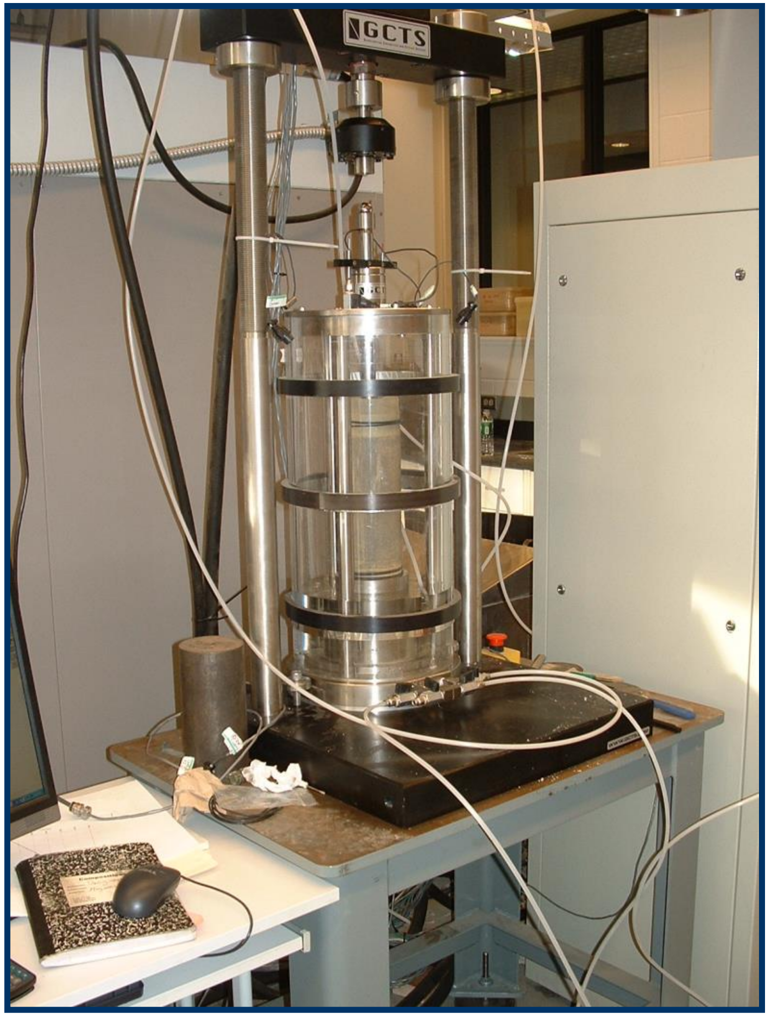


- Stiffness a measure of how much deformation for a given load.
- For high stiffness, there is less deformation, but for low stiffness there is more deformation, possibly permanent.
- For the unbound layers, rutting is the primary failure mode.
- Can think of rutting as the accumulation of permanent deformation due to vehicle loading.
- Want to measure ability of road materials to recover from deformation.

