Confined Aggregate Concrete in a Load Bearing, Segmental Column Subject to Axial Compression Loads

By Samuel G. Bonasso, P.E.

Abstract: The potential use of Mechanical Concrete® in load bearing columns and bearing walls and in bridge abutment structures is of significant interest in rural and other remote and hard to access locations. The behavior of a Mechanical Concrete® column is analogous to operation of a hydraulic cylinder with the hydraulic fluid being the stone aggregates, the hydraulic cylinder being the *Mechanical Cement®* cylinders, and the hydraulic piston being the external dead and live loads. *Mechanical Cement®* tire cylinders, six tires of the same size with both sidewalls removed, are combined with AASHTO #57 limestone aggregates to create a short column which is loaded to approximately 50,000 pounds or three times the AASHTO truck wheel load of 16, 000 pounds.

Introduction and Background

Creating a load bearing column of loose, dry stone particles in a collection of cylinders is a new concept. Rather than molecular bonds it uses gravity and external confinement to integrate the elements into a single mass. In Mechanical Concrete® dry aggregate materials are integrated together with a cylinder to form a cellular building unit. The result is a confined aggregate concrete, a new class of dry, non-chemical concrete. This technical report covers the laboratory testing of a column made from this new material technology.

Load Lifting Hydraulics—A Historical View

When materials transmit strain energy both tensile and compressive strains are always functioning in the three dimensions of space. Tensile and compressive strains operate in the three-dimensional material continuum. Around the middle of the 20th century the design and manufacture of heavy construction machinery began to move away from the use of winch powered tensile wire rope for load lifting. It moved toward levered, compressive hydraulic powered load lifting systems. And while cable cranes are still in use, the hydraulic ram is now the state of the art for most construction equipment; the primary lifting method used in heavy construction machinery. For short distance energy transmission, hydraulics provides greater movement precision and spatial flexibility than was considered possible using steel cables. Today large earth moving equipment grades sites with the on-board assistance of GPS technology partly because of the responsiveness and control accuracy of hydraulically operated components.

Because the hydraulic design philosophy involves the use of levered elements, it can reduce the length of powered movements necessary to create larger movements at the bucket, blade or working surface. This energy transmission philosophy is stated as follows: compressive strain energy is efficiently transmitted over small distances while tensile strain energy is more efficient for longer distance transmissions. Cables are still used for longer distance crane lifts.

Another, more basic engineering philosophical difference is also at work. Mechanical engineers regularly deal in three dimensions due primarily to the dynamic nature of their design challenges. Civil engineers deal primarily with two dimensions, due primarily to the static nature of their design challenges. For a civil engineer the third dimension is assumed to be another, similar, differential slice of reality. The material behavior in the third dimension is similar enough to the two dimensional slice being designed that it will be adequately considered by the two dimensional design approach. So from roadway cross sections to collections of beams and columns, two dimensional civil engineering approaches are functionally effective and sufficiently scientific to assure predictable behavior. Any unique third dimensional stresses that occur in these two dimensional cross-sections or in frames and beams are usually handled in the connections, sections and other details.

For example, in the wire rope, a civil engineer usually sees a pure tensile element; while a mechanical engineer sees a dynamic collected system of moving wire elements subject to high compressive and contact bearing stresses perpendicular to the primary tensile forces. The shift from wire rope to hydraulic cylinders for the mechanical engineer is a shift in how the tensile and compressive energy, forces, stresses and strains are projected, transmitted, managed and dissipated. The hydraulic cylinder stroke reduces the distance for strain energy transmission while improving precision. The hydraulic cylinder handles hydraulic fluid pressure as a tensile hoop stress in the hydraulic cylinder, perpendicular to the direction of hydraulic ram compressive force. From the dynamic, 3-D, mechanical engineering perspective, the hydraulic cylinder with the hydraulic fluid is the functional inverse of the wire rope. However, in contrast to the wire rope, the hydraulic fluid has virtually no tensile strength perpendicular to the main compressive loading.

Confined Aggregate Concrete and the Hydraulic Cylinder Analogy

In the confined aggregate concrete cell the collection of similar size, aggregate particles functions somewhat like a thick hydraulic fluid. They tend to be a pure compressive material. Except for the friction between them, the particles have little or no lateral tensile strength and they tend to flow like a fluid under compressive forces. The confined aggregate concrete cell is a collection of similar size, aggregate particles confined by a thin-walled cylindrical segment similar to a hydraulic cylinder. The applied bearing-load is analogous to the operation of the piston in a hydraulic cylinder. The aggregate particles transfer the main supported loads downward along the axis of the cylinder to the earth and these particles also transfer the transverse lateral pressure to the cylinder device which is resisted as a hoop stress.

