TRC1005

Roller Compacted Concrete for Roadway Pavement

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by

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1. Introduction

Roller-compacted concrete (RCC) pavements are generally described as zero-slump concrete mixtures that are constructed using techniques similar to that of hot-mix asphalt (HMA) pavements. RCC is made up of the same components as traditional concrete mixtures – cementitious materials, water, crushed aggregate, and sand; however, it is a much drier mixture that somewhat resembles damp aggregate. After mixing, the mixture is placed on the roadway using an asphalt paver, and is then compacted using steel-wheel vibratory rollers. RCC is usually constructed without forms, dowels, joints, or reinforcing, and does not require finishing.

RCC has been used for many years for a variety of applications including dams, lumber storage yards, heavy haul roads, loading docks, intermodal port facilities, and parking lots. The most prominent use of RCC has been in dam construction. In fact, RCC has been cited as being the single greatest improvement in recent history to the process of dam construction because of the significant reduction in construction time (ACI Committee 207, 1999). More recently, RCC has received greater consideration for streets, highways, and airport paving.

2. Problem Statement

The rising cost of oil and associated difficulties within the asphalt industry have been a cause for concern in recent years. In effort to combat this problem, several states such as Florida, Alabama, Georgia, and Ohio have used alternative paving materials such as roller compacted concrete (RCC) to replace conventional concrete and/or asphalt on certain types of projects. RCC pavements have been used successfully for a number of years in ports, intermodal facilities, and other areas serving extreme loads; however, the use of RCC technology has only recently been applied to highways. Research is necessary to establish the features of this product, as well as the economic benefits for the State of Arkansas.

RCC is a zero slump concrete mixture. The RCC mixture utilizes the same materials as conventional concrete, but contains less paste. Thus, the mixture is stiff enough to support the weight of a roller during compaction. RCC pavements are constructed without forms, joints, steel reinforcing, or dowels, and do not require finishing. A number of methods for designing RCC mixes are currently available. To date, the industry has not adopted a standard method for these designs. The goals of this research project were to determine whether RCC can be utilized efficiently as an alternative roadway paving material within the State of Arkansas, to identify any associated economic benefits, and to provide a standard RCC mix design procedure that can be implemented within the context of current AHTD specifications.

3. Background and Literature Review

The first RCC pavement in North America was an airport runway at Yakima, Washington, which was constructed in the early 1940s, and a similar type of paving was reported in Sweden as early as the 1930s (ACI, 2001). In 1976, an RCC pavement alternative was presented in British Columbia, Canada. The success of this pavement was followed by several more projects within Canada, and as a result, the U.S. Army Corp of Engineers (USACE) decided to further investigate potential uses of the material. The first full-scale RCC pavement in the U.S. designed and built by the USACE was a 3.75 acre facility at Ft. Hood, Texas, in 1984. The project specified a slab thickness of 10 inches, and the RCC mixture had a flexural strength of 800 psi. Information on specific topics was generated by this project, including maximum aggregate size, single vs. multiple lift construction methods, compaction, curing, and sampling of RCC. This project was determined to be a success and other industries began to incorporate RCC pavements, including the Burlington Northern Railroad intermodal facilities in Houston and Denver, the Port of Tacoma in Washington State, and the Conley and Moran Marine Terminals in Boston, Massachusetts.

Large parking lots have also been paved with RCC. In the late 1980's, a 134-acre area was paved at the General Motors Saturn automobile plant near Spring Hill, Tennessee, and an 89-acre area was placed at Ft. Drum, New York (ACI, 2001). These pavements were 8 and 10 inches thick, respectively, and had compressive and flexural strengths similar to that of traditional concrete pavements. Later, a 207-acre area was placed at the Honda manufacturing facility in Alabama (Adaska, 2008).

The use of RCC for traditional roadway paving has since expanded, and has been implemented by a number of agencies, being used for municipal streets and secondary highways in Portland, Oregon and Columbus, Ohio, as well as a number of Canadian cities. The states of Missouri, Tennessee, South Carolina, Georgia, and Kansas have also used RCC for roadway paving (Kim, 2007, PCA, 2010, and Missouri, 2008).

RCC Materials

In general, the materials used for RCC are the same as those used in conventional concrete mixtures. These materials are coarse aggregate, fine aggregate, cementitious materials (including supplementary cementitious materials such as fly ash, blast furnace slag, and silica fume), and water. However, there are five major differences in the components of RCC as compared to conventional concrete mixtures (ACI, 2001).

1. RCC is generally not air-entrained
2. RCC has a lower water content
3. RCC has a lower paste content
4. RCC requires more fine aggregate to achieve proper compaction
5. RCC aggregates do not exceed a nominal maximum aggregate size (NMAS) of ¾ inch

The aggregates in RCC typically comprise 75 to 85 percent of the volume of the mixture (ACI, 2001, Adaska, 2008). Crushed or uncrushed coarse aggregates may be used, although crushed aggregates are preferred. Uncrushed gravels usually require less water because they tend to naturally provide greater workability, however the increased angularity in crushed stone provides a more stable aggregate skeleton and generates higher flexural strengths. Relative to size, coarse aggregates in RCC should not be larger than ¾ inch. Limiting the size of the aggregate particles helps to reduce segregation and increase the smoothness of the pavement's surface.

A dense, well-graded aggregate blend is considered to provide the best RCC mixture. The recommended gradation is shown in Figure 1 (Harrington, et. al., 2010). In some cases, a single aggregate source meeting this requirement may be used. In most cases, however, a blend of two or more materials may be used to generate the desired gradation. In general, a blend of coarse aggregate (such as size #57 coarse aggregate for concrete mixtures) and fine aggregate (natural or manufactured sand) may be used to meet the recommended RCC blend gradation. Fine aggregates used in RCC pavements may be natural or manufactured, crushed or uncrushed. Crushed screenings are often considered a waste product by the asphalt industry, especially as Superpave mix design procedures have tended to encourage coarser gradations using limited quantities of screenings. Fine aggregate angularity is very important for fine aggregates used in asphalt mixtures because the aggregate skeleton is the primary source of strength and stability for flexible pavements. As a result, natural sands are not recommended. Although RCC pavements depend more upon aggregate interlock than their conventional concrete counterparts, the rigid nature of the paste allows some natural sand to be used without diminishing the structural quality of the RCC pavement (Harrington, et. al., 2010). In addition, a small portion of natural sand helps to improve the workability of the RCC mixture, while also helping to maximize the density of the mixture.