Resilient Modulus M_R



Resilient Modulus Test Pictures



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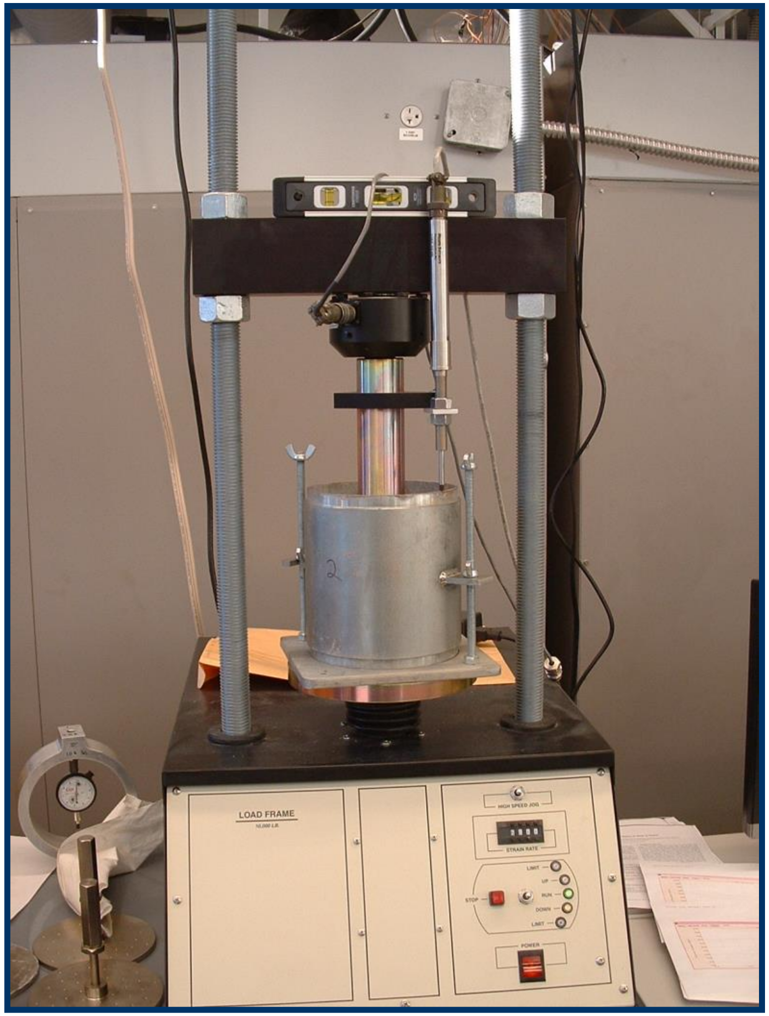
CBR Test



- Resilient modulus test is not fast test, and there is a learning curve.
- A number of agencies are currently using the CBR test to measure the bearing capacity of material.
- CBR is faster and cheaper to run. Not a very high learning curve.
- There are relationships relating CBR to the resilient modulus.
- $M_R = 2555 * CBR^{0.64} [psi] = 17.6161 * CBR^{0.64} [MPa]$