This research shows that confined aggregate concrete cells

1. can be vertically stacked in a collection of segmented pure tensile, common diameter, cylinder elements,
2. they can filled with pure compressive dry, stone aggregate particles, and
3. that gravity and the imposed load effectively combines and transforms these discrete tensile and compressive elements into an integrated, solidified, efficient compressive load bearing column structure.
4. This integration is accomplished through internal tensile and compressive support. The internal lateral stresses within the aggregates particles generated by the external compressive load and is contained as a hoop stress in the cylinders.

Why Make and Test Such a Column?

Concrete is the most manufactured product in the world and it consumes large amounts of energy both in cement manufacturing and in the construction process. It also requires a predetermined amount of technological infrastructure to use. For example it is extremely expensive and difficult to use in remote rural regions of the world were there is limited energy and equipment, no skilled labor, and a small educated workforce. Comparing Mechanical Concrete® to one cubic yard of redi-mix concrete: nine, 28 inch diameter by 8 inch wide *Mechanical Cement®* tire cylinders replaces six bags, 564 pounds, of cement. These cylinders also replace the skilled labor required to form and place the concrete.

In a wide variety of rural civil engineering structural column applications, such as piers, small bridge abutments, small dams and impoundments; these columns of confined aggregate concrete can be constructed faster and much more economically than a steel column or one made of portland cement concrete. The uses of these constructions may be industrial/commercial or for general public infrastructure.

Mechanical Concrete® confined aggregate concrete technology also allows waste manufactured material to be reused. For example, a *Mechanical Cement®* cylinder can be a used tire with both sidewalls removed. Tire cylinders can function as the segmented cylindrical elements and industrial aggregates such as blast furnace slag can function as the compressive material. This material reuse allows large civil engineering structures, such as bridge abutments and retaining walls to not only be more economical but also to be greener, more sustainable, and more consistent with modern environmental philosophy.

Origins of Mechanical Concrete® Column Test Research

Initial laboratory load tests and research were performed on aggregate materials confined in single steel cylinders. These tests measured the behavior of four aggregate materials and the results were reported in Mechanical Concrete® Technical Report #1.

Field tests and applications of Mechanical Concrete® in constructing walls showed that *Mechanical Cement®* tire cylinders could be vertically stacked on each other and functionally contain stone aggregate materials. These walls were constructed as a series of side by side columns made of discrete, vertically stacked cylinders. Each wall column was constructed by placing a *Mechanical Cement®* tire cylinder and filling it with stone aggregates and then placing a new tire cylinder on top of it and filling the new cylinder with stone aggregate.

Because the initial confined aggregate concrete research was directed to the load bearing capacity of a single cylinder, the question naturally arose regarding the load bearing capacity of a column composed of multiple cylinder elements.

Design Philosophy for Mechanical Concrete® Walls

These Mechanical Concrete® walls are designed using conservative masonry wall design standards regarding wall height to thickness ratios. In designing and stacking masonry elements engineers follow the general principle of keeping the resultant compressive force within the middle third of the cross sectional area. Following this principal assures that the stacked, discreet masonry elements will always be compressed against each other throughout the stack. As a wall gets taller it is less likely that the compressive force resultant will fall in the middle third area, primarily due to geometric limits on precision of wall construction and load application. Masonry standards reflect this principle by restricting the height of unbraced masonry walls to twelve (12) times the thickness of the wall. Simple Mechanical Concrete® segmental unbraced walls are currently limited in height to six (6) times the cylinder diameter. This conservative restriction is based on the lack of knowledge and experience with building these walls and may be modified in the future.

Questions Addressed by this Research

To the knowledge and experience of Samuel G. Bonasso, P.E. and Dr. Roger Chen, a column of this segmental cylinder/aggregate composition with its inherent hydraulic-cylinder-like behavior had never been tested before.

Many questions arise regarding the behavior of such a column under load. The questions addressed by this research are the following: *First,* could the *Mechanical Cement®* tire cylinders effectively contain the dead load of the aggregates stacked up to 6 times the diameter of the cylinder and could such column support an AASHTO truck wheel load of 16,000 lbs? *Second,* could the column support a multiple of two or three times such a wheel load without distress or failure? And then such questions as: 1. Would the aggregates stay in place or be forced out through the cracks between the cylinders? 2. Would the deflections be in an acceptable range and be linear with respect to the loading? 3. Would load bearing behavior be similar to aggregate/ steel cylinder tests? 4. Would a large load produce immediate deflection creep due to the use of tire cylinders? The research objective was to acquire engineering answers to these questions.

Test Set Up

The test was conducted at the Large Structures Laboratory of the Department of Civil and Environmental Engineering at West Virginia University College of Engineering and Mineral Resources, Evansdale Campus, Morgantown, WV. The test was conducted under the direction of Professor Roger H.L. Chen, PhD and Joseph G, Sweet. The author was in attendance.