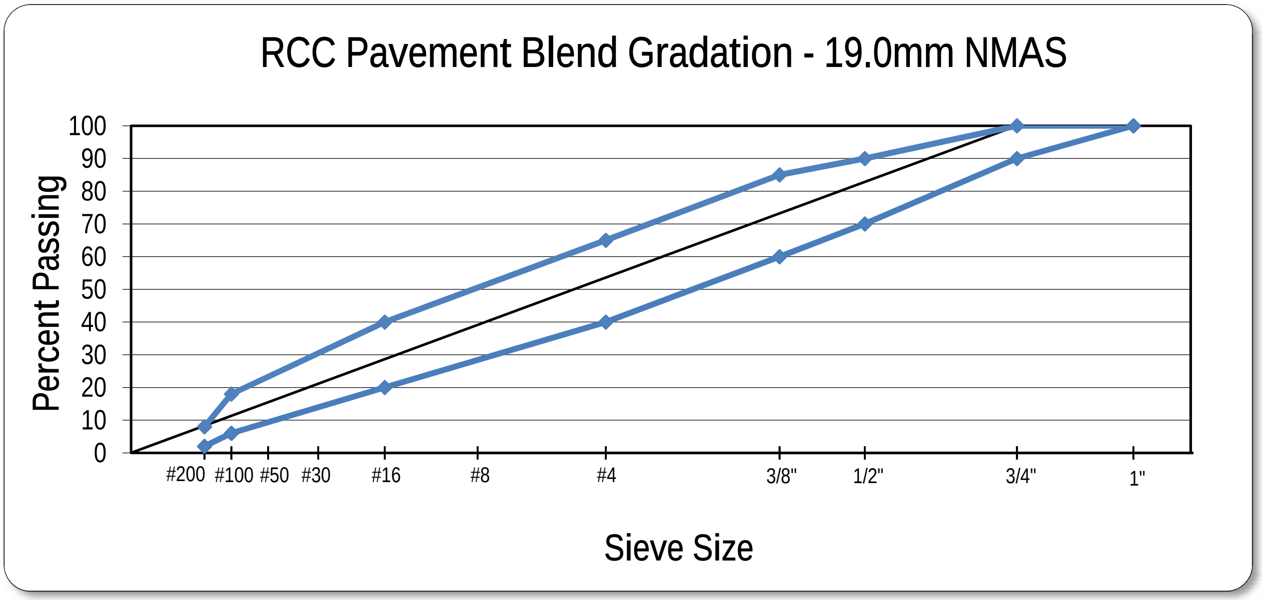

Figure 1. Recommended Aggregate Gradation for RCC Paving Mixtures

The desired strength of the pavement is a deciding factor in determining the type of cementitious material used. Most RCC pavements use Type I or Type II Portland cement. Fly ash may also be used in RCC mixtures; most commonly Class F or Class C fly ash. Fly ash is used to increase the fine material needed to achieve appropriate compaction, and generally provides 15 to 20 percent of the volume of the cementitious material in the RCC mixture.

Admixtures have been used sparingly in RCC mixtures. Air entraining admixtures (AEA) are used in most conventional concrete mixes to improve pavement durability and reduce the detrimental effects of freezing and thawing, but are not required for use in RCC. Most RCC mixtures address frost concerns by proportioning mixtures with a low water cement ratio, which reduces the permeability of the paste. When the pavement is properly compacted, the amount of entrapped air voids decreases and strength increases, providing increased frost resistance. Retarding agents are not typically used in RCC unless a longer set time is required in order for the pavement to be fully compacted. High-range water reducers are rarely used, and are typically dependent upon the percentage of fines passing the No. 200 sieve.

RCC Mixture Design

There are two primary approaches used to proportion RCC mixtures. The first is proportioning by use of soil compaction (modified Proctor) tests, and the second is a consistency or workability approach, which employs proportioning by consistency tests. The most commonly used RCC mix design method is the modified Proctor method, in which an aggregate structure and cement content are chosen, and RCC samples are compacted using a series of moisture contents to develop a Proctor curve. Based on the parabolic relationship of density and moisture content, the optimum moisture content is chosen as that which corresponds with the maximum density (i.e., the peak of the parabola). This portion of the mix design is performed in accordance with AASHTO T 180 or ASTM D1557. After the optimum moisture content is determined, RCC cylinders are prepared using a range of cement contents. The minimum cement content that is capable of generating the desired compressive strength is selected for the design (PCA, 2004, Amer, et. al., 2004).

The proportioning by consistency evaluation has been adopted by the USACE, and is based on the use of an apparatus known as the Vebe table. The Vebe test measures the optimum workability at the required level for strength. In this method, performance parameters are determined for the RCC pavement, and then estimates of mixture proportions are determined from tables and a series of calculations including the paste:mortar ratio. Trial batching completes the process of mixture assessment. This assessment employs the Vebe apparatus, which utilizes a vibrating table and a weighted surcharge to evaluate the workability of the mix as well as the consistency and paste content. The "Vebe time" is recorded as the time required for a ring of paste to become visible around the circumference of the surcharge. Vebe times of 15 to 20 seconds are typical of reasonably workable mixes (Amer, et. al., 2004, ACI 2000). In general, RCC used in dam construction will exhibit lower Vebe times than RCC used in pavements. RCC mixes used in pavements often have Vebe times of greater than 30 seconds, indicating a relatively stiff mixture.

In addition to the Proctor and Vebe design methods, the solid suspension model, the optimal paste volume method, and gyratory compaction have also been considered for the design of RCC. The solid suspension model is a more theoretical approach to design, and involves proportioning the dry solid ingredients to optimize the dry packing density of the mixture. The optimal paste volume method is typically used for large RCC structures, and is based on the idea that RCC mixtures should have a quantity of paste that just fills the void spaces when the aggregate structure has reached its maximum density after compaction.

The gyratory compaction method has been considered because RCC pavements are compacted in a manner similar to that of asphalt pavements, and it is sensible that a similar mixture design method might also prove beneficial. Asphalt pavements are compacted using vibrating and static steel drum rollers, and these rollers provide a kneading action which is somewhat different from the impact action of the Proctor hammer. Therefore, the Proctor density may not be the best representation of the actual achievable density during construction. A similar discrepancy in the asphalt industry was responsible for the shift from the Marshall hammer's impact style of compaction to the gyratory-style of laboratory compaction. The gyratory compaction was believed to more accurately mimic the kneading action of the rollers during field compaction. One shortcoming of RCC methods for producing laboratory specimens is that the lab specimens did not consistently represent or predict actual field performance. In an Alabama study, the gyratory compactor was used to produce RCC test specimens in the laboratory, and it was determined that the gyratory could be used to produce specimens of consistent density and strength (Amer, et. al., 2003). It was estimated that approximately 60 gyrations would produce laboratory RCC specimens that most closely matched field properties of compressive and splitting tensile strength. Further research was then performed to investigate a mix design procedure for RCC using the gyratory compactor (Amer, et. al., 2004). The gyratory compactor was again shown to produce consistent RCC specimens in the laboratory, and a comparison was made between densities derived from the Proctor test and the theoretical maximum constituent density (TMCD), which is defined as the density of the RCC constituent materials if it were possible to remove all air voids from the mixture. TMCD corresponded to approximately 106 percent of the Proctor density. It was also suggested that because the gyratory compactor produces consistent specimens, RCC design procedures could be adjusted to select material proportions based on resulting specimen densities rather than strength. Relationships of density and strength indicated that an increase of 1 to 2 percent in density could result in strength increases of approximately 10 to 17 percent.

RCC Construction

RCC pavements are constructed in a manner much like asphalt pavements. The general process consists of the placement and compaction of a zero-slump concrete mixture where large quantities can be placed rapidly with minimal labor and equipment. When preparing the subgrade/subbase for the placement of RCC pavements, the same requirements must be met as would be expected for conventional concrete. The subbase and subgrade must provide a way to drain excess water from under the pavement to prevent saturation and subsequent problems associated with freeze/thaw cycles. When RCC is placed on top of a subbase, the subbase is saturated to prevent it from “robbing” the moisture from the RCC mixture.

RCC mixtures are typically batched in a continuous mixing pugmill or a rotary drum plant. In some cases, RCC has been mixed in revolving drum mixers as it is transported to the jobsite. The continuous mixing pugmill is used most frequently, and is preferred because it produces adequate mixing efficiency, can be easily constructed on site, and provides a relatively large output capacity.

The placement of RCC is much like that of asphalt pavement construction. In some recent cases, pavers have been modified by adding a tamping bar to the screed to provide additional consolidation. This results in additional compactive effort and can lead to increased smoothness and density of the finished pavement. In some cases, cracks have formed as a result of the extra compactive effort provided by heavy-duty screeds. Although these superficial defects may be removed during the rolling process, care should be exercised when using heavy-duty equipment.

