The Effects of Aggregate Size and Gradation on Hoop Stresses in Steel Cylinders and the Reuse of Waste Tire Tread Cylinders for Aggregate Confinement in Confined Aggregate Concrete

By Samuel G. Bonasso, P.E.

Abstract: New aggregate building material, confined-aggregate (CA) concrete is introduced and load tested to greater than HS 20 wheel loads. CA concrete, made by using a cylinder to confine and give lateral support to stone aggregates, increases the aggregates load bearing capacity and uses. Commercial-off-the-shelf stone aggregates are load-tested in strain-gauge-instrumented steel cylinders to measure stress levels and confirm behavior. Technical foundation is laid for civil engineering uses in road bases, retaining and bearing walls, and other engineered structures. The reuse of discarded, tread-worn, automotive tires with both sidewalls removed, is assessed and recommended for use as the confining cylinder.

Introduction

This report introduces a new, cellular-reinforced, aggregate building material, *confined aggregate, CA, concrete*. This new material is made using a cylinder to confined stone aggregates. The cylinder increases the load-bearing capacity of natural and man-made aggregates by providing direct lateral support. It is comparable in bearing load applications to common Portland Cement (PC) concrete. This report describes and tests material behavior and discusses model tests and laboratory load tests on four, common, aggregate gradations. Based on these tests it makes a recommendation on an optimal, commercially available, aggregate gradation and assesses the reuse of tire tread cylinders in making *CA concrete*.

Definition of Confined Aggregate (CA) Concrete

C*onfined aggregate (CA) concrete* is aggregates confined in a thin walled cylinder segment. It is generally compared and contrasted with Portland Cement (PC) concrete as a building material in bearing load applications.

Portland Cement (PC) concrete is a wet, chemically generated material made from sand, stone aggregates, portland cement and water. In PC concrete an anhydrous, exothermic chemical reaction between the water and portland cement causes curing and results in a solidified cement-water matrix. The cured, cement-water mortar confines the sand and stone laterally and vertically, and integrates the mixture into a single, load resisting, three-dimensional material.

In contrast, CA concrete is a dry concrete, that is, it does not use water or portland cement. In CA concrete the lateral confinement and integration of the stone aggregates is accomplished with a cylindrical device, verses in PC concrete with cement, water, sand mortar. Like filling a pipe with water, CA concrete is made by placing similar size aggregates within the space bounded by a cylindrical segment. This combination creates a cellular building unit. The CA concrete cellular unit is vertically supported by the surface of the earth or some other structure and vertically integrated by its own weight. When combined, the cylinder and the similar size aggregates become a unitized cell which is laterally confined and integrated into a single, circular, load resisting, three-dimensional building unit. CA concrete structures are constructed of single or multiple cellular units placed in layers or stacked in columns. CA concrete trade name is Mechanical Concrete® and the cylinder trade name is Mechanical Cement®. These names are owned by The Reinforced Aggregates Company.

Mechanical Cement®

Mechanical Concrete®

<u>The Cylinder—Cell Wall</u>

The cylinder is thin-walled and can be made of any sufficiently strong tensile material, i.e. steel, wire, fibers, fabric, etc. Aggregates behave somewhat like a fluid when placed under pressure, i.e. an external pressure on a loose collection of aggregates generates lateral pressure in all directions within the collection and they tend to move away from the pressure. The lateral pressure generated by a tire on pavement, for example, is perpendicular to the applied load and is generally distributed in a circular-like stress pattern within the aggregate material. This circular-like stress distribution is the basis of the well known Boussinesq curves and load distribution factors used in geotechnical engineering to predict pressures within soils generated by foundation loads. The efficiency and effectiveness of using a cylinder to create a CA concrete cell is this natural tendency of aggregates to generate a circular, fluid-like, internal, lateral load distribution when place under an external load. The aggregate's fluid-like, lateral pressure creates a circumferential hoop stress within the cylinder wall. This is similar to the hoop stress in a pipe generated by hydraulic pressure. Other geometric forms can be used to confine fluids or aggregates, e.g. a square, a triangle, or an octagon; however, any such geometric form would tend to deform into the shape of a circle due to the fluid-like nature of the internal lateral pressure. So a thin walled, tensile, cylindrical segment is an optimal and very efficient engineering form for this structural application.

The Aggregates

The aggregates in CA concrete may be composed of any relatively uniform-particle-size, natural or man made material. Same-size aggregates tend naturally to flow together and achieve their maximum density when placed within a confined space, without the use of additional compaction energy. For example, grains, beans, or uniform sized ball bearings or marbles placed within a box or a cylindrical space naturally assume their approximate, maximum density. A stone aggregate collection possessing a range of sizes from small to large, e.g. crusher run limestone, usually requires additional compaction energy to achieve optimum bearing-load density to support loads without excessive settlement.

CA Concrete and The Problem Definition

Confined aggregate concrete was discovered by the author in the summer of 2004, concluding a six year search for a viable reuse of whole waste auto tires. A tire-tread cylinder solves two problems which prevent whole tire reuses in civil engineering applications; 1. Whole Tires cannot be completely filled with anything but air and 2. Whole Tires hold water. A US patent application is pending on this idea. Confining and laterally integrating stone aggregates by means of a cylindrical device is a relatively simple construction technique to produce and understand. However, in design, engineering and construction practice, questions arose regarding the cylinder and aggregate size and behavior which required guidance before CA concrete could become an effective, efficient, economical construction material for application and use.

These questions included the following:

1. Does the ratio of the cylinder diameter and the diameter of the aggregate have an impact on the overall behavior under load of the cellular unit?

2. To assure primarily tensile behavior in the cylinder, what should be the ratio of thickness of cylinder wall with respect to the diameter?
3. Can a tire-tread cylinder—a tire with both sidewalls removed—function safely as a commercial-off-the-shelf cylinder and be structurally effective and economical?
4. Are there commercial-off-the-shelf, standard, uniform size AASHTO aggregate gradations, e.g. No. 57s or No. 3s, which would work and naturally promote integrated behavior with respect to the cylinder?

Some answers to these questions are discussed in the conclusion.

Failure Modes

<u>Portland Cement(PC) Concrete</u>

The tensile cracking failure mode of PC concrete is well known. It originates from the 3-dimensional Poisson effect of strains. It consists of cracking or splitting in the material perpendicular to the direction of the primary, live, compressive loading. From the behavior of materials under stress, this internal lateral strain is predicted by Poisson's ratio, (approximately 0.2 for portland cement concrete) and is, in PC concrete, a tensile strain generated perpendicular to the direction of the primary, live, compressive load.