The Mechanical Concrete® confined aggregate concrete (CAC) column tested was made from of six, same size, tire tread cylinders made from used tires with both sidewalls removed. The tire tread cylinders were stacked one at a time on top of each other and filled with #57 limestone aggregates. See **Figure 1** for the final CAC column. The aggregates were tamped by hand as each respective tire cylinder was being filled. The dimensions of the CAC column were approximately 60 in. tall by 28 in. in diameter, an h/t ratio of 2.1. It was a short, stout column. The tire tread cylinders were then labeled 1 through 6 in order from top to bottom.

Figure 1: Tire Tread Cylinder CAC Column with Instrumentation

A hydraulic jack was used to apply the load to the CAC column, and this load was distributed over the top of the CAC column using a 1-inch-thick steel plate, 18 inches in diameter (see **Figure 2**)

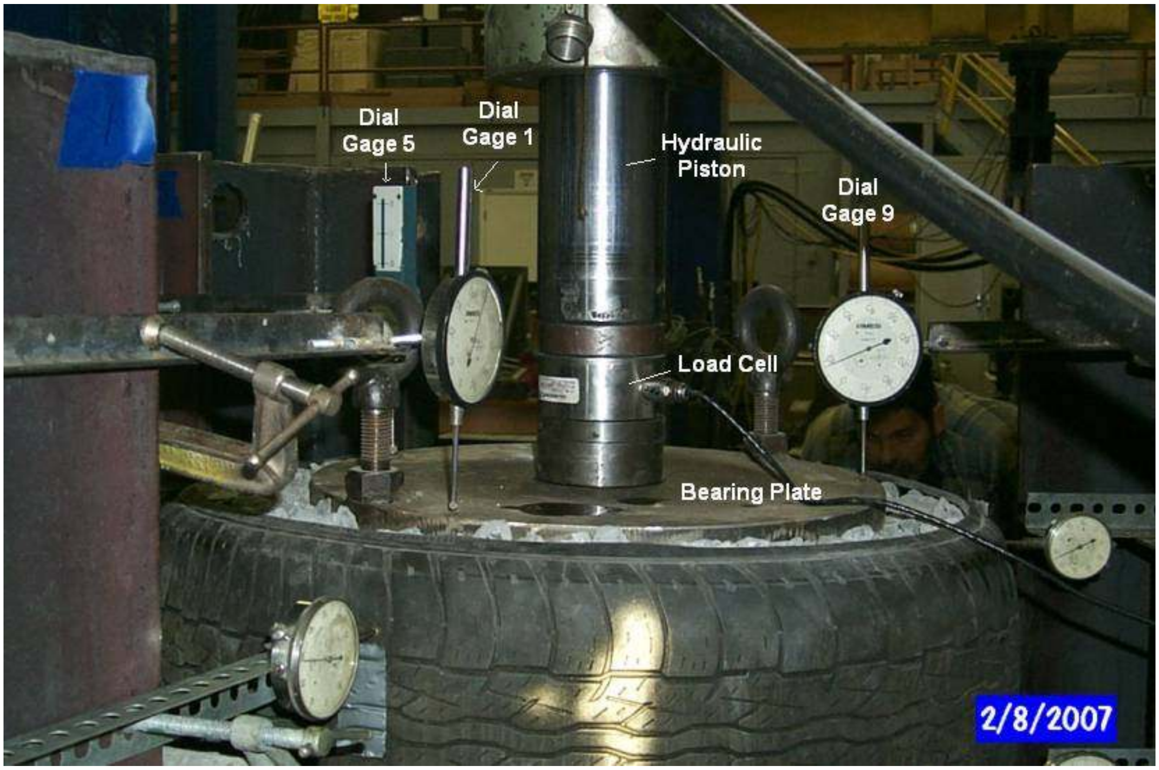

Figure 2: View of Testing Equipment and Instrumentation at Top of Tire Column

The instrumentation for the test included a total of 12 dial gages, one load cell, and a strain indicator box which was used to take readings from the load cell. The dial gages were held in place using angular sections that were clamped to sturdy, yet moveable, steel H columns, as shown in **Figure 3**. The three steel H columns used were spaced and oriented such that readings could be taken at approximately 120° apart around the circumference of the tire tread cylinder. From each of the steel H columns, one dial gage was attached to measure the vertical deflection of the loading plate, and three were used to measure the radial deflections of Tire Tread Cylinders 1, 2, and 4, totaling four dial gages for each steel H column. The gages used to read the radial deflections were positioned normal to the tire tread cylinder surface and at mid-depth of their respective tire tread cylinder. The gages used for measurement of the vertical deflections of the plate were placed from the outer edge of the plate a distance of ½" in toward the center of loading.