The timing of RCC placement and compaction is critical to the quality of the finished RCC pavement. Placement and compaction should occur while the concrete is still fresh and workable, usually within 45 to 90 minutes of mixing. Thus, proximity of the mixing operation to the jobsite, as well as the consistency and coordination of production and construction speeds are critical to pavement quality. For these reasons, the timing for placement of additional lifts and joint construction techniques are also important.

Compaction of RCC is usually accomplished by use of a 10-ton dual-drum vibratory roller, which immediately follows the paver (ACI, 2001). Two passes in the static mode may be used to “set” the surface before primary compaction is performed in the vibratory mode. Four to six passes of a vibratory roller are usually adequate for achieving the desired 98 percent minimum density (Harrington, 2010). Finish rolling can be accomplished by either a static steel-drum roller or a rubber-tire roller.

Joint construction is probably the most important part of the placement of RCC. Excellent joint construction produces adequate smoothness and density for the RCC pavement structure. Longitudinal joints are constructed parallel to the direction of paving between adjacent lanes, and transverse joints are produced at the ends of the paving lane perpendicular to the direction of paving. Depending on weather conditions, approximately one hour is the maximum time frame for constructing a monolithic bond between lanes. Thus, paving in echelon is the best method for construction. However, this method is not often a practical option due to traffic considerations. Thus, construction joints, or “cold joints” are formed when one lane has hardened to the extent that it can no longer be compacted with the fresh lane. To properly form a cold longitudinal joint, the hardened lane should be sawed to produce a clean vertical face, and the fresh lane should be placed such that it slightly overlaps the hardened lane. Next, the overlap should be raked toward the fresh lane, forming a “hump” at the joint that is compacted by the static roller as it travels along the joint to form a smooth and solid joint.

Curing is important for RCC pavements because of its minimal water content. Moist curing is often used because it aids in the development of design strength, and helps to prevent scaling and reveling of the hardened surface. In some cases, it is recommended that RCC pavements be moist cured and protected from traffic for 7 to 14 days; however, RCC pavements are more commonly opened to traffic after 24 hours. This practice is more desirable because it offers obvious advantages relative to traffic management during construction.

Quality Control/Quality Assurance Testing

During construction of the RCC pavement, quality control and quality assurance (QC/QA) testing is performed by determining a number of properties of the compacted mixture, including gradation, moisture content, density, smoothness, strength, and thickness. The nuclear gauge (in direct transmission mode) is used to measure the in-place density, which is then compared to the Proctor value (maximum density from the mix design) and a minimum of 98 percent compaction is typically required. Another method used to monitor the density of RCC during construction is to place a test strip that can be used as a basis for QC/QA measures of RCC density. This practice is logical in that the compaction achieved in a full-scale test section should truly represent the compaction that can be achieved throughout the project. However, the level of compaction achieved on the test strip is often based on experience, making the quality of the constructed pavement solely a function of the subjective quality and density achieved on the test strip.

RCC Performance

Most references to RCC pavement performance are linked to properties of the surface of the pavement, including items such as surface condition, skid resistance, smoothness, rideability, durability, and load transfer. Surface defects may include joint condition, weathering or raveling, joint sealant damage (if jointed), patched areas, and shattered areas. In general, these distresses result primarily from freeze/thaw damage. In a research study performed by the USACE, these types of distresses were evaluated for 11 sites in the U.S. and Europe. Ratings were assigned based on a 0 to 100 scale, with 0 representing a failed pavement and 100 representing excellent condition. Actual ratings ranged from 44 to 82, and it was concluded that a positive correlation did exist between deteriorating surface conditions and number of freeze/thaw cycles. In general, performance of all sites was good, ranging in status from "fair" to "very good".

Skid resistance is another concern for RCC pavements, particularly in high-speed applications. Because early uses of RCC included heavy-duty industrial applications, speeds were generally low and skid resistance was not a prime consideration. Skid resistance testing of RCC has been done both in the U.S. and in Australia, where poor to marginal test results were obtained (ACI, 2001). The low friction characteristics were attributed to the macrotexture and microtexture of the RCC surface. For conventional concrete surfaces, texture is added to the surface by brooming, dragging, or tining. These surfacing techniques create avenues for water to escape from the pavement's surface during rain events to prevent vehicle hydroplaning. RCC pavements, however, do not include these steps to generate additional skid resistance, and the surface texture is believed to be highly dependent upon mixture proportions and compaction methods.

Smoothness and roughness are also considerations affecting the performance of RCC. Smoothness describes the deviation of the pavement surface from a plane, such that smoother pavements have less deviation. Lack of smoothness is primarily a function of the construction procedure, and has been the primary reason for RCC pavements being limited to low-traffic, low-speed applications. Roughness is a descriptor of the ride sensation felt by a vehicle passenger traveling on the pavement. In limited testing, the roughness of RCC pavements has been deemed unacceptable; however, it has been suggested that with experience, roughness can be reduced and RCC pavements may be acceptable for high-speed wearing surfaces. Diamond grinding is typically used to generate a proper surface, or an additional wearing course, such as a dense-graded HMA mix, may be placed on top of the RCC.

Freeze-thaw durability has been of some concern with respect to RCC pavements. Although very little evidence exists to suggest that RCC is susceptible to freeze-thaw damage, the fact that most RCC is not air-entrained tends to create worry regarding this topic. In a study performed at the U.S. Army Corps of Engineers Waterways Experiment Station (WES), it was determined that RCC mixtures that did not contain AEAs were susceptible to frost damage, and those containing AEAs were not. As a result of this study, it was determined that RCC mixtures could be successfully air-entrained in the laboratory (ACI, 2001). Other studies have reported RCC mixtures to have good resistance to frost damage.

Load transfer is another important consideration in the performance of RCC. Because no load transfer devices are placed in RCC pavements, all load transfer is derived from the aggregate interlock in the mixture. Thus, crack widths critically affect the load transfer capacity of the mixture, and can be expected to vary seasonally. Average crack widths have been reported as 0.05 inches to 0.06 inches (ACI, 2001). Other sources have reported that although cracks may develop within the first few days after paving, they remain tight and are not considered to create performance problems.

In 2007, the results of a study to assess fatigue damage in roller-compacted pavement foundations with recycled aggregate and waste plastic strips were published. The primary measures of performance included repeated-load tests to evaluate the flexural fatigue behavior and the accumulation of fatigue damage in the material. It was determined that the RCC material exhibited levels of performance that were comparable, if not better than, that of HDPE-reinforcement specimens. Results showed that the fatigue strength and endurance were similar to that of typical stabilized pavement foundation materials. It was also determined that the cumulative permanent deformation produced by repeated cyclic loading was directly correlated to the expended fatigue life by a nonlinear power equation, and that the damage accumulation in the recycled alternative material followed Miner's rule for cumulative damage (Sobhan and Mashnad, 2007).

Structural Design of RCC

Because the primary use for RCC pavements originated with heavy-duty haul roads and other industrial applications, many design procedures were developed accordingly, focusing on the heaviest vehicle and number of load repetitions expected on the pavement. Design procedures employing this approach include the Portland Cement Association (PCA) procedure (the RCC-PAVE computer program), and the USACE procedure. The PCA procedure is based on Westergaard's elastic analysis for the mechanical response of a rigid pavement on a subgrade. In this method, the RCC pavement is assumed to be monolithic (even if constructed in multiple lifts), and a conservative design fatigue curve is used for RCC. This method is typically used for pavements serving less than 700,000 load repetitions. The USACE procedure is similar to conventional concrete pavement design, but assumes zero load transfer at joints for RCC. For traditional roadways, the designs must often provide for mixed traffic streams, and require a different approach. Design tables for pavements with mixed traffic are given by the American Concrete Institute (ACI). Specific procedures include the Guide for Design of Jointed Concrete Pavements for Streets and Load Roads (ACI 325.12R-02) and the Guide for the Design and Construction of Concrete Parking Lots (ACI 330R-08). RCC pavements may also be designed using conventional concrete pavement design software such as WinPAS or StreetPave. However, it is recommended that the design reliability level be increased by 5 percent in order to achieve proper results for RCC (Harrington, et. al., 2010). The StreetPave computer program was developed by the American Concrete Pavement Association, and is basically an update to the 1984 PCA design procedure. It can also be used to generate comparable flexible pavement designs using the Asphalt Institute procedure. When using the StreetPave program, material properties are used as input values, although limited data is available regarding the fatigue performance of RCC. One approach for managing this risk is to increase the design reliability in order to increase the conservatism of the design.

