MAXIMIZING THE PERFORMANCE AND VALUE OF CRUSHED AGGREGATE BASE

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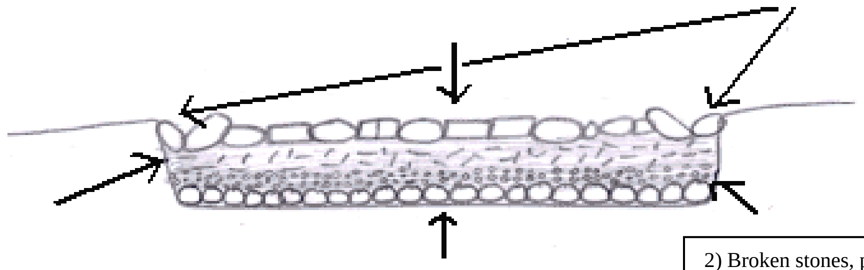
The highway construction industry has many issues confronting it; warranties, life-cycle costs, 50/100 year designs, funding, inflation, potential materials shortages, Mechanic-Empirical Pavement Design Guide (MEPDG), etc. At times like these it is good to stop and reflect on fundamentals and history. Through one lens, we see we have come far since road building began; through the other lens, not so far. The delivery of our unbound crushed aggregate base (CAB) pavement construction is very advanced, mostly due to the advancement in machinery, but the basic principals of design have not changed much since the 18th century.

History of CAB

Variations of crushed aggregate base date as far back as 4,000 BC. Evidence of broken stone streets has been found in the village of Ur, Iraq, about 225 miles south of Baghdad. (1) During the period 400 BC -200 AD, the early Roman highways, which covered over 50,000 miles across the empire, used variations of broken stone roads.(2) Figure 1 represents a schematic of the typical section of a Roman road.(3)



5) Kerb stones at the sides held in the paving stones and channeled water away.

4) Paving stones formed the surface of the road. These were cut so they fit together tightly.

2) Broken stones, pebbles, cement and sand made a firm base.

1) A layer of big stones was placed at the bottom of the trench.

3) Cement mixed with broken tiles was placed in layers.

Figure 1. Cross Section of Roman Roads

It was not until the late 1700's that significantly new methods for building roads were used. John McAdam developed advanced technology for road building using broken or crushed aggregate.(4) These methods were later refined by Thomas Telford to include selection of stone based on thickness, taking into account traffic, alignment and slopes. (5) Now recognized as ‘macadam’, the construction consisted of using broken sized stone, a cambered road surface and a large stone foundation. Side ditches to handle rainwater were also integrated with a raised roadbed to protect the integrity of the pavement from water damage. Further improvements in the construction methods resulted from the invention of power crushers and steam rollers in the latter 1800’s. Construction equipment and methodologies are continuing to improve.

The first macadam road in the US was constructed between Hagarstown and Boonesboro, Maryland in 1823. Many of the characteristics of modern construction were applied in a more basic form on this project, as depicted in a painting by Carl Rakeman.(6) It consisted of three layers of compacted stone with the top layer choked with fines and cemented with water. Surface drainage was created by the cambered cross section and side ditches. The following project characteristics highlight some of the principles that were characteristic of macadam construction:

- A local quarry, probably close to the roadway
- Crews with hammers to reduce the rock to about a 2 inch size
- One-size rock placed in successive layers between side forms
- A ring tool was used to control the rock size
- A final layer choked with fines and cemented with water to aid compaction and seal the surface
- A cambered cross section to shed water from the surface

AASHO Road Test

Current design practices for crushed aggregate base (CSB) have evolved from the original macadam process and from research like the AASHO Road Test. At this research facility, unbound crushed limestone base was compared to cement and bituminous treated gravel, both plant mixed. The limestone base was well-graded with about 12.5 % passing the No. 200 sieve. Current practice would consider this level of fines excessive for use in a region susceptible to frost action. (7)

Construction standards for the AASHO Road Test required compaction of the CAB to AASHO T-99, Standard Proctor. As learned later, this limited the performance of the CAB in comparison to that expected from similar materials compacted to a higher density using AASHO T-180, Modified Proctor.

Results of the AASHO Road Test led to the development of ‘structural coefficients’, which were a means of comparing the structural value of different materials, and were subsequently accepted and applied to other similar materials by many states. These coefficients were readily accepted on CAB regardless of material differences, gradings, density or placement in the pavement system.