The so-called '*compressive strength*' of PC concrete may also be spoken of as 'the compressive stress at which the material will develop lateral splitting or cracking due to internal tensile stresses.' This lateral tensile crack is also the failure mode of the stone aggregates used within the PC concrete. These internal, lateral tensile forces and strains cause cracking or splitting, and are the primary generators of failure in PC concrete.

In PC concrete this tensile cracking characteristic is used to create beam-type structures which require both tensile and compressive strength. In beams, where PC concrete develops lateral tensile strains it is reinforced with steel or other tensile materials perpendicular to these cracks; thereby resisting these internal tensile stresses. Tensile crack control is a primary function of reinforcing steel used in PC concrete.

These well known, familiar PC concrete material characteristics are relevant since they will point to how similar characteristics are addressed in CA concrete.

<u>Confined Aggregate(CA) Concrete</u>

Failure in the confined aggregate concrete cellular structure is not lateral cracking since the collection of aggregates in CA concrete is already infinitely cracked. Within the CA concrete cell the cylinder supports the stacked and interlocked, discrete aggregate particles; restraining them in place so they do not move with respect to each other even while cracked. The CA concrete cell's expanded ability to support external loads on aggregates is based on both the tensile properties of the lateral supporting cylinder and the compressive properties of the aggregate materials. When the cylinder's tensile ability to provide lateral support is diminished or reduced or reaches its limit, the aggregates move laterally and collapse with respect to each other. Therefore, the primary failure mode in a CA concrete cell, used in bearing or compressive loading applications, is defined as excessive deformation, settlement or deflection of the aggregates in the direction of the externally applied loadings. This occurs due to lateral failure of the cylinder. This is similar to the aggregate materials failure mode in the pot-hole or the roadway shoulder collapse.

CA Concrete Research & Development

Early Models

The first CA concrete behavior tests were performed with small scale models. The model cylinders were 3.5" in diameter by 1" high by 0.025" thick steel cylinders. The aggregate was organic material of a nominal, uniform 1/4" diameter. These small cell tests assessed general material behavior and the effect of the ratio of cylinder and aggregate diameters. See photos 1 and 2. This combination of 1/4" aggregate and a 3.5" diameter cylinder has a ratio of aggregate/cylinder diameters of 0.25/3.5 or 1/14. Another cylinder of the same diameter and width was made of a flexible cloth using 'drywall' mesh. While the steel cylinder was stiffer than the mesh, the diameter to thickness ratio of both cylinders was in excess of 0.025/3.5or 1/14. See model photos.

Steel Band Cylinder Model

Drywall Mesh Cylinder Model

Some basic questions addressed by these models and the lab tests were:

1. Does the aggregate material effectively 'solidify' and 'integrate' into a cellular unit when it is placed within the confines of the cylinder?
2. What is the impact of the ratio of the cylinder diameter to the aggregate diameter?
3. What is the impact of the thickness and height of the cylinder relative to the diameter?
4. Does the cylinder effectively contain, confine, and provide lateral support of the aggregates?

Some answers to these questions are discussed in the conclusion.

Mechanical Concrete® / Mechanical Cement® Reduction to Practice

General Description

The first full scale demonstration of Mechanical Concrete®, CA concrete, was conducted in April, 2005 at the shop of geotechnical professional engineer and contractor, Onas Aliff, P.E. at Omega Construction in Morgantown, WV. The demonstration used eight pairs of two Mechanical Cement® tire cylinders bolted together and filled with AASHTO #8's, handed-compacted, limestone. The Mechanical Cement® cylinders were made from P195/65R15 tires by eight different tire manufacturers and were supplied by Marion Zuccari of Tireland, Inc. Morgantown, WV. See photos. This demonstration used general construction labor to construct a segment of wall approximately four feet four inches, (4'-4"), wide, two feet two inches, (2'-2"), in thickness and about five feet four inches, (5'-4"), high.

Procedure

The wall was build by placing a pair of Mechanical Cement® tire cylinders on the floor of the shop and filling them about half full with AASHTO No. 8 limestone and hand-compacting the stone. Then the other half of the cylinder was then filled with stone and compacted. Then a second pair of Mechanical Cement® cylinders were placed on top of the first pair and filled and compacted in the same manner. This procedure was repeated until all eight pairs were stacked, filled and compacted.

This process was accomplished in less than one hour with three men and a small skid-steer loader. It was quickly apparent to the experienced engineer/builder considering the wall area produced and the associated time and materials costs that Mechanical Concrete® could be a highly economical method for constructing wall systems. The CA concrete material combination of cylinder and stone functioned structurally similar to crib-walls or gabions, with a more dense final result and a simpler, faster and easier construction method.

First CA Concrete wall and Mechanical Concrete® reduction to practice April, 2005

This experiment raised other field related construction questions such as:

1. Will the variation in tire diameters and width negatively effect construction methods?
2. Will different aggregate gradations behave well in such a confinement application?
3. Will small equipment work effectively in the field to perform the filling functions?
4. Will the speed of construction carry over under real construction conditions?

Further field tests and demonstration projects indicated that the variation in tire diameters was controllable and would not negatively impact construction. The speed and efficiency of construction was also carried over in the field. These projects showed that common construction equipment such as font end loaders and bull dozers could also be used to fill the cylinders. However, to accurately assess aggregate behavior under confinement and the effect of various aggregate gradations required laboratory research.

West Virginia University Large Structures Laboratory Research

Based on these initial model tests, field research activities and other office, lab and field tests it was decided that a series of load tests were necessary to accurately define and confirm the structural behavior of the both the aggregate materials and the cylinders. These tests used thin-walled steel cylinders and four different aggregate gradations were designed by the author with input from Dr. Roger Chen of West Virginia University Department of Civil and Environmental Engineering and others and were conducted by Dr. Chen and his graduate assistants.

Steel Cylinders

To assess the cylinder stresses two, thin-walled steel cylinders were fabricated by Universal Fabricators, in Shinnston, WV. The cylinders, one twelve inches, 12", long and one thirty-six inches, 36", long were made from 14gauge, 0.075", A-36 steel and were rolled to a twenty inch, 20", inside diameter, t/d ratio of 0.075/20 = 1/267. These cylinders were instrumented with strain gauges on their exterior surface, opposed at 180°, to measure and average the tensile hoop stresses generated by the vertical loads. See photo.

WVU Large Structures Lab Steel Cylinder / Aggregate Tests

Aggregates

To assess a range of aggregate structural behavior four aggregate mixtures were selected: 1. regular construction sand, 2. AASHTO #8 Gradation Limestone, 3. AASHTO #57 Gradation Limestone, and 4. 3/4" crusher run gradation limestone. For testing all the aggregates were hand compacted in the cylinders.