The numbering of dial gages was as follows: each steel H column was assigned a number, and the dial gages were then numbered sequentially from top to bottom for each column, starting with H Column 1. So for H Column 1, Gage 1 measured the vertical deflection of the plate, Gage 2 measured the radial deflection of Tire Tread Cylinder 1, Gage 3 measured the radial deflection of Tire Tread Cylinder 2, and Gage 4 measured the radial deflection of Tire Tread Cylinder 4. Likewise, Gages 5 through 8 were attached to H Column 2, and Gages 9 through 12 were attached to H Column 3 in the same manner. The numbering system is shown in **Figure 3** for H Column 1 and H Column 3.

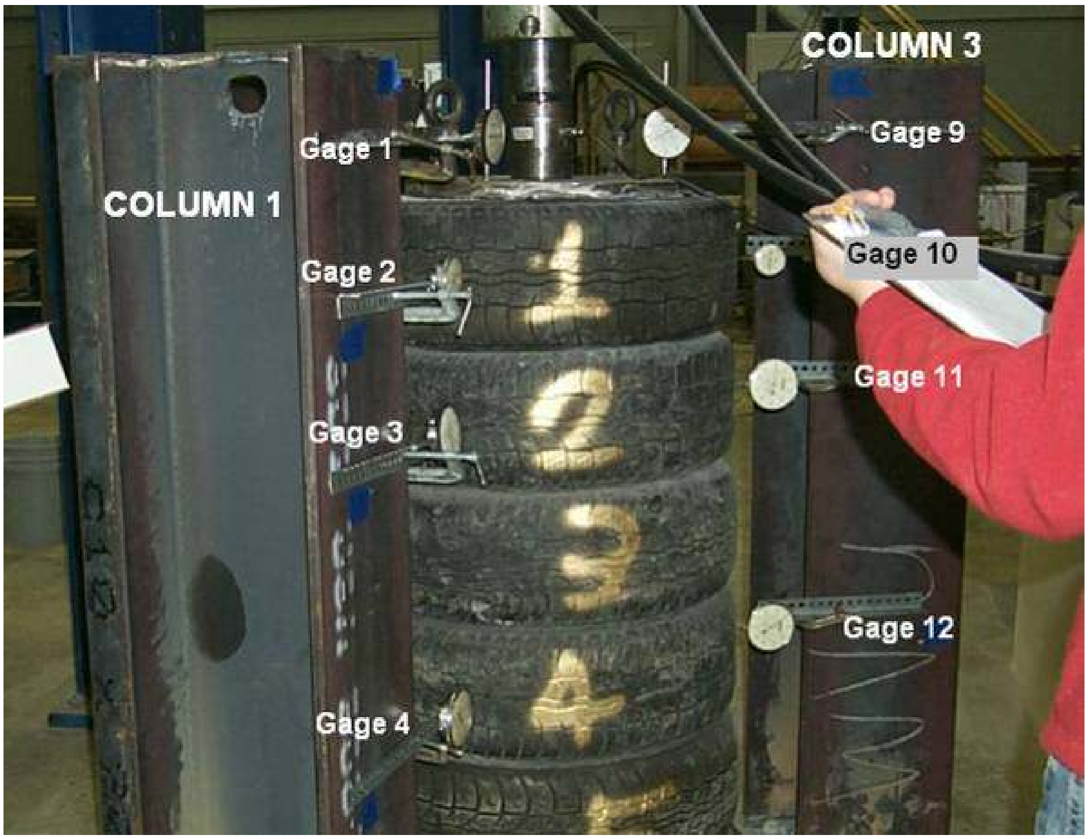

Figure 3: Attachment System Used for Holding Dial Gages in Place and Numbering System for Steel H Columns and Dial Gages (Steel H Column 2 Not Visible)

Loading Procedures

The Mechanical Concrete®, CAC column was subject to three Load Tests. For Load Test 1 it was loaded to a maximum jacking force of 10,000 lb. Load readout and dial gage readings were taken at 5,000 and 10,000 lb. Each time readings were taken for all tests, the jacking force was increased to the desired level, or what will be referred to as the Nominal Load, and then pumping ceased while the readings were being taken; in this time it was noticed that the load magnitude dropped to a sustained level, so the final load value before the next phase of pumping was recorded as the "Sustained" Load.

Load Test 2 was performed in a similar fashion as Load Test 1, with a maximum attained load of 55,000 lb. For this test, load was increased and readings were taken in 5,000 lb increments using the same procedures described above. Also, readings were taken after the release of the load to see the rebound effects.

For Load Test 3, the CAC column was loaded to 10,000, 20,000, and 30,000 lb, and readings were taken at each loading. Unlike Load Test 2, the load was not released immediately after the readings were taken for the maximum load. Instead, the CAC column remained subjected to a loading for a period of about 4 hours afterward; during this time, the load gradually decreased to approximately 25,000 lb. After the 4 hour period, readings were taken at this decreased load, then the load was increased again to 30,000 lb, more readings were taken, and then the load was completely released to determine the rebound deflections.