CAB Quality

Most standards for CAB quality adequately cover the recognized physical properties such as mineralogy, hardness, toughness, grading, shape and plasticity. Typical requirements include:

- Grading- well-graded from coarse to fine with a nominal maximum of 1- 2 1/2 inches
- Durability- soundness and hardness based on sulfate soundness loss and LA degradation
- Fines- a maximum level of minus No. 200 material based on environment and a limit on Plasticity (max. 6, but often lower)
- Control of moisture content to aid compaction and to minimize segregation

The two most critical properties of CAB are grading, including passing No. 200, and density. Performance of CAB can be enhanced by selecting a grading generally following the maximum density line created through the 0.45 power curve plot. The grading does not need to fall on the line, but should follow a similar shape and not stray far from the line and have no dramatic gaps. In addition, the maximum nominal size should be the largest that can be accommodated without segregation and consistent with lift thickness. These properties generally provide acceptable strength when tested for CBR, Triaxial or resilient modulus.

Caution should be taken when attempting to design unbound granular layers for permeability. Grading modifications which increase permeability will also decrease strength and stability. Besides losing strength and performance, stability of the structural base layer as a construction platform is also diminished which can cause difficulties in constructing the subsequent pavement layers.

Characterizing Properties

Methods used for testing CAB strength in the laboratory did not change much over the last 50 years, until recently, when the resilient modulus became the test of choice based on development of the MEPDG. Otherwise, basic properties such as grading, Atterberg Limits, moisture-density relationships, CBR and triaxial methods have sufficed. The triaxial tests has been successfully used to measure the shear properties of soils and aggregate materials used in highway construction because shear strength has been determined to be the single most important property of granular materials for use in unbound pavement layers.(14) New methods for determining shape using optical and laser equipment have been developed to enable the particle shape of aggregate to be evaluated digitally and in much greater detail than was possible using visual methods.(8) Eventually, these methods will be used to aid in the characterization of CAB.

The most common and basic characteristic of CAB is grading. Most project specifications are reasonably consistent in specifying grading envelopes with variations based on nominal particle size and local materials. There are three critical elements of grading that need to be considered.

First, the largest nominal maximum size, up to 2 ½ inches should be considered, consistent with lift thickness and placement procedures. Triaxial testing has shown the improvement in strength and the reduction in deformation under load when larger top-size aggregates are used. (Figure 2 & 3)

The second grading characteristic is the overall grading from coarse to fine. An optimum grading is that generally following the maximum density line represented by the 0.45 power curve graph. (Figure 4) This general rule of thumb provides a grading that will usually provide close to the maximum densification and maximizes particle contact. No single grading needs to be specified, but a consistent grading is key.

The third characteristic to address is the portion passing the No. 200 sieve. The maximum value should be selected based on the characteristics of the fines and the environment of the project. In general, maximum allowable values range from 8 – 15 %, depending on rainfall and frost depth. The lower ranges are suggested for areas with frost penetration.

Regardless of the actual grading selected, it should provide acceptable strength properties as tested by CBR, triaxial or modulus. Caution is needed when gradings are selected for the purpose of achieving increased permeability. These specs often create gaps in the grading or reduce fines to a level that significantly reduces both strength and density properties. Levels of passing No. 200 sieve below 8 % will tend to result in increased permeability but decreased strength. (7)