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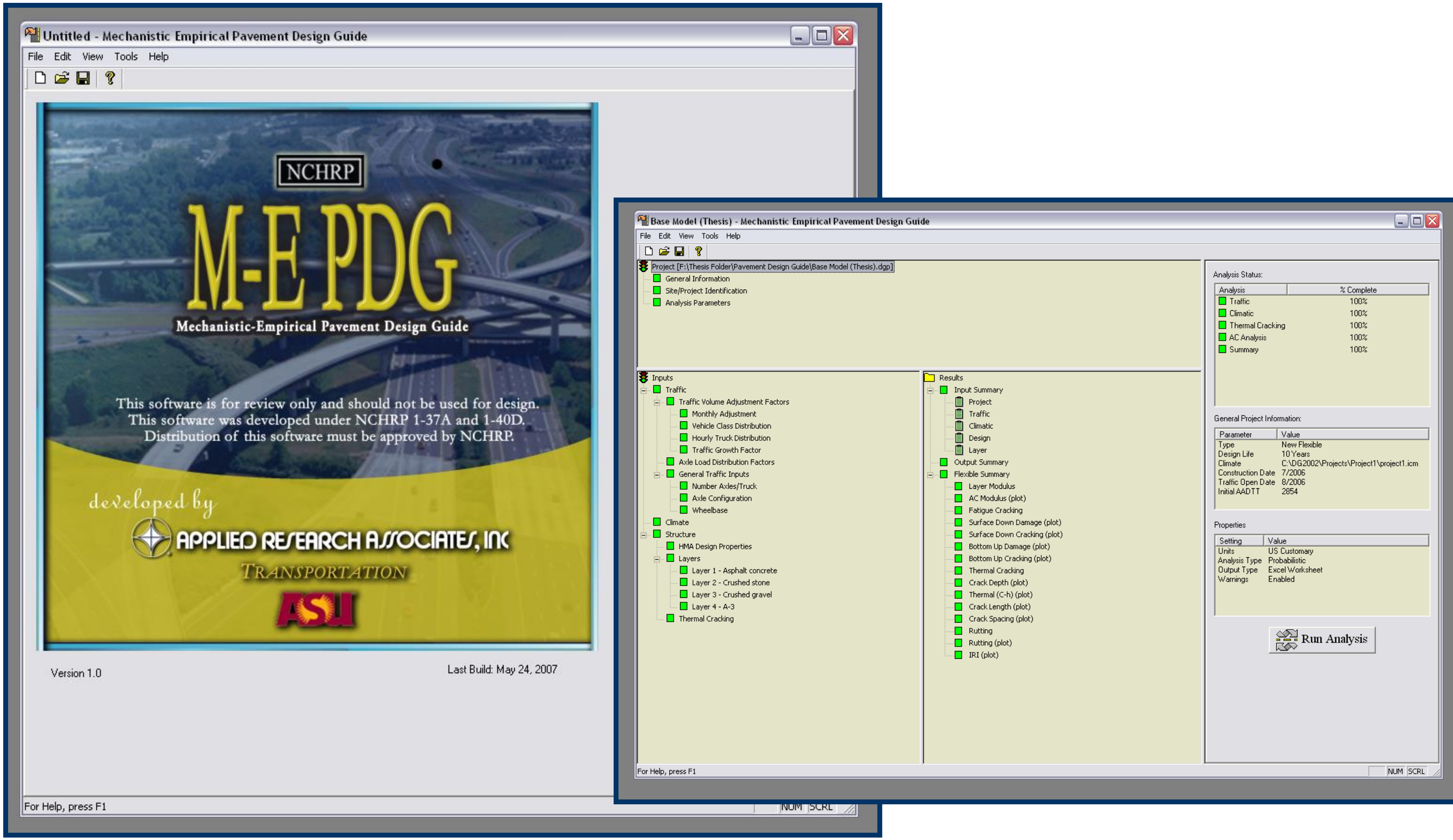