Test Results

Deflections at the Loading Plate

Figures 5 and **6** represent the applied load vs. the vertical deflection data collected from Dial Gages 1, 5 and 9 located at the loading plate during Tests 1 using the Nominal Loads and the Sustained Loads, respectively. In all plots for the vertical deflection, a positive value is representative of a downward deflection. Similarly, **Figures 7** and **8** represent that of Test 2, and **Figures 9** and **10** represent that of Test 3.

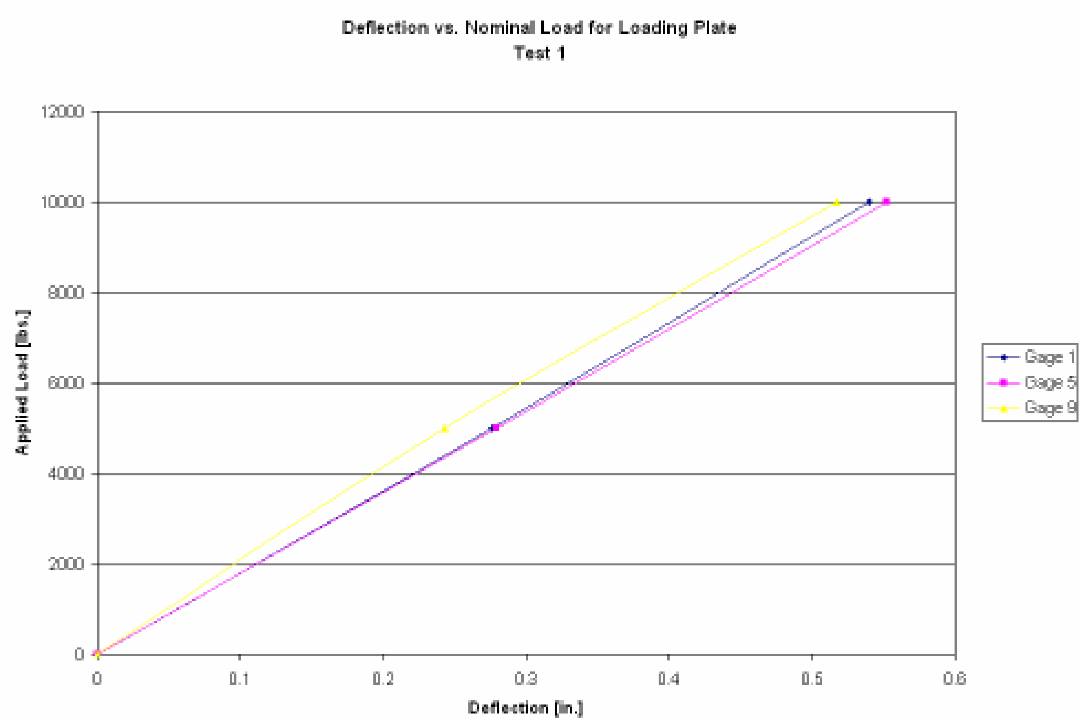

Figure 5: Vertical Deflections and Nominal Loads Measured at the Loading Plate for Test 1