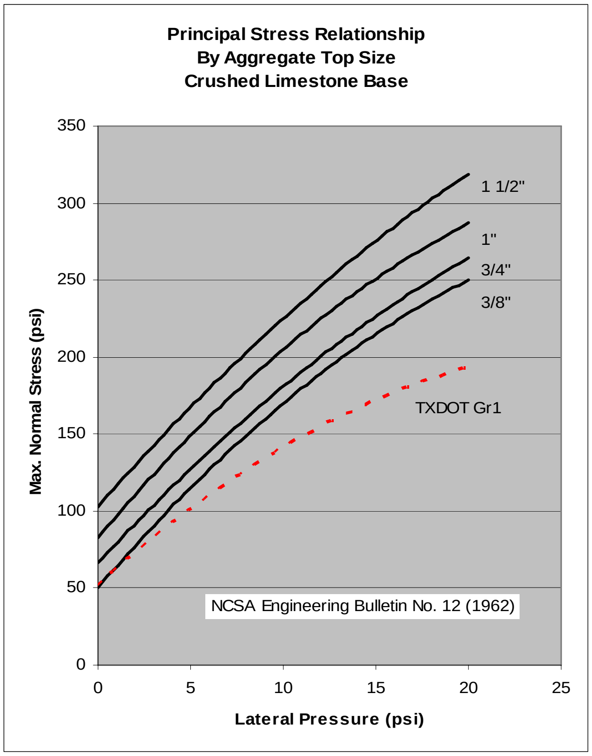


Figure 2. Effects of Particle Size on Triaxial Properties

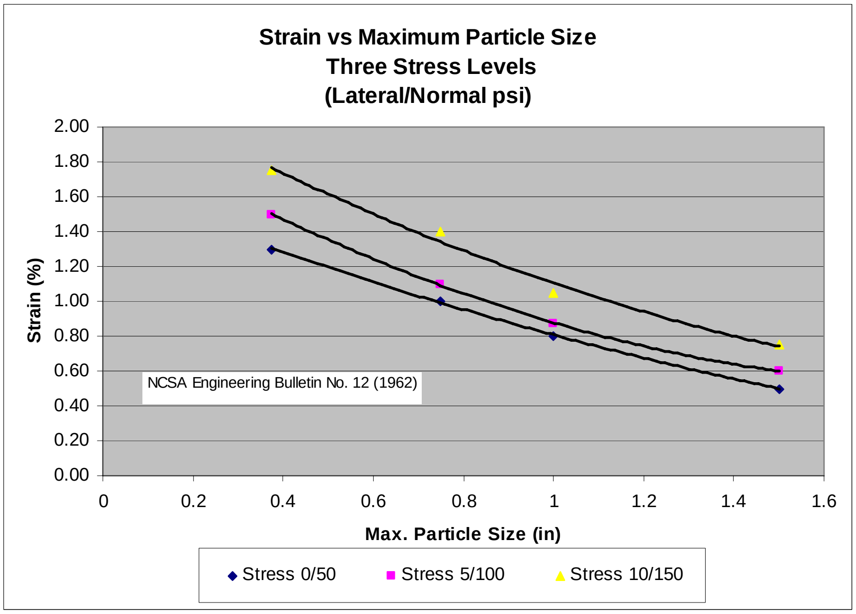


Figure 3. Effects of Particle Size on Deformation

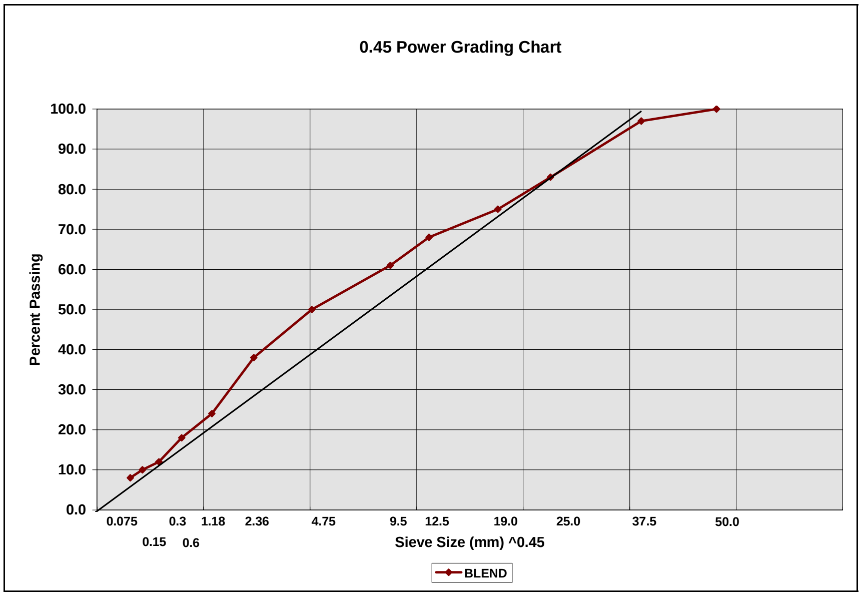


Figure 4. Example of 0.45 Power Curve Grading Plot

Testing for Atterberg Limits is useful to measure the sensitivity of the fines to changes in moisture. Warm, dry climates with relatively free-draining soils may allow for low levels of Plasticity; however a maximum of 6 would be suggested. For the highest level of service, a non-plastic material is recommended. Other tests, such as the sand-equivalent and methylene blue are also available to measure similar properties. (9, 10)