Loading Apparatus'

Each steel cylinder was hydraulically loaded in increments up to a maximum of 200 psi, approximately 14TSF, using three circular load heads with respective diameters of 6 inches (28.3 sq. in.) , 12 inches (113.2 sq. in.) and 18 inches (254.7 sq. in.). This generated approximate maximum loads for each load head in the range of (6") 6000 pounds, (12") 23,000 pounds and (18") 50,000 pounds respectively.

As a field load reference, the AASHTO HS 20 wheel loading is 16,000 pounds. In addition, the air pressure on semi or medium truck tires is 100psi, approximately 7TSF. Our general test objective was to load, where possible, up to or above these truck wheel and tire loadings by a factor of 2.

Test Results

The following graphs for these lab load tests are as follows: 1. Left Graph—loading vs. deflection curves; and 2. Right graph—depth vs. horizontal pressure curves.

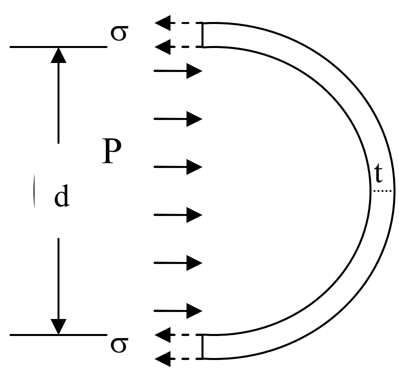
In the Left Graphs the vertical scale is the loading in pounds and the horizontal scale is the deflection in inches.

In the Right Graphs the vertical scale is the depth in inches from the top of the cylinder and the horizontal scale is the pressure in psi. Each curve represents, from top to bottom, a vertical stress distribution within the cylinder. In the small box in the Right Graph is the vertical pressure from the applied load for each curve from right to left.

The horizontal pressure, shown in each Right Graph, was calculated by the following equation, assuming a thin-tube with thickness t and a uniform circumferential hoop stress σ, tube diameter d the uniform internal horizontal pressure, P, can be obtained as:

$$P = \frac{2 \times \sigma \times t}{d}$$

Where the circumferential hoop stress $\sigma = E \times \varepsilon$, with $E = 29 \times 10^6 \, psi$, and ε = the circumferential strain measured by the strain gages attached on the surface of the steel tube; and t = steel tube thickness, 0.075", and d = steel tube diameter 20".

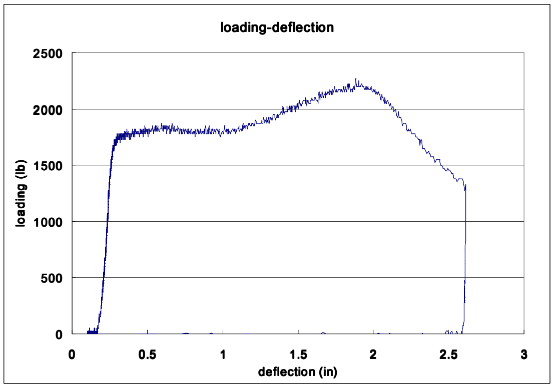


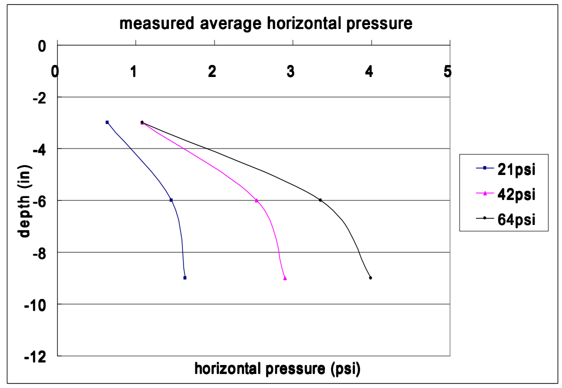
Cylinder Stresses and Forces

Test Results 12” Long 20”φ Tube

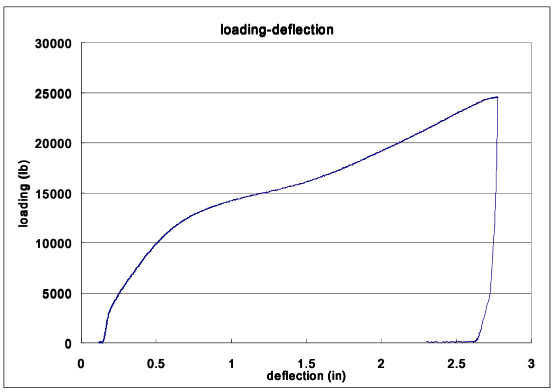
SAND AGGREGATE

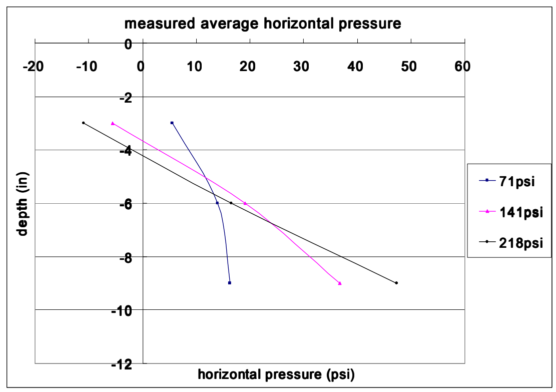
12” tube / 6” loading plate sand (6000lb max)



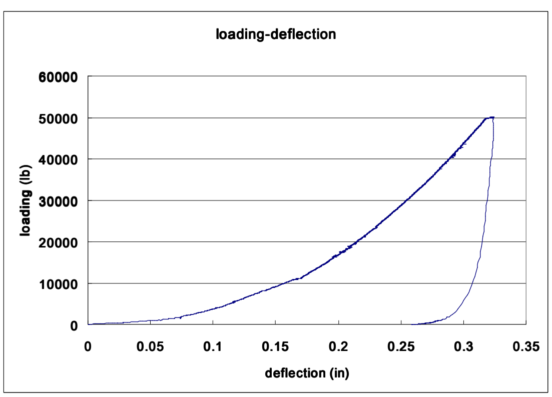


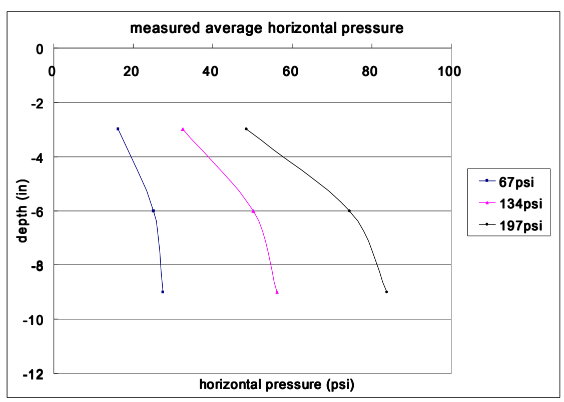
12” tube / 12” plate sand (23,000lb max) (HS 20 Wheel 16,000lbs / 100psi)