For multi-layer pavement systems serving high-speed traffic, the StreetPave or WinPAS programs may be used, but designs of this type are more commonly performed using either 1) the American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures (1993, 1998) or 2) the AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) (Harrington, et. al., 2010). A summary of design procedures and applicable uses is included in Table 1.

	USACE	RCC-Pave	ACI Streets	ACI Parking Lots	StreetPave	WinPAS	AirPave	AASHTO 1993/98	MEPDG
Ports	X	X							
Intermodal Facilities	X	X							
Logging Facilities	X	X							
Heavy Industrial	X	X							
Light Industrial	X	X	X	X	X	X			
Airport Pavements	X	X	X	X	X	X	X		
Arterial Streets			X	X	X	X		X	X
Local Streets			X	X	X	X			
Widening/ Shoulders			X		X	X			
Multi-Layer Systems								X	X

Table 1. Summary of RCC Structural Design Procedures and Uses (ACI, 1999)

Experience with RCC

The Missouri Department of Transportation (MoDOT) began investigating RCC as an alternative material that could be used to combat the rising costs of conventional pavement overlays on low-volume highways in the state (Missouri, 2008). In October of 2008, a 6-inch overlay of RCC was placed on a rural route in Boone County, just south of Columbia. The test section was 2000 feet long and consisted of two 10.5-foot wide lanes. Although the route had low traffic (ADT = 694), an increase in truck traffic was expected after a new overpass was completed nearby. Extensive testing was performed for the test section, including in-place density by the nuclear method, compressive strength of cores, compressive strength of cylinders, rapid chloride permeability of cores, coefficient of thermal expansion (CTE) of cores, freeze/thaw durability of beams sawed from the pavement, thickness of extracted cores, calculated density of cores and cylinders, moisture content on the mixture sampled from the paver, and macrotexture and smoothness of the compacted surface. Initial strength testing results are shown in Table 2.

Compressive Strength Testing Results		
	From Day 1 Construction	From Day 2 Construction
1 day	2030	2765
3 day	3500	3940
7 day	5040	4570
14 day	5240	5465

Table 2. Strength Data From Boone County RCC Project by MoDOT (Missouri, 2008)

The $143,000 overlay was constructed in two days, with traffic allowed on the overlay within 24 hours of placement. Initial findings indicated that the project was successful. However, after two years, performance suffered. Upon closer investigation, it was determined that several factors relating to the construction of the section were to blame for the loss of serviceability. The primary issues included segregation, and a failure to control the water content of the RCC mixture closely enough.

In February 2008, MoDOT began allowing RCC as an optional material for new shoulder construction, but did not formalize a specification for mainline paving (MoDOT, 2008). The shoulder specification requires a specific aggregate gradation, a design compressive strength of at least 3500 psi at 28 days, a minimum water-cement ratio of 0.25, and a minimum cementitious content of 400 pounds per cubic yard. Supplementary cementitious materials are allowed, but do have specific limitations, as shown in Table 3.

Supplementary Cementitious Material (SCM)	
SCM Type	Max.% of Total Cementitious Material
Fly Ash (Class C or Class F)	25
Ground Granulated Blast Furnace Slag (GGBFS)	30
Silica Fume	8
Ternary Combinations	40

Table 3. SCM Requirement from RCC Shoulder Specification by MoDOT (MoDOT, 2008)

MoDOT requires that the RCC be mixed in a mixing plant capable of meeting production rates that are consistent with rates of placement, and that the RCC be placed using a high-density or conventional asphalt-type paver. Vibratory rollers are required for primary compaction, and static steel drum rollers or rubber-tired rollers must be used for finish rolling. The shoulders may be opened to light traffic after 3 days, and to unrestricted traffic after 14 days. Quality control testing includes deleterious content, aggregate gradation, coarse aggregate absorption, thin or elongated pieces, shoulder thickness, and in-place density. The core density is required to be at least 95 percent of the maximum laboratory density, and the core thickness must be at least 90 percent of plan thickness (MoDOT, 2008).

The South Carolina Department of Transportation (SCDOT) also has a specification for RCC pavements, and allows RCC for mainline paving (SCDOT, 2001). The gradation specification is similar to that of MoDOT, but is slightly more restrictive. SCDOT requires a design compressive strength of at least 2000 psi at 3 days and 5000 psi at 28 days. The mixing plant may be a pugmill plant (central plant type) or a rotary drum batch mixer, must be capable of providing a homogenous mixture at a rate consistent with placement, and must be located within a 30-minute haul time of the jobsite. RCC must be placed with an asphalt-type paver that provides a minimum of 90 percent of maximum laboratory density. Subsequent rolling shall provide primary compaction by vibratory steel rollers and finish rolling by either static steel drum or rubber-tired roller, and in-place density shall be not less than 98 percent of maximum laboratory density, tested no more than 30 minutes after rolling has been completed. Lanes may be opened to light traffic after 24 hours, provided the compressive strength of the RCC mixture reaches 2000 psi. Unrestricted traffic is allowed on the pavement after 4 days unless the temperature drops below 40 °F, in which case this time will be extended. Pavement thickness is used as a basis of payment.

South Carolina has been very innovative in implementing various uses of RCC. To date, 10 RCC projects have been successfully completed (Zollinger, 2011). Two notable projects have incorporated RCC, both as the driving surface and as a base in an integrated pavement system (PCA, 2010). The first project was a 4-lane, 1-mile long section of failed asphalt pavement in Aiken, South Carolina. A 10-inch RCC pavement was chosen as the replacement for the failed asphalt roadway because of a desire to provide a long-term solution with minimal traffic disruption and low cost. To generate an acceptable surface for high-speed traffic, the RCC surface was diamond ground. The target International Roughness Index (IRI) for high-speed roadways was 85 inches per mile or less. Prior to grinding, the RCC placed on a weak subgrade had an average IRI of 200 inches per mile, and the RCC placed on a stiff subgrade had an IRI ranging from 100 to 200 inches per mile. After grinding, this value was reduced to 50 to 60 inches per mile, which was well within the target range. The option of diamond grinding was believed to provide considerable cost savings as compared to the use of a HMA overlay for rideability. A savings of approximately $10 per square yard was estimated by SCDOT. Although there have been a few instances of surface raveling, the RCC is considered to be performing well. This project was reported to have an installed cost very similar to a comparable asphalt alternative, but the life-cycle cost of the RCC was estimated to be 30 percent lower over a 50-year analysis period. The construction time was also said to be faster than that of the HMA alternative, cited as 15 days for RCC, and an estimated 33 days for HMA (Zollinger, 2011).

In a second project near Charleston, SCDOT decided to repair a heavily rutted 5-lane section of US78 with a composite pavement system made up of a 10-inch RCC base and a 2-inch asphalt surface. All construction was performed while maintaining at least one open lane at all times to serve the 40,000 AADT with 10 percent truck traffic. The speed of construction was a great advantage for the project, with the asphalt surface being placed in as little as two days after placement of the RCC base.