Density

The most critical field property of CAB for performance is density. Most performance measures improve with increased densification. Laboratory tests such as the Standard Proctor and the Modified Proctor methods are used to establish the maximum dry density and optimum moisture content. The role of moisture is to coat and lubricate the particles so they can be properly densified. A lack of moisture or an excess in moisture, compared to optimum, will result in decreased densification. The Modified Proctor uses a higher compaction effort resulting in higher dry densities with lower optimum moisture contents and is recommended for CAB materials to be used for pavements. A field target of 100 % of Modified Proctor is also recommended for maximum performance. (13)

In the construction of the AASHO Road Test, a Standard Proctor test was used to establish dry densities and moisture targets for construction of the CAB. Research following the Road Test by the National Crushed Stone Association (NCSA) evaluated the differences in performance between densification using the Standard densities compared to the Modified densities. Subsequent research by NCSA found remarkable improvements in performance with a direct correlation to the higher density. Figure 5 shows a correlation of dry density and CBR for various sources of crushed limestone similar to that used in the Road Test.(13) A significant improvement is shown when the result for one of the sources is plotted.

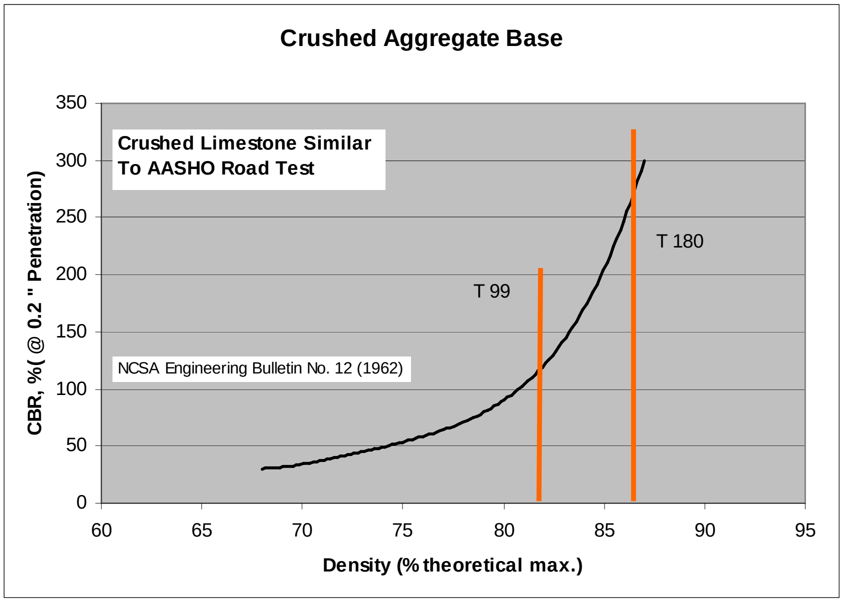


Figure 5. Impact of Density on CBR of CAB

Based on experience, a rule of thumb to use for evaluating the appropriateness of a target density is to look at the relationship of the compacted dry density to the theoretical voidless density based on Bulk Gravity. The target density should be a minimum of 85 % of the theoretical density. An example is shown below.

Aggregate Bulk Specific Gravity 2.69

2.69 x 62.4 pcf = 167.9 pcf (density of solid rock)

The target dry density = 85 % (167.9 pcf) = 142.7 pcf

This simple check will insure that the grading and particle shape are suitable for achieving a density that will provide acceptable performance.

The differences in dry density between Standard and Modified methods, as shown in Figure 6, are typical for well graded CAB. The increase in CBR is quite significant and by itself justifies the higher target density.

Comparisons using triaxial testing also show the impact of higher density. Further work by NCSA was conducted to support this concept. Figure 6 confirms the improvements in higher density based on the reduction in specimen deformation at five different stress levels when the dry density is increased from 138.0 pcf to 144.3 pcf. These density levels represent the Standard and Modified conditions respectively. For each stress state, the deformation of the triaxial specimen was reduced by 50 %. Figure 7 also shows this in another format.