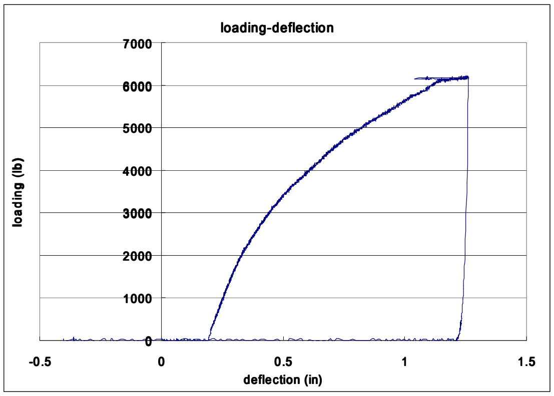
12” tube / 18” plate sand (50,000lb max) (HS 20 Wheel 16,000lbs / 100psi)

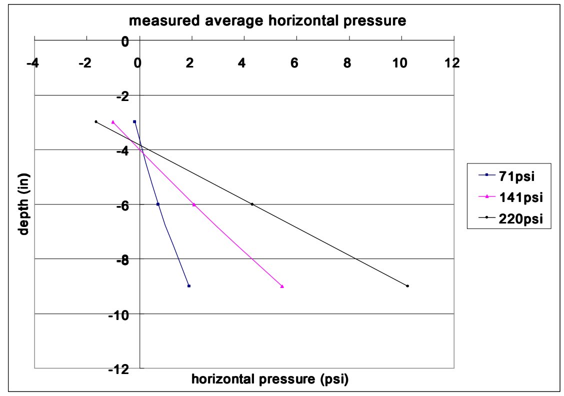




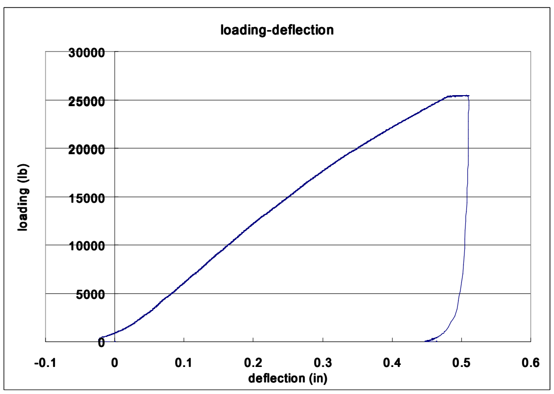
AASHTO No. 8 LIMESTONE

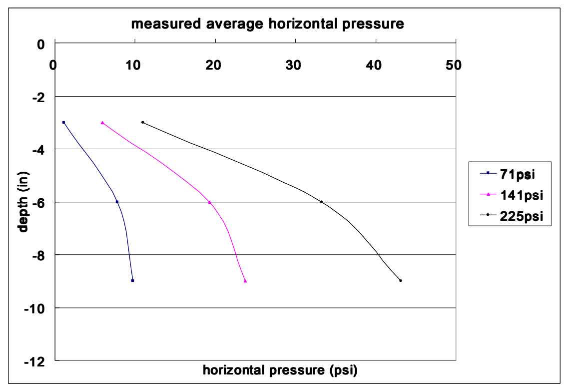
12” tube / 6” plate AASHTO No. 8 (6000lb max) (HS 20 Wheel 16,000lbs / 100psi)



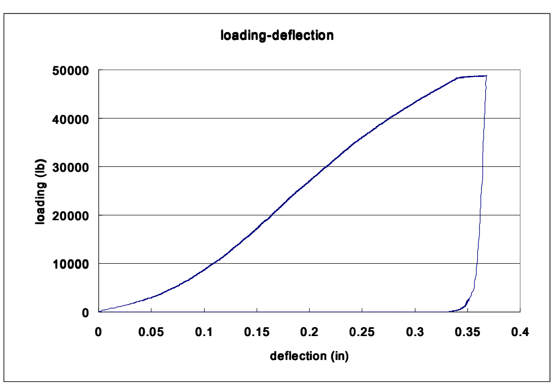


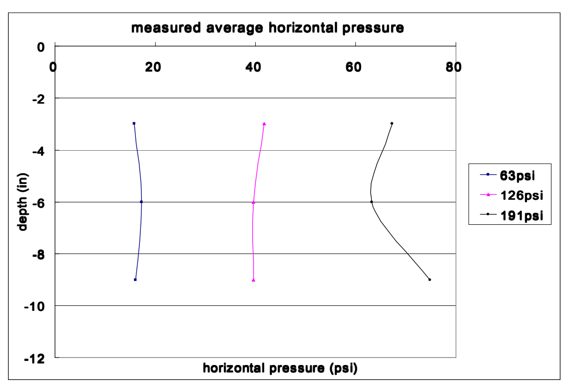
12” tube / 12” plate AASHTO No. 8 (23,000lb max) (HS 20 Wheel 16,000lbs / 100psi)





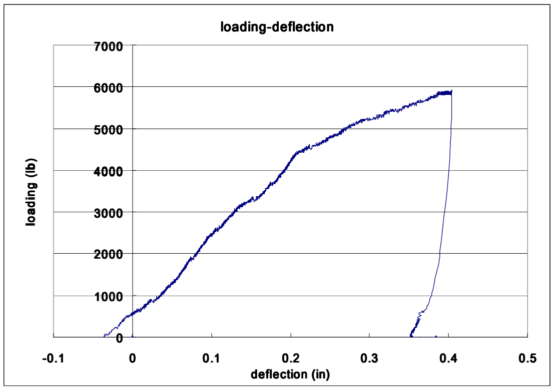
12” tube / 18” plate AASHTO No. 8 (50,000lb max) (HS 20 Wheel 16,000lbs / 100psi)