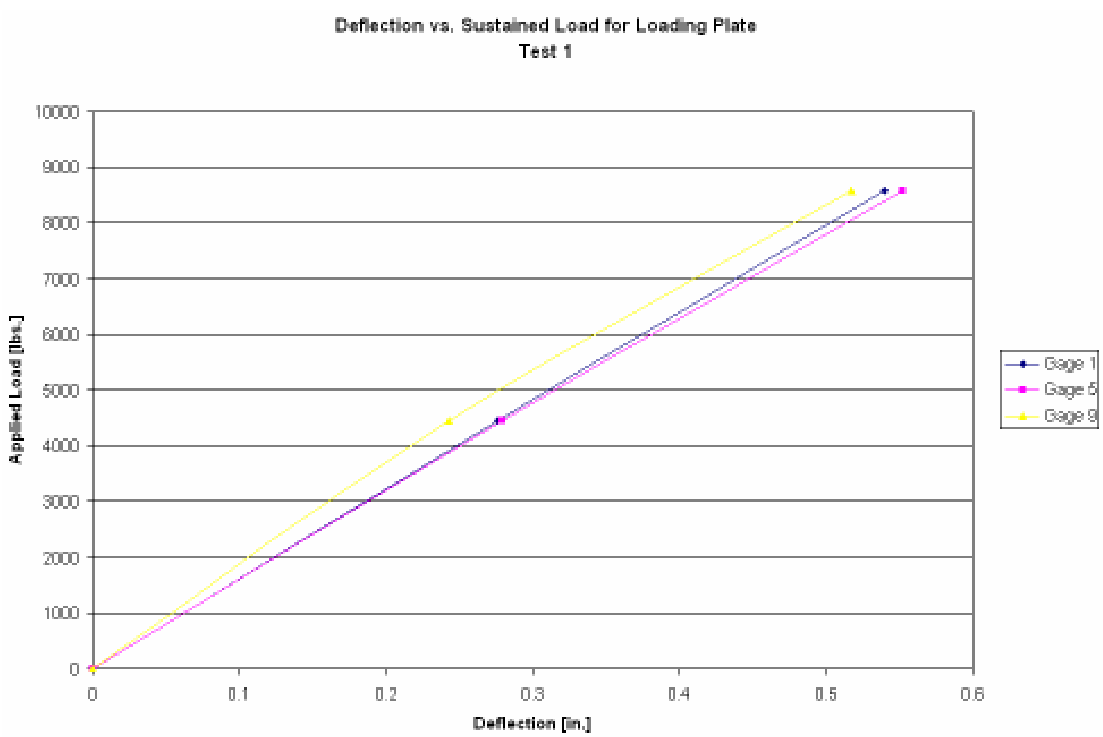

Figure 6: Vertical Deflections and Sustained Loads Measured at the Loading Plate for Test 1

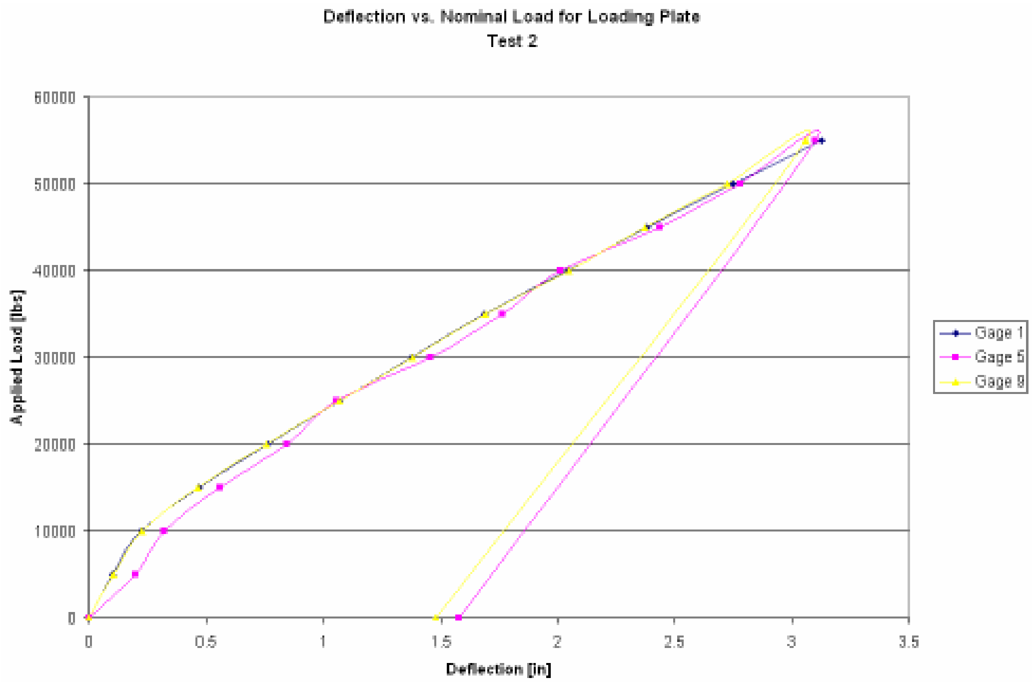

Figure 7: Vertical Deflections and Nominal Loads Measured at the Loading Plate for Test 2