One critical construction element that must be considered when specifying the Modified density is that construction procedures and material used for the underlying subgrade must assure that a good foundation is in place for compacting the CAB layer. This layer can not be adequately compacted if the layer below is too soft. Suitable compaction equipment is available to allow a contractor to meet the increased density levels using the Modified density method.

Resilient Modulus

Future CAB testing for performance will be tied to the resilient modulus. This test has been selected by the American Association of Highway and Transportation Officials MEPDG as the measure of performance. This test is similar in equipment and specimen preparation to the triaxial. However, for resilient modulus testing, a cyclic loading is used and measurements of resilient strain of a compacted specimen over a range of stress states are evaluated. The final test protocol is in development but will be similar to AASHTO T 307 Determining the Resilient Modulus of Soils and Aggregate Materials. Different test sequences and stress states are used for base/subbase compared to subgrade materials. An example of modulus data is shown in (Figure 9)

As seen from Figure 8, there is no one modulus value, rather a range of values depending on bulk stress state. This represents the stress dependency of unbound granular materials whereby the compacted material becomes stronger as the stress condition increases. The bulk stress condition is a combination of the confining stress and the vertical load (traffic and overlying pavement). The stress condition will vary based on traffic and placement of the CAB layer in the pavement. The closer the CAB layer is to the surface, the higher the stress level and the higher the modulus. One conclusion to draw is that the value of granular material increases as the overlying pavement layers are reduced, so long as there is adequate thickness for protection.