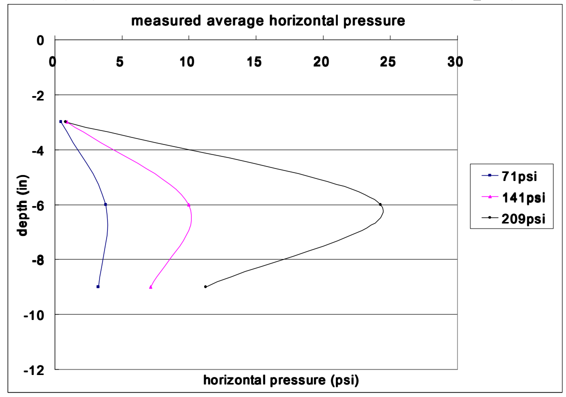




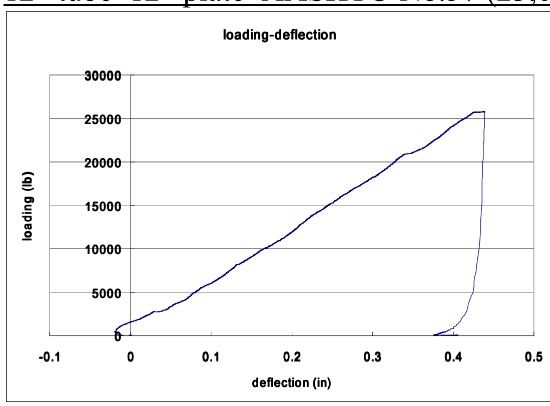
AASHTO No.57 LIMESTONE

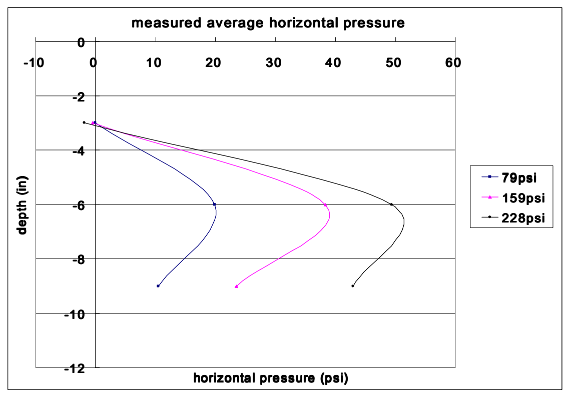
12” tube 6” plate AASHTO No.57 (6000lb max) (HS 20 Wheel 16,000lbs / 100psi)



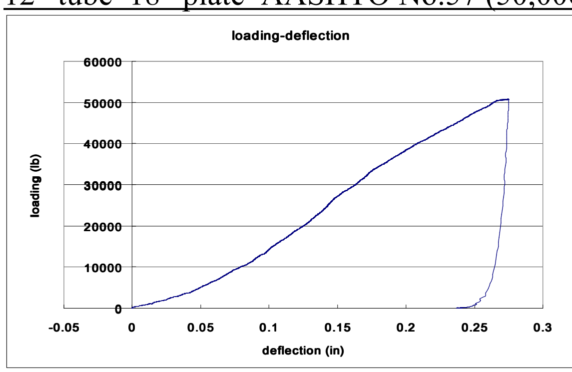


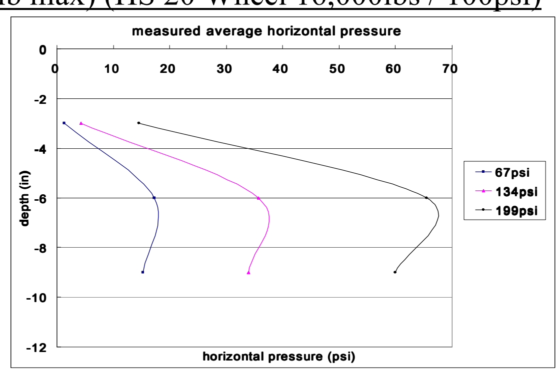
12” tube 12” plate AASHTO No.57 (23,000lb max) (HS 20 Wheel 16,000lbs / 100psi)





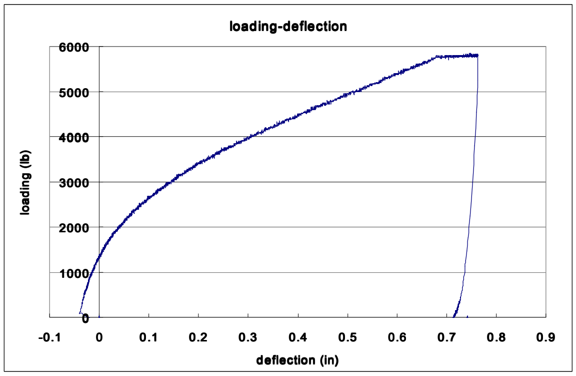
12” tube 18” plate AASHTO No.57 (50,000lb max) (HS 20 Wheel 16,000lbs / 100psi)

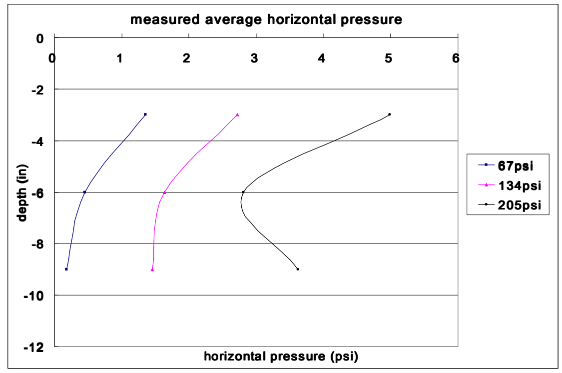




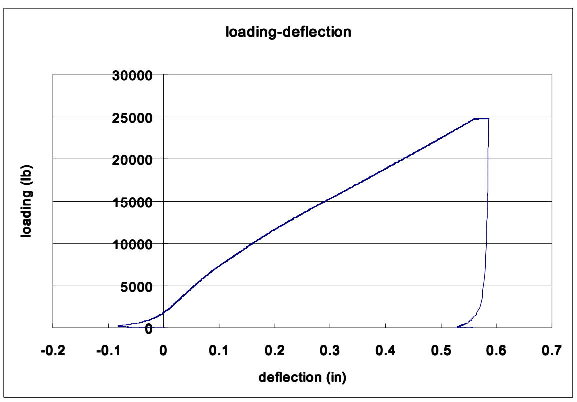
¾ Inch Crusher-run LIMESTONE

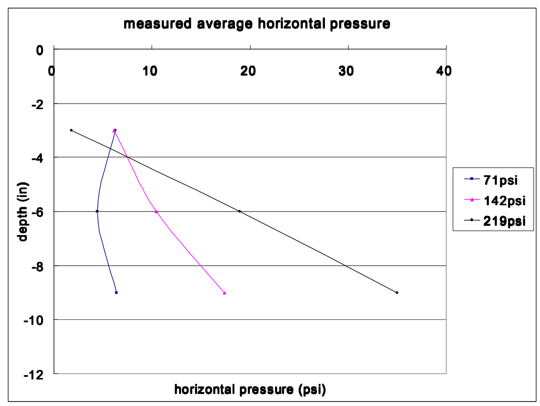
12” tube 6” plate ¾ inch crusher-run (6000lb max) (HS 20 Wheel 16,000lbs / 100psi)