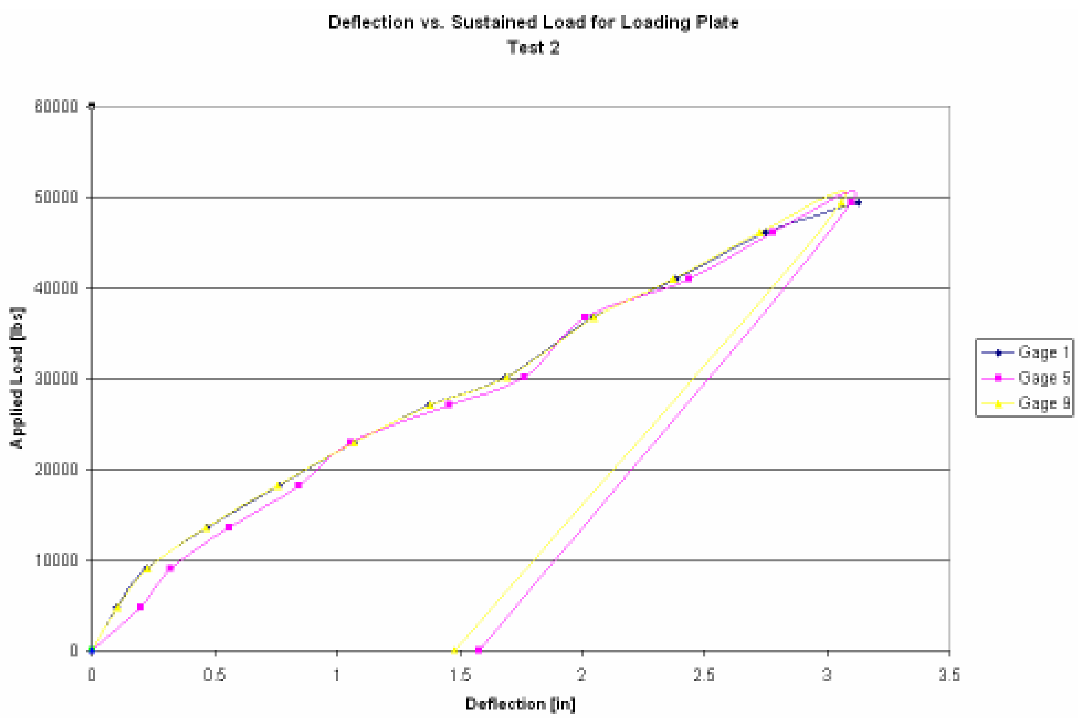

Figure 8: Vertical Deflections and Sustained Loads Measured at the Loading Plate for Test 2

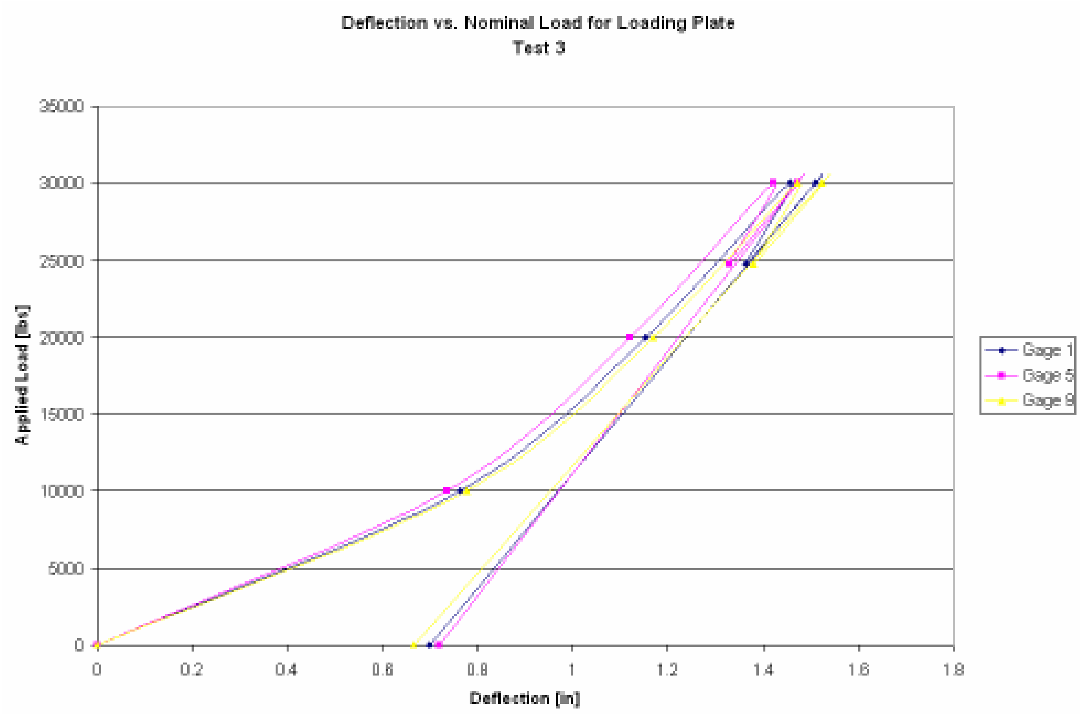

Figure 9: Vertical Deflections & Nominal Loads Measured at the Loading Plate for Test 3