The Tennessee Department of Transportation (TDOT) first implemented RCC for industrial access roads because of its advantages with respect to construction efficiency and load carrying capacity. Successes were demonstrated in areas where RCC pavements were used to replace failed asphalt pavements that required constant maintenance. In 2001, TDOT drafted a special provision for the use of RCC for mainline paving (Tennessee, 2001). In addition to a gradation specification, the design compressive strength of the mixture must be at least 4000 psi at 28 days. Central batch plants are required for mixing, such that the mixing process generates a homogeneous mixture at a rate that is consistent with the capabilities of the placement equipment. RCC lift thickness is restricted to a minimum of 4 inches and a maximum of 8 inches. The density of each lift is required to be at least 98 percent of the average maximum laboratory density, with no test below 95 percent. Transverse joints may be placed, but are not required. The pavement may be opened to traffic after reaching a minimum compressive strength of 3000 psi.

In 2004, the first usage of RCC on the U.S. interstate system was performed, as the Georgia Department of Transportation used RCC for a 17.3-mile shoulder reconstruction project on Interstate 285 in Atlanta (Kim, 2007). Six-inch and eight-inch thick sections were constructed with minimal interruption to traffic, and both have performed well to date. The mixture was designed using a 0.5-inch maximum aggregate size and a 4000 psi design compressive strength. Field density was required to be at least 98 percent of the maximum wet density (as determined in the laboratory). The RCC mix design is shown in Table 4.

Component	Quantity (lb)	Weight Ratio (%)
Cement	500	12.3
Aggregate	3300	81.2
Water	266	6.5
Total	4066	100.0

Table 4. RCC Mix Design for I-285 Shoulder in Atlanta, Georgia (Kim, 2007)

Extensive testing was performed on the project, with focus placed on density, thickness, and strength. Density measurements were taken at various locations, at five points spaced transversely across the width of the shoulder. The middle portion of the shoulder width exhibited the greatest average wet density. Densities to the left and right of the middle were very close to the middle densities. The density of the left joint section was slightly less than that of the right section, and the density of the right edge had the lowest average value, which was approximately 96 percent of the density in the middle of the shoulder. In terms of variability, the middle showed the least variation and the right edge showed the greatest variation. When comparing the densities of the 6-inch and 8-inch sections, the 8-inch section displayed slightly greater densities.

The compressive strengths of cylinders were tested at five different ages, and the trends of strength gain over time were very similar to that of conventional concrete. The average early strength of cylinders after 4 days was approximately 3000 psi, which surpassed the 2000 psi required for the RCC pavement to be opened to traffic. The average 28-day strength was 4099 psi, and the average core strengths of the middle section were in close agreement with the design strength of 4000 psi. The average core strengths from the left joint and right edge were reasonable – 97 and 89 percent, respectively, of that of the middle section. The average core strength of the 8-inch sections was higher than that of the 6-inch sections. Unfortunately, core strengths and cylinder strengths did not correlate, and only a weak correlation was developed between strength and density.

A performance evaluation was also conducted to determine the presence of shrinkage cracks. Overall, the RCC shoulders were in excellent condition. In the 6-inch sections, only two shrinkage cracks were noted, while 23 shrinkage cracks were noted in the 8-inch sections. The average shrinkage crack width was 1/16 inch and exhibited some minor erosion. The most unpleasant features were noted around the transverse cold joints, where rough surfaces, corner cracks, and spalls were observed. Surface smoothness and skid resistance data were collected, but were adversely affected by the presence of debris and rumble strips that had been previously installed.

The costs associated with the Georgia Interstate shoulder construction were reported to be approximately $8 million, which was slightly higher than that estimated for an equivalent placement of asphalt shoulders. The cost reported for the RCC was $115 per cubic yard, which was compared to a 2004 current asphalt cost of $42 per ton. The asphalt alternative represented an initial cost savings of about 10 percent, which was believed to be easily offset by the savings in long-term maintenance costs.

The Kansas Department of Transportation (KSDOT) has used RCC on one project thus far, where thirty miles of RCC were laid as a base for an asphalt shoulder of a highway. The project was determined to be a success, though the RCC was not jointed, which led to reflective cracking in the asphalt surface. As a result, it was recommended that future RCC pavements be jointed at a spacing of 15 – 20 feet (Harris, 2012).

Other agencies in Kansas have also begun using RCC for roadway paving, using it on roads and streets with and without curb and gutter. Several cities in the Wichita area have used RCC for residential roadways and intersections that had previously experienced shoving failures in the asphalt surface. One of the primary advantages associated with RCC was the quick construction process, which pleased the affected residents. The City of Haysville placed an RCC section in the summer of 2011, and is performing very well with no spalling or surface deterioration.

Additional successful applications of RCC have been documented in Ohio and Nebraska, where RCC has been used as the driving surface on several city street reconstruction projects. Several streets were paved with RCC in Columbus, Ohio, including the reconstruction of Lane Avenue. This route is a major arterial close to the Ohio State University campus, which handles over 30,000 vehicles per day, and had become severely distressed. Local traffic was allowed on the surface as soon as the RCC pavement was constructed to the proper density, and initial performance was positive. In Alliance, Nebraska, collector streets in a residential subdivision were constructed using RCC, and after 11 years, the pavement has performed extremely well with no faulting or surface distress.

4. Project Objectives

The primary objective of this project was to thoroughly evaluate and develop the technologies associated with RCC and to make appropriate recommendations concerning the applicability of incorporating RCC into AHTD Standard Specifications. Specific objectives included:

- *An assessment of current RCC mix design methods*. The available mix design methods were investigated with the intent of determining the particular methods and/or features of the design that were most critical. Focus was placed on the design procedures and their applicability to typical Arkansas aggregate sources
- *An evaluation of the performance of RCC mixtures*. The performance of the mixture is one of the key determinations in the evaluation of RCC mixes. The performance characteristics investigated included compressive strength, density, durability, shrinkage, and texture.
- *A review of existing methods for thickness design of RCC*. A number of mix design methods were available for review, and were used to determine design thicknesses. Comparisons were made to assess the relative thicknesses of alternative pavement sections.
- *A determination of the plausibility of using RCC in Arkansas*. Based on the results determined from the previous objectives, the applicability of using RCC for roadway paving in Arkansas was assessed. Economic factors were considered, and a set of conditions was developed in order to give guidance regarding the situations in which RCC would be appropriate for use.
- *A recommendation regarding the implementation of RCC for roadway paving in Arkansas*. Based on the results of the study, recommendations are provided to facilitate the implementation of RCC for roadway paving. Language for a proposed specification is also included.

The research was performed in two phases. Phase 1 included a thorough review of the existing practices associated with RCC, which were used to formulate preliminary recommendations. A review of AHTD projects was conducted, as well as a thorough comparison of pavement designs for equivalent sections meeting a variety of traffic and soil conditions. Phase 2 included the more intense portion of work, including a laboratory evaluation of RCC mixtures. The results of both phases of work were then used to formulate project conclusions and recommendations.

5. Research Approach and Discussion

When investigating a new technology or material for use in roadway construction, it is important to thoroughly assess its potential for success. Design and performance features should be researched, and potential problems should be anticipated. The first phase of work involved a review of literature and consideration of the plausibility of RCC pavements for the state of Arkansas. Many experiences have pointed toward the successful implementation of RCC pavements in a variety of roadway applications. In concept, RCC pavements offer a number of advantages in terms of cost, performance, and construction time. In light of rising oil costs and the resulting uncertainty in the asphalt industry, RCC stands to provide a viable alternative for affordable highway construction.