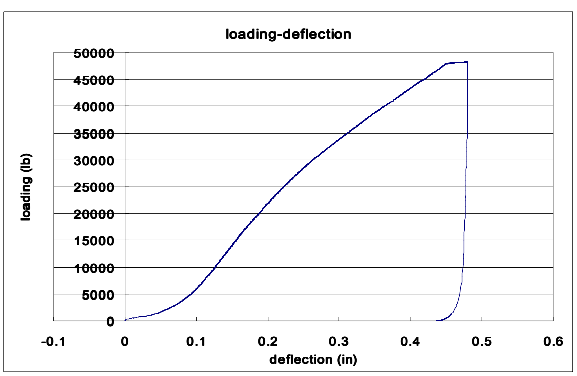


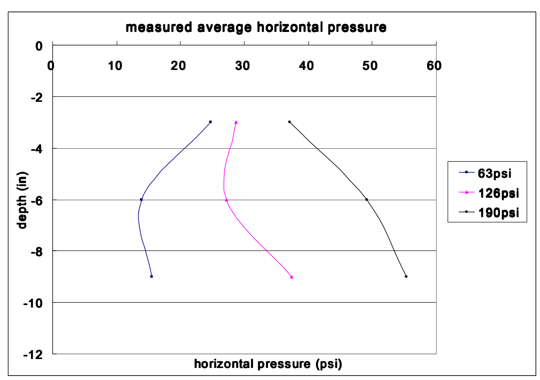
12” tube 12” plate ¾ inch crusher-run (23,000lb max) (HS 20 Wheel 16,000lbs / 100psi)





12” tube 18” plate ¾ inch crusher-run (50,000lb max) (HS 20 Wheel 16,000lbs / 100psi)

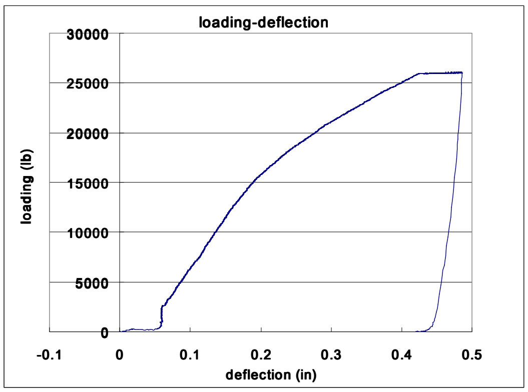


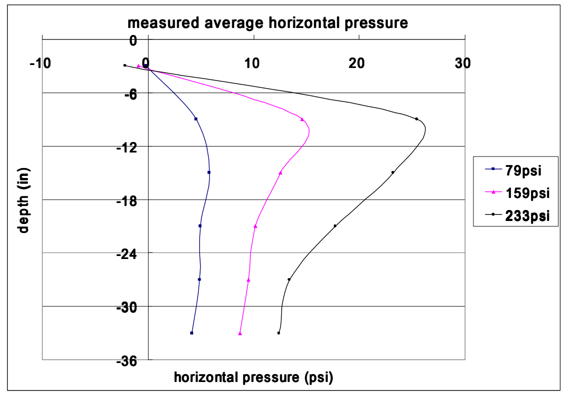


Test Results 36" Long 20"φ Tube

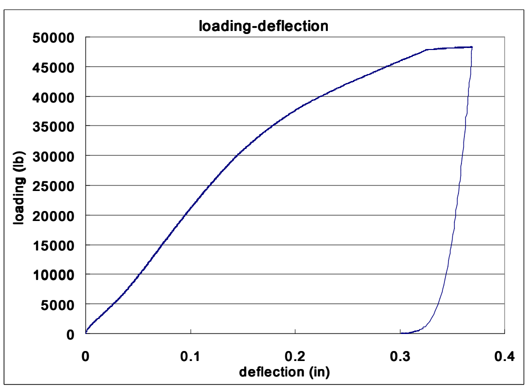
AASHTO No. 8 LIMESTONE

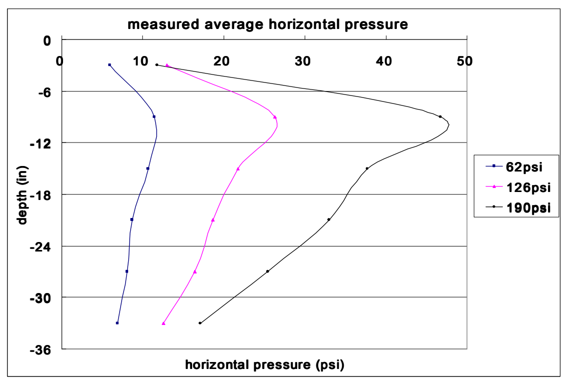
36" tube 12" plate AASHTO No. 8 (23,000lb max) (HS 20 Wheel 16,000lbs / 100psi)





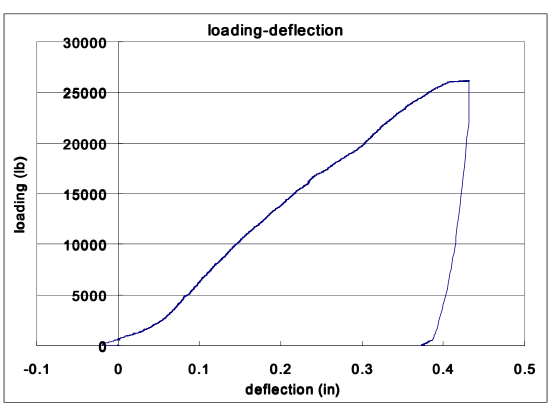
36" tube 18" plate AASHTO No. 8 (50,000lb max) (HS 20 Wheel 16,000lbs / 100psi)