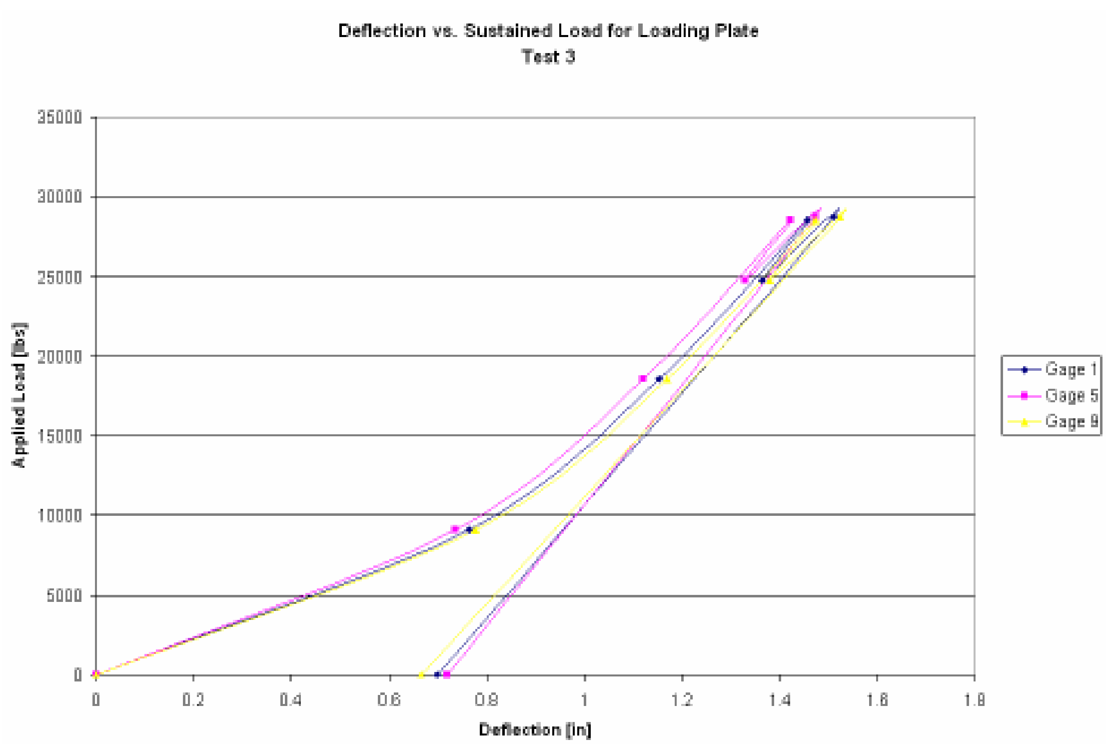

Figure 10: Vertical Deflections and Sustained Loads Measured at the Loading Plate for Test 3

General Observations

The vertical deflection data of all three tests indicate that the loading plate, for the most part, moved uniformly downward, as the variations in readings for each of the gages measuring these deflections was small (see **Figures 5** through **10**). However, evem though the loading plate seemed to descend evenly, there may have been some loading eccentricity on the column. This is evidenced by comparing the generally negative radial deflections seen at Support Column 1 to the positive radial deflections seen at Support Column 2, especially in Test 2 and Test 3 (as illustrated in **Figures 15** and **21**, for example).

Another observation from the testing was that the radial deflections were influenced by the curvature of the tires themselves. Although the dial gages were originally located at the vertical center of the tire for each test, throughout the course of the tests this position changed relative to the starting position (see **Figures 38a** and **38b**). The result was an overall decrease in the measured redial deflections for all gages at higher loads, and also some localized influence from the tread patterns could be seen. This was especially evident for Tire 1, which had larger vertical displacements than the other two instrumented tires, Tires 2 and 4.

General Conclusions

- The Mechanical Concrete®, CAC column constructed of *Mechanical Cement®* tire tread cylinders and AASHTO #57 limestone, accepted and sustained superimposed loadings in the range of 200 psi or 50,000 pounds. The loaded test column performed without material distress or failure of any kind to either the tire tread cylinders or the aggregate.
- The AASHTO Truck wheel load of 16,000 lbs produced a deflection of approximately 1.1 inches in the initial loadings. It appears a between 50% and 75% of this deflection may be associated with compacting of the stone.
- The column maintained its integrity throughout the tests. No aggregates were forced out through the interfaces between the cylinders.
- Deflections were generally linear in relation to the loading. Increases in loading showed a proportional increase in deflection. While some creep did occur when the loading was stopped for reading it did stop at the sustained load level. This further

indicates a level of compaction occurring in the stone and some creep from the tire cylinders.

- The deflection in the tire cylinder column compared to the deflection in the steel cylinders which were the subject of Mechanical Concrete® Technical Report No. 1 was significantly greater for comparable loading. This indicates that the vertical deflection of the tires may have played a significant role in the overall deflection.

The test column effectively and safely supported the loads for this test. The sizes of the deflections were within engineering design limits for geotechnical applications. It appears that rubber tire cylinders could have a role in construction of some load bearing columns where live loads are short term and not sustained such as a low volume road bridge abutment. For larger and more sustained loads thin walled steel cylinders would be more effective for containing and integrating the stone aggregates. A Mechanical Concrete® column with *Mechanical Cement®* steel tube cylinders could be designed to meet any generally accepted construction and building codes and specification criteria.

References

1. Joseph G. Sweet and Roger H. L. Chen, Ph.D., *Results of Axial Compression Test of Tire/Aggregate Column,* West Virginia University, Department of Civil and Environmental Engineering, Morgantown, WV June, 2007.