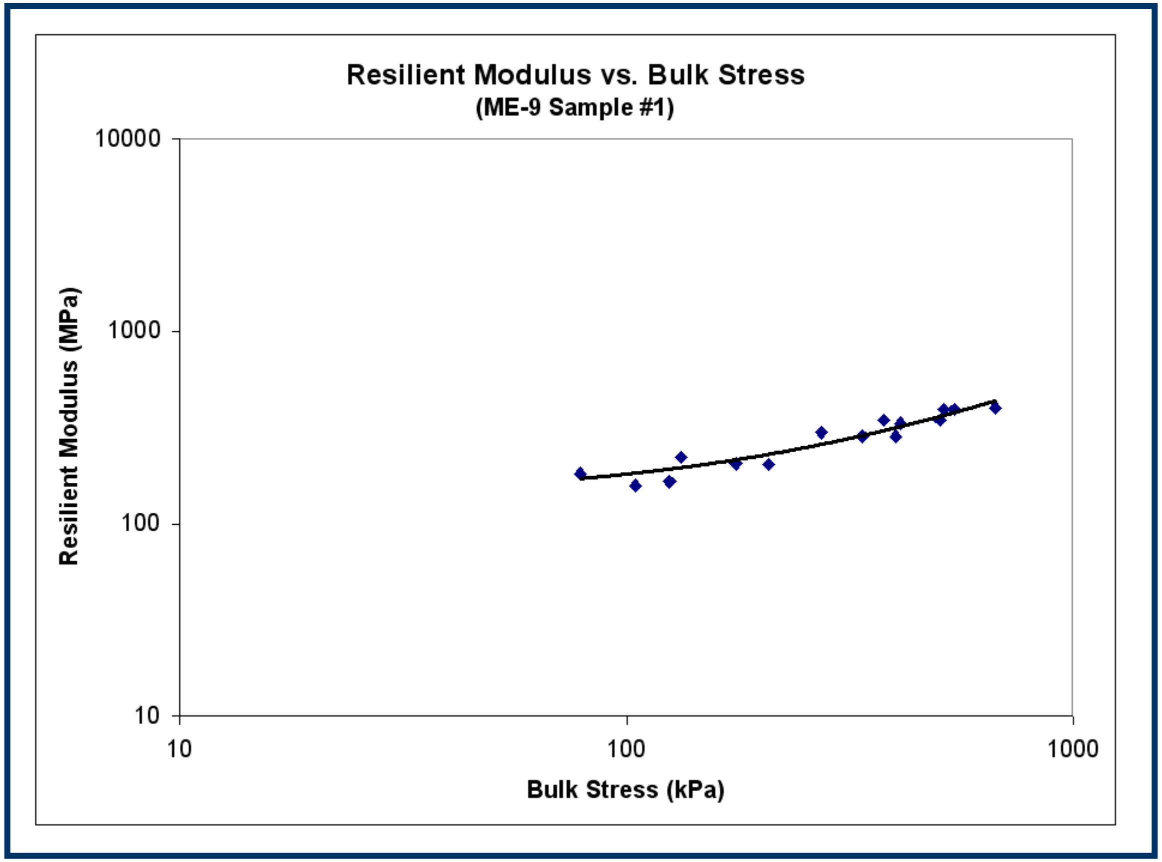
MEPDG - Newest Design Guide