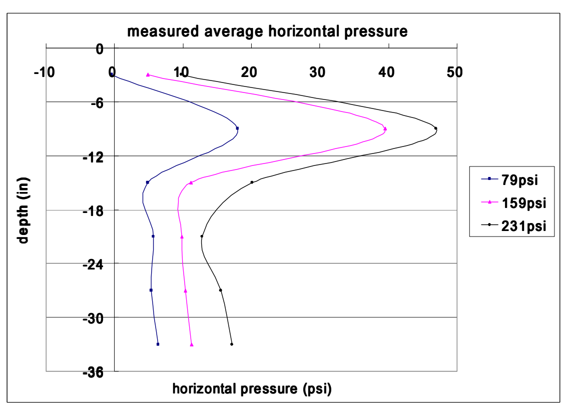




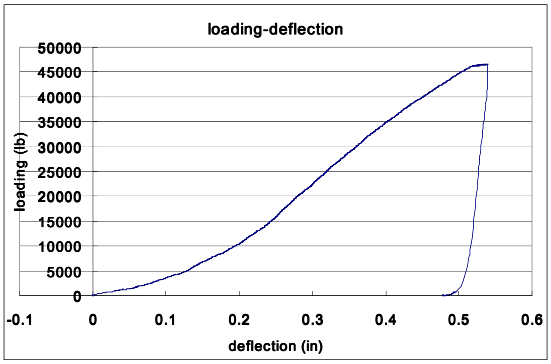
AASHTO No. 57 LIMESTONE

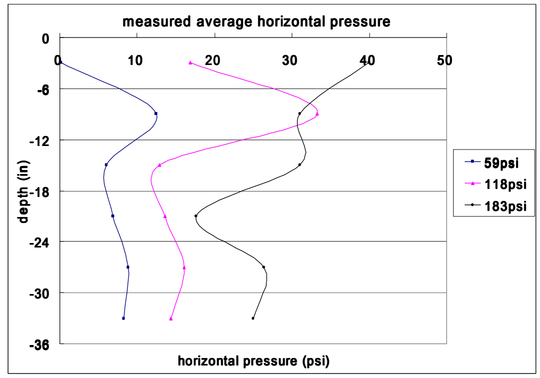
36" tube 12" plate AASHTO No. 57 (23,000lb max) (HS 20 Wheel 16,000lbs / 100psi)





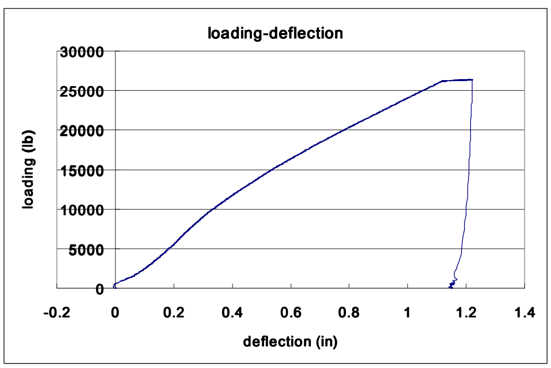
<u>36" tube 18" plate AASHTO No. 57 (50,000lb max) (HS 20 Wheel 16,000lbs / 100psi)</u>

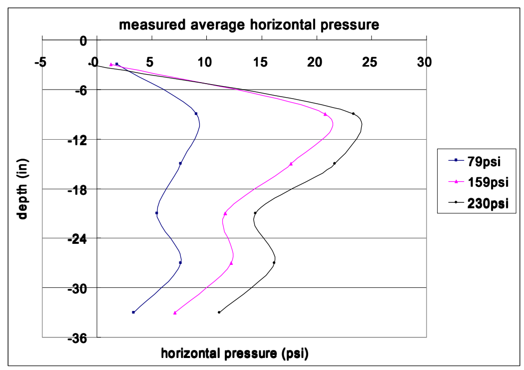




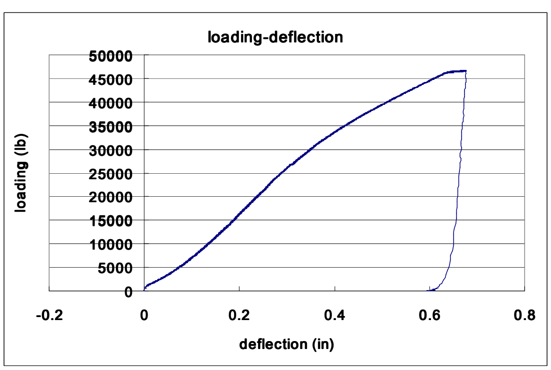
<u>¾ Inch Crusher-run LIMESTONE</u>

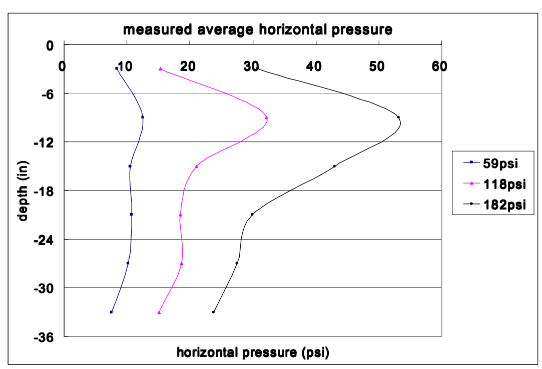
<u>36" tube 12" plate ¾ inch crusher-run(23,000lb max) (HS 20 Wheel 16,000lbs / 100psi)</u>





<u>36" tube 18" plate ¾ inch crusher-run (50,000lb max) (HS 20 Wheel 16,000lbs / 100psi)</u>





<u>Discussion of Test Results and Conclusions</u>

The influence of the ratio of cylinder diameter to particle diameter and the integration of aggregate materials by the cylinder were the primary inquiries of this testing. The four construction materials chosen for testing represent a range of commercially available, common aggregate materials.

<u>Aggregate Material Behavior 12" Long Cylinder</u>

A local failure occurred in the sand with the 6" diameter load head due to the relatively small particle diameter aggregate. This resulted in local, lateral failure, large deflection and inability to sustain load. This behavior was anticipated due to the concentrated nature of the load and the small sand particle size relative to the cylinder diameter. The combination of the 6" diameter load head and small sand particle size did not allow for the lateral pressure to be transmitted by the sand to the cylinder wall. This local failure can be seen in the first Left Graph load/deflection curve and the low horizontal pressures in the first Right Graph, page 11.

With the 12 inch load head the sand transmits significant lateral pressure to the cylinder but it also deflects significantly due to local lateral failure. It is not until the 18 inch load head is applied that the deflection is reduced throughout the load cycle while significant lateral pressure is transmitted to the cylinder. With the larger load head a more uniform pressure is applied throughout the sand without local lateral failure. This confirms well know criteria that compacted coarse to medium sands make good foundation material with bearing pressures up to 6 tons per square foot allowed by some codes. It is likely that even these sand bearing pressures could be increased by confining the sand within a cylinder device. These results are also shown in the graphs on page 11.

In the AASHTO No. 8 aggregate the load is sustained with the 6" diameter load head. Deflection is reduced as the loading-head area is increased. Larger loads also function in a similar manner but there is inconsistency in the amount of deflection verses load. These results are seen in the graphs on page 12.

In the tests with AASHTO No. 57, the larger and more uniform diameter gradation, the load/deflection curves are more consistent and relatively independent of the load head diameter. This behavior is shown in the graphs on page 13.