Applicability in the Industry

Initial considerations for uses of RCC pavements included overlays, full-depth pavement construction, and shoulder construction. Many sources have cited the successful use of RCC in each of these applications; however, the surface characteristics of RCC may not be adequate for standard use on Arkansas highways. While RCC surfaces can certainly be produced that are acceptable as a riding surface, there are many features of the construction process that can adversely affect surface quality. When the mixture is placed and compacted, the rolling operations are crucial to the appearance of the finished surface. Asphalt roller operators would likely be most experienced at the process of forming a smooth surface, but would probably not have the necessary experience in working with concrete materials. Conversely, a contractor that has experience in forming concrete pavements would have a greater level of comfort with the concrete materials, but would lack the experience in rolling operations. A learning curve would be necessary in order to integrate the talents of various contractors. The reviewed literature clearly suggests that RCC pavement surfaces become more acceptable when construction personnel become more familiar with RCC materials and gain experiences in working with those materials. Thus, it is suggested that, at least initially, contractors selected for building RCC pavements should be those having experience with both asphalt and concrete paving materials, as well as experience in producing and placing RCC.

RCC Contractors in Arkansas

In the review of contractors who typically work in the state of Arkansas, very few were identified as having any recent experience with RCC. APAC Tennessee, Inc., Memphis Division based in Memphis, Tennessee was previously selected to use RCC for a railroad project. In this project, the owner was not familiar with the RCC product, and determined that the appearance of conventional concrete was preferred over RCC. APAC Central, Inc., in Van Buren, Arkansas has also gained some recent experience with RCC. They produced an RCC mix for the construction of a dam spillway in Bunch, Oklahoma. Although APAC produced the mix, the mix design and quality control were performed by Fall Line Testing, Inc. – a consulting company that specializes in RCC for dam construction. Construction operations were also supervised by the consultant. In further discussions with contractors in the state of Arkansas, it was learned that an attempt was made approximately 10 years ago to implement RCC in the northeastern section of the state for private work. The contractor invested time and money in the

RCC concept, but first attempts were unsuccessful. Although future attempts resulted in much greater success, it was felt that the lack of interest in the market did not warrant further investment in the RCC concept.

Feasibility of Constructing RCC Pavements in Arkansas

In order for a new technology to be wisely and successfully implemented, tangible advantages must be identified, which usually involve one or more of the following:

- Cost savings
- Time savings
- Simplification of processes (often resulting in cost or time savings)
- Increase in performance

However, it is also important that realizing savings in one or more of these categories must not inadvertently create a noticeable decrease in performance.

Cost Savings

The potential for cost savings was investigated by generating a series of soil/traffic condition combinations, and developing a number of alternatives for pavement structures that could be used to meet the structural requirements. Then, recent AHTD bid tabulations and weighted averages were reviewed to determine current cost information to estimate the cost of materials for the designed pavement section. The cost summary is given in Table 5, and contains the cost per inch of thickness for one lane-mile (i.e., a 5280-foot long, 12-foot wide, 1-inch thick section) for the given material. It should be noted that all cost estimates are merely estimates, but are based on actual weighted averages from 2008 through 2010 as reported for AHTD projects. It was unknown whether material costs given in the bid tabulations were abnormal due to special project considerations. Material costs, in general, have decreased from 2008 to 2010, and for some materials, a large variation existed from year to year. The costs associated with the cement stabilized base material was based on the sum of the cost of materials (aggregate and cement) per inch of thickness. The processing costs were based on an assumed 6-inch thickness, which was then proportionally applied to one inch of layer thickness. The average cost per inch calculated for RCC was based on aggregate cost estimates plus the cost for cement. The resulting estimate for RCC materials reflects the in-place cost, and is equivalent to approximately $25.00 per square yard for a thickness of 8 inches, which is consistent with that reported by the SCDOT for recent construction, as well as by the Georgia DOT for its 2004 shoulder construction project.

Material	**Component**	**Avg. bid price**	**Cost/inch for lane-mile**
HMA Surface (assume 5.7% AC)	Aggregate	\$54.09 / ton	**\$31,862.76**
	Asphalt Binder	\$548.83 / ton	
HMA Binder (assume 4.5% AC)	Aggregate	\$56.12 / ton	**\$30,189.71**
	Asphalt Binder	\$541.66 / ton	
HMA Base (assume 3.7% AC)	Aggregate	\$59.03 / ton	**\$29,737.67**
	Asphalt Binder	\$539.35 / ton	
Class 7 Base	Aggregate	\$21.23 / ton	**\$7,286.14**
Cement Stabilized Crushed Stone Base (assume 6” thickness)	Aggregate	\$19.53 / ton	**\$15,075.04**
	Cement	\$120.26 / ton	
	Processing	\$5.08 / sq. yd.	
PCC Base	6” Uniform Thickness	\$45.86 / sq. yd.	**\$42,258.02**
	9” Uniform Thickness	\$45.63 / sq. yd.	
	11.5” Uniform Thickness	\$62.25 / sq. yd.	
	13” Uniform Thickness	\$64.42 / sq. yd.	
PCC Pavement	6” Uniform Thickness	\$33.00 / sq. yd.	**\$33,292.67**
	8” Uniform Thickness	\$47.00 / sq. yd.	
	9” Uniform Thickness	\$33.76 / sq. yd.	
	9.5” Uniform Thickness	\$54.00 / sq. yd.	
	10” Uniform Thickness	\$50.65 / sq. yd.	
	12” Uniform Thickness	\$35.00 / sq. yd.	
	13” Uniform Thickness	\$52.09 / sq. yd.	
RCC Base (assume 12% cement)	Aggregate	\$50 / ton	**\$22,047.17**
	Cement	\$120 / ton	

Table 5. Cost Estimates for Various Pavement Material Components

Next, a series of pavement design estimates were performed to assess the overall impacts of these cost estimates. For performing pavement thickness designs, the AASHTO 1993 guide for structural pavement design was used because it is the method currently used by AHTD, and is also a recommended method for the design of multi-layer and composite pavement systems including RCC. A layer coefficient between 0.47 and 0.52 was felt to be appropriate, and a layer coefficient of 0.50 was used for the designs in this exercise. Although several procedures were identified during the literature review, the AASHTO or MEPDG (DARWin-ME or Pavement ME Design) methods are most appropriate for roadways carrying heavier traffic, or multi-layer pavement systems. Because these types of roadways are more typical of state highway routes, the AASHTO design procedure was believed to be most applicable for the pavement sections included in this analysis.

Each of the designs encompassed multiple combinations of soil and traffic conditions, including the following:

- Condition 1: Weak, poorly draining soil and low traffic. A design reliability of 80 percent was used.
- Condition 2: Average soil conditions and low to moderate traffic. A design reliability of 90 percent was used.
- Condition 3: Average Soil and moderately high traffic. A design reliability of 90 percent was used.
- Condition 4: Good, well-draining soil and high traffic. A design reliability of 95 percent was used.
- Condition 5: Average Soil and high traffic. A design reliability of 95 percent was used.
- Condition 6: Weak, poorly draining soil and high traffic. A design reliability of 95 percent was used.
- Condition 7: Very weak, poorly draining soil and moderately high traffic. A design reliability of 95 percent was used.
- Condition 8: Very weak, poorly draining soil and very high traffic. A design reliability of 95 percent was used.

Table 6 provides information regarding the pavement layers and thicknesses, and initial material costs for each alternative. For each condition, six alternatives are provided which are intended to represent a solution for equivalent sections, with each case assuming the same subgrade conditions for the various alternatives. It is noted that multiple alternatives are possible in each case. The six alternatives are:

1) Full-depth HMA
2) HMA over a Class 7 crushed aggregate base
3) HMA over a cement-stabilized crushed stone base (CSB)
4) HMA over a Portland Cement Concrete (PCC) base
5) Portland Cement Concrete Pavement (PCCP) on crushed aggregate base
6) HMA over a Roller-Compacted Concrete (RCC) base

For moderate to heavy traffic volumes, a 4-inch crushed stone subbase layer was included for the HMA over RCC option; however, the additional structural capacity of the subbase was not included in the calculation for design thickness.