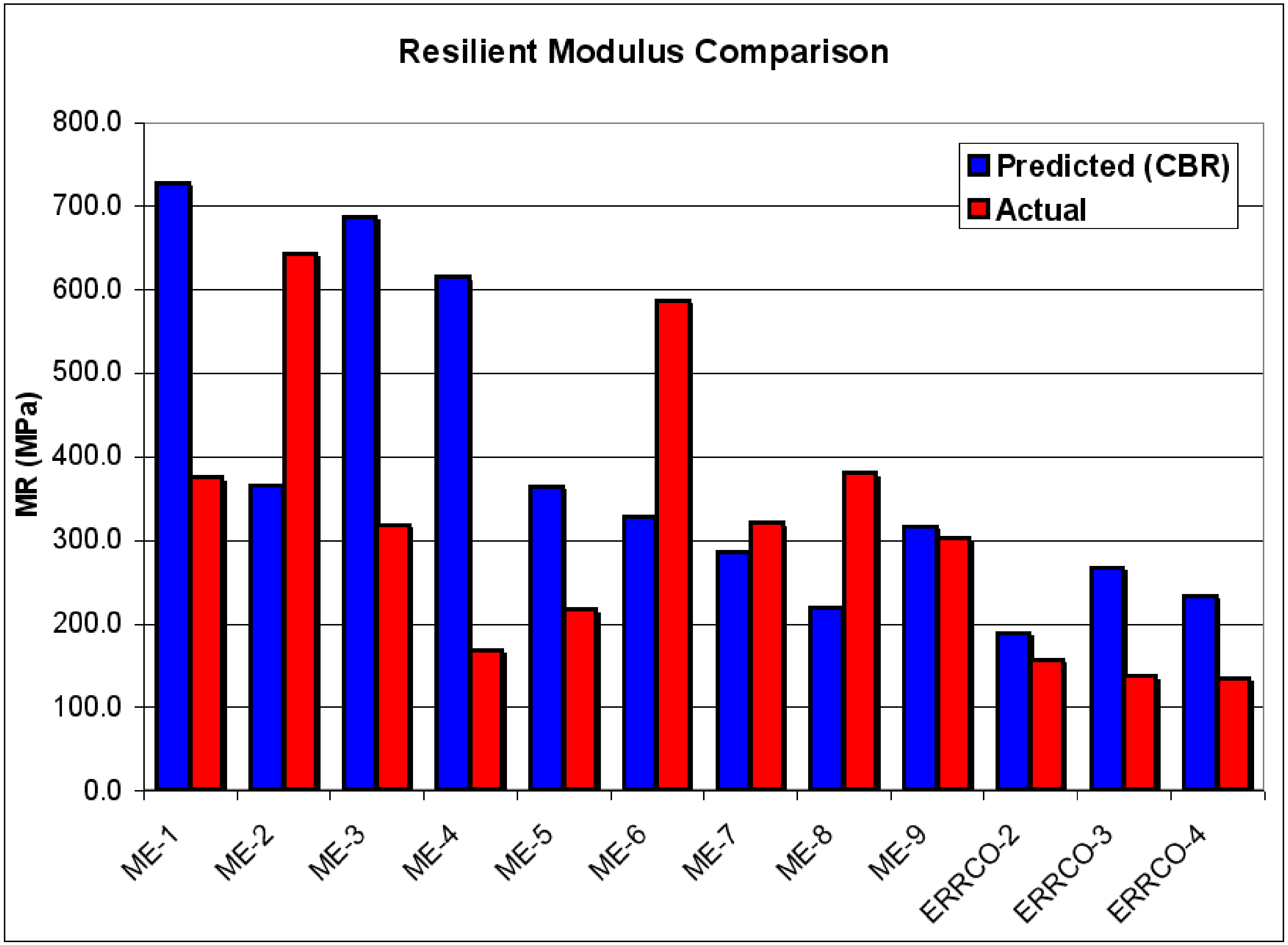


Resilient Modulus Results



$$M_R = K_1 \, Pa \left[\frac{\theta}{P_a}\right]^{K_2} \left[\frac{\sigma_d}{P_a}\right]^{K_3}$$

Predicting M_R from CBR



Correlation doesn't work for coarse materials.

SRM M_R Values From RMRC

- **RCA/RAP/RPM Project**
- RPM → 215 MPa
- RAP → 200 MPa
- RCA → 178 MPa
- Class 5 Aggregate → 152 MPa

- **BDC Project**
- BDC → 223 MPa
- Crushed Gravel → 174 MPa
- Sand → 181 MPa

Summary Resilient Modulus evaluated at a bulk stress of 208 kPa. In both studies the recycled materials performed better than natural aggregates.

Impurities

- Like natural aggregates, the performance of recycled materials is adversely affected by impurities or “deleterious materials”.
- Materials should be largely free of plastic, geotextiles, metals, wood, the usual suspects.
- Brick is not an impurity, but it can loose integrity due to saturation. Should limit its use where significant infiltration (i.e. spring flooding) may occur. This is a judgment call for the engineer.
- RAP is considered by some as an impurity. While > 25% RAP may have adverse effects on performance, in general homogenized RAP/soil mixtures will provide good performance.

Freeze-Thaw and Wet-Dry

- The RCA and BDC (low brick fraction) usually have the fine fraction (< #4 mesh) removed, and are therefore non-plastic, with limited susceptibility to free-thaw or wet-dry cycling issues.
- BDC with more than 5% brick may have freeze-thaw or wet-dry issues. The interior brick core material tends to hold water, and has exhibited distress due to both free-thaw and wet-dry cycling. Should be tested and used accordingly.
- RAP/aggregate mixtures do tend to have more fines, but have limited susceptibility.
- The susceptibility of RPM depends on fines content due to crushing. In place pulverization may be susceptible, but stabilization would solve this problem. Ex situ processing usually limits the fines to avoid susceptibility.

Fly Ash Stabilization

- RSG and RPM have been stabilized using coal fly ash (CFA) and CFA/cement mixtures.
- CFA reduces the need for cements, which is considered a “green” use of CFA.
- CFA stabilized soils have increased strength, stiffness and durability, providing a better base for the HMA, which leads to better roads.
- Leaching from CFA in stabilized bases has been studied extensively. In general there is no increased risk from using CFA. In fact, some natural aggregates leach more metals the CFA.

Resources

- Recycled Materials Resource Center www.recycledmaterials.org
- User Guidelines for Byproduct and Secondary Use Materials in Pavement Construction www.recycledmaterials.org/tools/uguidelines/index.asp
- AASHTO M 319-02 (2006) Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course
- FHWA Report: Transportation Applications Of Recycled Concrete Aggregate www.recycledmaterials.org/Research/tools/RCAREPORT.pdf
- Fly Ash Facts for Highway Engineers http://www.fhwa.dot.gov/pavement/recycling/fafacts.pdf