On page 14, the load/deflection behavior of the 3/4" crusher run gradation also functioned similarly after it received additional compaction energy from the load-head. This compaction/energy behavior can also be seen on each graph at the beginning of the loading cycle. This occurs since the ¾ inch crusher run includes significant fine material and requires greater compaction. The AASHTO No.8 gradation had similar behavior seen in the graphs on page 12.

Cylinder / Diameter Aggregate Particle Ratios

Sand is aggregate material with a particle size in the 0.3mm diameter range. This provides a ratio of sand particle size to cylinder diameter for these tests was about 1 to 1700. The AASHTO No. 8 aggregate gradation has an average particle size of approximately 0.25 inches for cylinder diameter ratio of 1 to 80. The AASHTO No. 57 aggregate gradation has an average particle size of 5/8 inches for a ratio of particle size to cylinder diameter of 1 to 32.

In smaller aggregate/cylinder diameter ratios i.e. smaller than 1 to 100, the role of the cylinder shape in solidifying and integrating the aggregate is not significant unless the applied load covers greater than 80 percent of the cylinder circular area. As the aggregate size/cylinder diameter ratio increases *and* the size of the aggregates remain uniform; the role of the cylinder in solidifying and integrating the aggregate becomes more effective for smaller loads. With small particles, if the footprint of the load is small, as in the 6 inch diameter load head on sand, lateral failure can occur at relatively small loads, due to high local stresses.

Conclusion 1. A ratio of stone aggregate particle sizes to cylinder diameter of not less than 1 to 35 *and* uniform aggregate particle sizes effectively integrates the cellular unit; exhibits fluid-like behavior; laterally transmits the applied load to the cylinder; and functions well at the external load levels found on roadways.

Conclusion 2. Uniform size aggregates, such as AASHTO No. 57 and larger sizes such as AASHTO No. 3, solidify and integrate without significant compaction. They exhibit the representative, fluid-like behavior of uniform sized particles. Gradations with more fines and a greater spread of particle sizes will also integrate but require additional compaction energy either from the applied load or from compaction equipment.

Conclusion 3. Cylindrical confinement is effective to restrain, integrate and solidify relatively uniform size aggregate materials and increase their load bearing capacity.

Aggregate Material Behavior in 36” Diameter Cylinders

The tests with the 36” long tube were designed to observe the distribution of the lateral pressure as the distance from the load head increased. This deals with the effect of the height in relation to the diameter of the cylinder. Additional discussion of optimal size aggregates; ratio of cylinder diameter to thickness; and the effect of the cylindrical shape as an integrator of the aggregate material are offered.

One impact of the height / cylinder diameter ratio is the non-uniformity of the distribution of the pressure along the height of the cylinder. Lateral stresses in the aggregates are more concentrated and higher near the load point and more distributed and uniform at an increased distance from the point of load application.

<u>Conclusion 4.</u> In the longer cylinder, a higher lateral pressure occurs just below the load point and then reduces further down into a lower more uniform distribution. The load/deflection behavior is generally linear. See curves on pages 15 and 16.

<u>Conclusion 5.</u> A variety of additional aggregate/cylinder behavioral observations are further confirmed from these longer tube tests. These include the predictable Boussinesq pressure bulbs, the fluid like behavior of more uniform size aggregates, and the relative independence of larger size aggregates from point load failure.

The structural objective of the cylinder is to resist the aggregate-generated, lateral pressure with a pure tensile stress within the circumference of the cylinder—a hoop stress. The ratio of cylinder thickness to the diameter is a measure of the rigidity/flexibility of the cylinder material. A larger ratio points to a more rigid structure and a smaller ratio points to a more flexible structure. For example, in two cylinders made of the same material, a 10 inch diameter cylinder with a 1 inch thick wall (a t/d ratio of 1/10) will be more rigid than a 10 inch cylinder with a ¼ inch diameter wall (a t/d ratio of 1/40). The more rigid cylinder will tend to resist lateral stress with both compression and tension.

<u>Conclusion 6.</u> Ratios of cylinder thickness to diameter of smaller than 1 to 20 will produce relatively uniform tensile hoop stress.

<u>Conclusion 7.</u> Based on the distribution of stresses observed in the 12" and 36" steel cylinders, the circular cylindrical shape is optimally effective in confining and supporting the aggregate. The lateral, internal, fluid-like pressure generated in the aggregates is reflected as a pure tensile hoop stress in thin walled cylinders.

General Conclusions—Predictability and the Use of Tire Tread Cylinders

Another objective of these tests was to assess the predictability of aggregate/cylinder behavior using general physical principles. The test results confirm all these materials exhibited generally linear behavior.

General Conclusion 1. Based on these tests, internal cylinder pressure can be predicted within the normal range of engineering accuracy with basic statics principles represented by the hoop stress equation above on page 10.

The question "Can a used-tire provide a structurally sound cylinder for confining aggregates?" is now addressed. The standard, maximum allowable, internal pressure for an auto tire is 44psi. This maximum pressure includes a design factor. In a tire cylinder used in CA concrete, a 50,000 pound vertical load on a 28" diameter tire cylinder 8" wide filled with stone aggregates, with a Poisson's ratio of 0.3, will generate an internal, lateral load of 15,000 pounds on the inner surface of the tire cylinder. This 50,000 pound vertical load compares to a soil bearing pressure of approximately 14 TSF, tons per square foot. We assume the 15,000 pound lateral load is uniformly distributed on the internal surface of the tire cylinder, an area of 704 in^2; i.e. 8" wide by 88"—the cylinder's circumferential length. Over this area the 15,000 pound load generates approximately 21 psi pressure. So, in a CA concrete application a used-tire will have a design factor in excess of 3.0, since the 44 psi also includes a design factor.

General Conclusion 2. Using a tire tread cylinder, i.e. any standard automotive tire with both sidewalls removed, in a construction application; i.e. where the supported vertical loads are in the range of 100psi, 7 TSF; provides a rugged, very conservative materials engineering approach to confining aggregates in CA concrete.

Further research on confined aggregate concrete may be needed to refine the understanding of its behavior. This basic research and the lab and field tests confirm that CA concrete made with used, tire-tread cylinders is a rugged, effective, economical, method for extending the usefulness and improving the load bearing capacity of aggregate materials.

References

1. Tuan-Chun Fu and Roger H. L. Chen, PhD, *Test Results of Stone Aggregates Contained in Open-Ended Steel Cylindrical Pipes*, West Virginia University Civil and Environmental Engineering, November, 2005.

2. Fredrick S. Merritt, Editor, *Standard Handbook for Civil Engineers*, McGraw-Hill, New York, 1968.