Condition		Full-depth HMA	HMA over Class 7 Base	HMA over CSB	HMA over PCC Base	PCC Pvmt over Class 7	HMA over RCC Base
1	Weak Soil Low Traffic	2.5” Surf 4” Binder $200,416	4” Surf 12.5” Cl 7 $218,528	2.5” Surf 10” CSB $230,407	2.5” Surf 6” PCCBase $333,205	7” PCC Pvmt 4” Cl 7 $262,193	2” Surf 6” RCCBase **$196,009**
2	Avg. Soil Low/mod traffic	4” Surf 4” Binder $248,210	2” Surf 4” Binder 6” Cl 7 $228,201	2.5” Surf 9” CSB $215,332	2.5” Surf 6” PCCBase $333,205	8” PCC Pvmt 6” Cl 7 $310,058	2” Surf 6” RCCBase **$196,009**
3	Avg. Soil Mod. Traffic	2” Surf 3” Binder 5” Base $309,983	2” Surf 4.5” Binder 12” Cl 7 $287,013	2” Surf 4” Binder 7” CSB $290,010	4” Surf 8” PCCBase $465,515	10.5” PCC Pvmt 6” Cl 7 $393,290	2” Surf 8” RCCBase 4” Cl 7 **$269,247**
4	Good Soil High Traffic	2” Surf 3” Binder 5” Base $302,983	2.5” Surf 4” Binder 11” Cl 7 $ 280,563	1.5” Surf 4” Binder 7” CSB $274,078	2.5” Surf 7.5” PCCBase $396,592	10.5” PCC Pvmt 9” Cl 7 $415,148	2.5” Surf 7” RCCBase 4” Cl 7 **$263,132**
5	Avg. Soil High Traffic	2.5” Surf 4” Binder 5” Base $349,104	4” Surf 4” Binder 12” Cl 7 $335,644	2” Surf 4” binder 9” CSB $320,160	2.5” Surf 9.5” PCCBase $481,108	11” PCC Pvmt 9” Cl 7 $431,795	2.5” Surf 8.5” RCCBase 4” Cl 7 **$296,202**
6	Weak Soil High Traffic	2.5” Surf 4” Binder 6” Base $378,842	4” Surf 5” Binder 16” Cl 7 $394,978	2.5” Surf 4.5” Binder 12” CSB $396,411	4” Surf 12” PCCBase $634,547	12.5” PCC Pvmt 9” Cl 7 $481,734	2.5” Surf 12” RCCBase 4” Cl 7 **$357,436**
7	Very Weak Soil Mod. Traffic	2.5” Surf 4” Binder 6” Base **$378,842**	4” Surf 6” Binder 13” Cl 7 $403,309	2.5” Surf 4.5” Binder 14” CSB $426,561	2” Surf 4” Binder 10” PCCBase $607,065	13” PCC Pvmt 6” Cl 7 $476,521	2.5” Surf 14” RCCBase 4” Cl 7 $417,462
8	Very Weak Soil Very High Traffic	2.5” Surf 4” Binder 8” Base **$438,317**	4” Surf 8” Binder 12” Cl 7 $456,402	4” Surf 5” Binder 13” CSB $474,375	2” Surf 4”Binder 13” PCCBase $733,839	13.5” PCC Pvmt 12” Cl 7 $536,885	3” Surf 15.5” RCCBase 4” Cl 7 $466,464

Table 6. Cost Estimates for Equivalent Pavement Designs for 8 Soil / Traffic Combinations

In every case except conditions 7 and 8 (very weak soil), the alternative containing RCC was the least expensive option. It should be noted that for full-depth asphalt alternatives on weak and very weak soils, some form of soil stabilization or other type of subbase would likely be necessary; however, the cost for this stabilization was not included in the structural design or the cost estimates. Thus, the actual cost for the RCC alternative of Conditions #7 and #8 could again be the least expensive option. These cost comparisons demonstrate that RCC pavements used as a base material could generate significant monetary savings while providing equivalent structure.

The cost comparisons shown in Table 6 indicate initial material/construction costs, but do not include life-cycle costs. In many cases, the RCC alternative was the least expensive, and the full-depth asphalt alternative was the next most advantageous alternative. Alternatives containing conventional concrete materials were more expensive, but might be chosen based on reduced maintenance needs and long-term performance. Because RCC is a concrete material and possesses similar strengths to that of conventional concrete, many of these same performance advantages could be offered by the RCC alternative while also providing cost efficiency. Thus, RCC has the potential to provide the structure of conventional concrete at a cost similar to that of cement stabilized crushed stone base.

Next, a life-cycle cost analysis (LCCA) was performed to compare the six alternatives for each of the eight soil / traffic conditions. LCCA is important to consider because it incorporates the initial construction costs as well as the costs associated with recurring maintenance and rehabilitation activities for each alternative. In this analysis, deterministic and probabilistic analyses were performed. The deterministic approach results in a fixed, single estimate for the alternative in terms of present value, and does not consider the uncertainty associated with the estimates. The probabilistic approach incorporates a level of uncertainty with each input variable, and increases the potential for accuracy in the estimates. For these probabilistic analyses, a Monte Carlo simulation was used, and input variables were assumed to be normally distributed. A 40-year analysis period and 4 percent discount rate were used for all alternatives. The results of the deterministic analysis are shown in Table 7, and the results of the probabilistic analysis are shown in Table 8. All costs represent one mile of roadway such that high traffic conditions require multiple lanes in each direction.

		Present Value – Agency Cost ($1000)					
Condition		Full-depth HMA	HMA over Class 7 Base	HMA over CSB	HMA over PCC Base	PCC Pvmt over Class 7	HMA over RCC Base
1	Weak Soil Low Traffic	646.93	665.04	676.61	779.41	540.30	513.47
2	Avg. Soil Low/mod traffic	783.02	773.75	796.50	844.88	730.68	557.61
3	Avg. Soil Mod. Traffic	811.17	788.20	790.84	966.35	701.19	636.32
4	Good Soil High Traffic*	1208.41	1225.12	1171.01	1283.40	1089.81	902.44
5	Avg. Soil High Traffic*	1192.43	1178.97	1162.90	1323.84	932.35	891.42
6	Weak Soil High Traffic*	1222.17	1238.31	1239.15	1477.28	982.29	952.66
7	Very Weak Soil Mod. Traffic	880.03	904.50	927.39	1107.89	784.43	784.53
8	Very Weak Soil Very High Traffic*	1281.65	1299.73	1317.11	1576.57	1037.44	1061.68

**Note: For high traffic, multiple lanes are included in the cost estimate.*

Table 7. Life Cycle Cost Analysis – Deterministic Results

		Present Value – Mean Agency Cost ($1000)					
Condition		Full-depth HMA	HMA over Class 7 Base	HMA over CSB	HMA over PCC Base	PCC Pvmt over Class 7	HMA over RCC Base
1	Weak Soil Low Traffic	634.92	654.46	611.38	709.36	601.19	516.12
2	Avg. Soil Low/mod traffic	769.45	762.70	725.17	768.23	787.70	557.74
3	Avg. Soil Mod. Traffic	799.93	778.67	711.13	889.38	764.41	631.68
4	Good Soil High Traffic*	1186.97	1207.81	1048.47	1150.75	1201.09	905.91
5	Avg. Soil High Traffic*	1174.83	1163.28	1037.18	1192.04	1050.55	893.70
6	Weak Soil High Traffic*	1204.05	1221.47	1112.01	1342.62	1099.59	953.64
7	Very Weak Soil Mod. Traffic	869.48	889.75	847.68	1026.05	842.08	775.34
8	Very Weak Soil Very High Traffic*	1262.29	1277.97	1190.13	1438.75	1156.36	1060.81

**Note: For high traffic, multiple lanes are included in the cost estimate.*

Table 8. Life Cycle Cost Analysis – Probabilistic Results

For nearly every set of conditions, the LCCA showed the RCC pavement option to be the least expensive over the analysis period. The exceptions were for the deterministic results for conditions #7 and #8. In condition #7, the RCC and PCC alternatives were nearly identical, and for condition #8, the PCC pavement option was less expensive. User costs should also be considered. Only agency costs are shown in the tables, however user costs are also an important part of the decision making process. User costs refer primarily to the costs associated with delays in the work zone during construction activities. These costs are difficult to define; however, in this case it was felt that the alternatives using RCC would have reduced construction processes and timing, as compared to the concrete pavement option, effectively reducing the relative cost of the RCC pavement alternative.