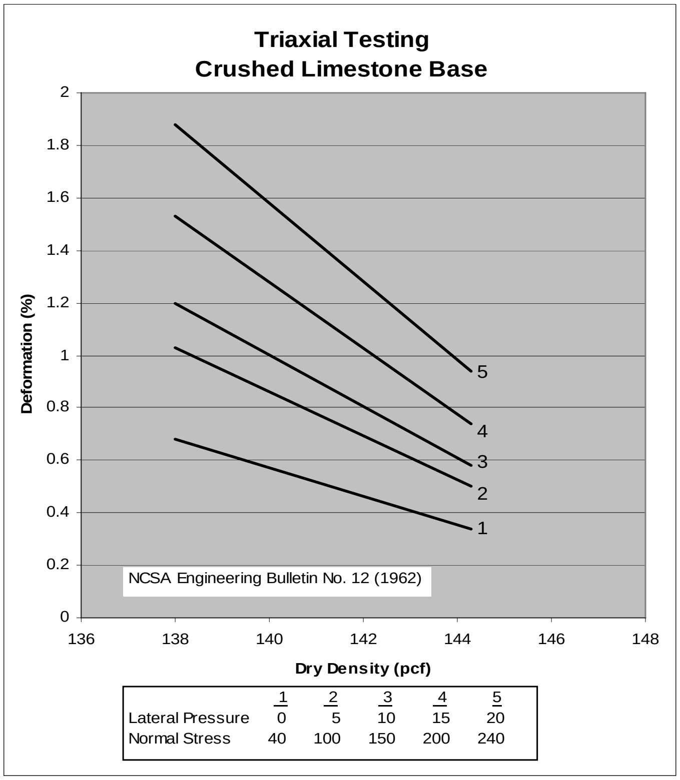


Figure 6. Reduction in Deformation at Increased Density

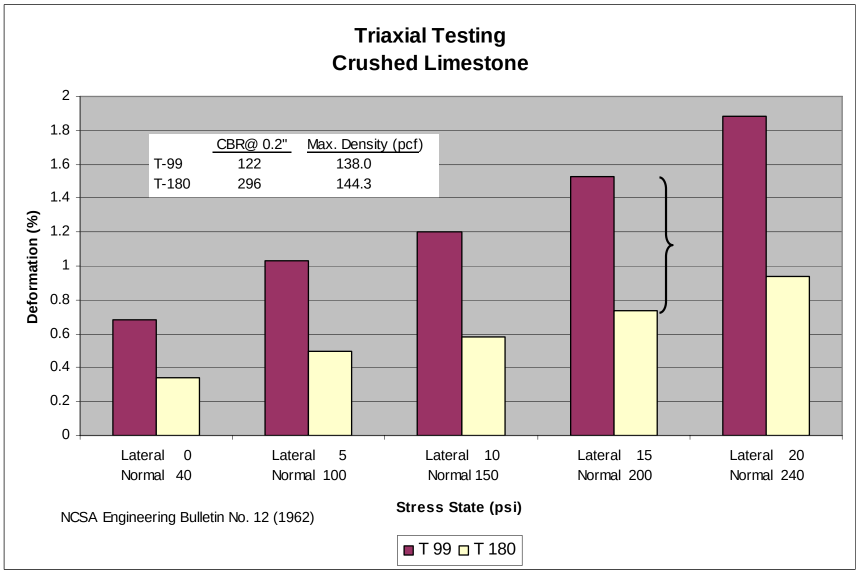


Figure 7. Influence of Density on CAB Deformation

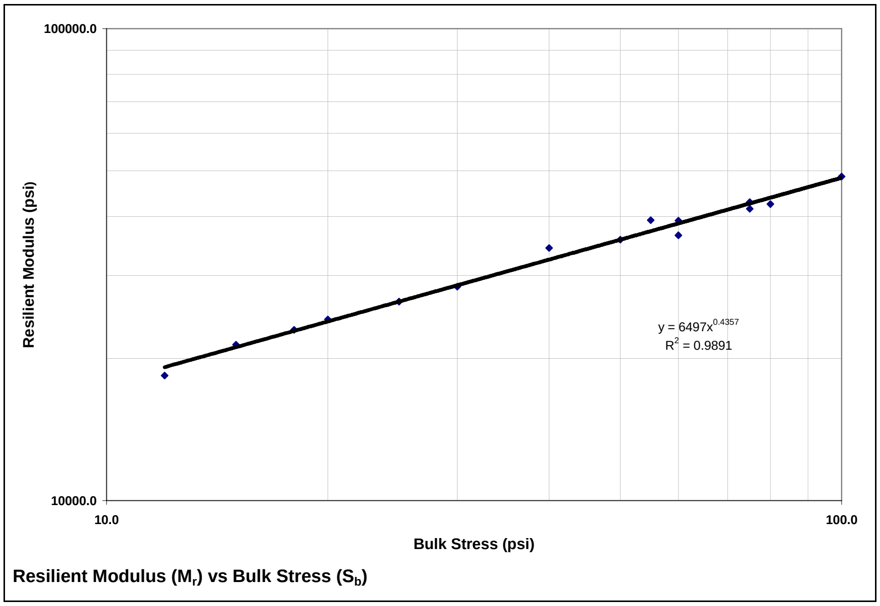


Figure 8. CAB Resilient Modulus Data (AASHTO T 307)

Body of Knowledge

If we properly evaluate the history and research that is available on crushed stone products used as unbound base, we can come to the following conclusions:

- Select a well-graded crushed stone product having a nominal maximum particle size between 1- 2 1/2 inches and a grading similar to the 0.45 power curve which insures a coarse aggregate structure
- Select a fines content of suitable quality and amount consistent with environmental factors
- Design the pavement structure to be well drained
- Insure adequate stability for the subgrade
- Test to evaluate strength properties
- Don't sacrifice strength for permeability
- Specify target densities based on 100 % of Modified densities
- Consider using minimum thicknesses of HMA to maximize CAB value and to minimize costs

Having quality materials for constructing high quality unbound CAB is only the first step. Getting the product in place requires a lot of attention, following good construction practices and using consistent quality products and proven construction techniques. The easy way is not the best way.

- Proper source approval to include a quality control plan which monitors grading and moisture; a pug mill for mixing and water control is preferred
- Establish a proper target density and optimum moisture content based on Modified test methods
- Place the CAB with a spreader box to control thickness and minimize segregation
- Allow for deep-lift base construction to minimize multiple lifts; research has confirmed adequate compaction in single lifts up to 21 inches (12)
- Avoid water additions on the roadway which then requires mixing on the roadway leading to segregation, variable density and moisture contents, and the potential to saturate the subgrade
- Control the compaction process immediately after placement with test gauges or intelligent compaction techniques
- Seal the surface soon after acceptance

As we look back at the history and development of unbound CAB construction, the principles that lead to success are pretty simple. Most of the knowledge we need to construct high quality unbound base, we have known for decades or centuries. Granted, we are continually creating and perfecting new tools to better characterize and model CAB, but the majority of engineering principles for testing and constructing serviceable CAB were developed long ago.

In the words of Josh Billings, the 19th century American humorist,

> "There is nothing so easy to learn as experience and nothing so hard to apply."

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