For concrete pavements and composite pavement structures, design thickness is not the only parameter that must be considered. Surface properties and rideability must be provided for concrete surfaces, and reflective cracking must be considered for concrete pavements with an asphalt surface. Concrete base layers provide the advantage in that a rigid material is better able to span soft spots in the subgrade. Asphalt pavements are flexible, and may be less likely to possess the stiffness necessary to resist subgrade weakness; but, because asphalt pavements are flexible, they do provide a smoother surface without joints, and are often preferred by drivers. Thus, the composite pavement structure of a concrete base and HMA surface would seem to provide the natural advantage. These types of pavement structures struggle with reflective cracking, which is likely the single most detrimental property of composite pavement structures. Reflective cracking is difficult to model, and even more difficult to prevent. The joints in concrete pavement layers, even when sealed, tend to reflect through the HMA surface. This has not, however, been reported to be a significant problem for RCC pavements. RCC pavements experience less shrinkage than conventional concrete pavements because of their low paste content. Also, the method used to compact RCC aids in creating interlock within the aggregate structure, such that load transfer is provided by the aggregates within the mixture. Although minor cracking of RCC pavements has been reported, these cracks tend to remain very tight, and do not adversely affect the ability of the aggregates to provide the needed load transfer. Reflective cracks have been documented for RCC pavements having an asphalt surface; however, these cracks have also been reported as very narrow and do not affect the rideability of the pavement surface.

Time Savings

RCC pavements provide for an efficient construction process, minimizing disruption to traffic, and can be quickly opened to traffic. Thus, RCC pavements are capable of providing many of the structural advantages of concrete pavements, while also possessing a speed of construction similar to that of asphalt. In general, RCC pavements can be opened to traffic as early as 24 hours after placement. This time frame is especially critical for projects in which the RCC serves as the wearing course, but less so for pavement structures employing RCC as a base layer. For RCC pavements with an asphalt wearing course, the HMA surface can be placed within 2 days after placement of the RCC. This is much sooner than for a conventional concrete base. Thus, significant time savings could be generated by the use of RCC pavements. In addition, a 6 to 8 inch lift of RCC can be placed in one pass (8 to 10 inches with a high density paver). A comparable asphalt thickness would be paved in multiple lifts, meaning greater investments in construction time and expense of equipment usage. In fact, one pass of RCC placement typically represents 2 to 3 passes of HMA placement.

Simplification

When compared to conventional concrete pavements, RCC pavements represent a great deal of simplification. RCC pavements do not require forms, steel reinforcing, dowels, joints, or finishing, but provide levels of strength that are similar to conventional concrete pavements. In terms of simplicity of construction, RCC pavements are roughly equivalent to asphalt pavement construction, which is generally considered to be a simpler process than that of conventional concrete. Therefore, RCC pavements do offer the advantage of simplification. In terms of maintenance, RCC requires less frequent planned maintenance. This would simplify the maintenance activities associated with the pavement, but may be less significant if a HMA wearing course were used in the pavement structure.

Performance

Although an alternative paving material may pose a number of advantages, those features are worthless if equivalent or improved performance is not achieved. Long-term pavement performance is the ultimate goal, and other advantages should not be sought at the expense of roadway quality. Based on the literature, all indications are that RCC pavements are structurally sound, are able to resist frost damage, and are good performers. Surface roughness and skid resistance are the characteristics that are most often cited as unacceptable, but this is only a concern for pavements utilizing RCC as the wearing course, and is not cited to be a problem when diamond grinding is used for smoothness and texture. For RCC pavements used as a base course, RCC appears to perform admirably. If used in appropriate situations, RCC should not cause a decrease in pavement performance.

Recommended Uses for RCC

As stated previously, RCC is not currently recommended for use as a wearing course on high-speed roadways. Thus, RCC is not suggested for thin overlay or resurfacing projects unless additional structure is desired for the roadway. However, the advantages relating to cost savings, time savings, simplification, and performance do suggest that RCC could be extremely advantageous in a number of applications. Possible applications include new construction, rehabilitation and reconstruction, notch and widening projects, and intersection rehabilitation jobs. RCC could also be used as an alternative for winterizing a construction project.

New construction and reconstruction. On new construction projects and major rehabilitation projects, it is advantageous to utilize the concept of value engineering, in which multiple alternative designs for a pavement structure are developed in order to compare costs. Then, the most efficient alternative that will provide adequate performance is chosen. Based on the cost estimates provided in Table 6, it is certainly reasonable that RCC could be efficiently used as a base course for new construction projects. RCC is more cost effective than either HMA or conventional concrete. Other states and municipalities have used RCC as a base course in a composite pavement structure, typically using 2 to 3 inches of an HMA surface over 5 to 10 inches of an RCC base course, depending on soil and traffic conditions. If the required RCC thickness is greater than 10 inches, then it is typically placed in two lifts.

Notch-and-widening projects. For projects in which a roadway is to be widened, it can be difficult to provide adequate stability to the subgrade and base of the widened area. Evidence of this phenomenon is often demonstrated by ruts and depressions in the newly constructed areas of the roadway. For example, if a two-lane highway is widened to accommodate a center turn lane or a passing lane, ruts or potholes often develop in the outer wheel paths that are in the area of extended width. RCC provides a rigid base structure that is capable of spanning some weak areas of a subgrade, and is also efficient at resisting rutting. Thus, the long-term performance of pavements on these types of projects could greatly benefit from the use of RCC.

Intersection rehabilitation. Intersections paved with asphalt are prime candidates for experiencing the distresses of rutting and shoving. The acceleration and deceleration of vehicles, combined with slow and standing loads, generate intense forces on intersection pavements. Concrete pavements are often preferred for intersection construction, but are difficult to use in rehabilitation projects due to considerations for interruption of traffic during construction. Because RCC pavements can be constructed much more quickly than conventional concrete pavements, the advantageous properties of concrete (i.e., resistance to rutting and shoving) can be incorporated into intersection rehabilitation projects through the use of RCC. Surfacing should include a rut-resistant asphalt wearing course in order to provide a durable surface with adequate skid resistance.

Special Categories. Special pavement applications can also benefit from the properties and efficiencies of RCC. Rest areas, parking lots, and weigh stations are acceptable applications for RCC. In fact, this type of application is consistent with the more traditional applications of RCC (i.e., industrial loading areas, etc.). In these situations, RCC would be suitable as a surface course because traffic speeds are low and loads can be significant. Thus, pavement smoothness requirements are not as critical. RCC for these uses could present significant cost savings and reduced construction times while providing equivalent structure and performance.

Construction Phasing. Large pavement construction projects are often constructed over a considerable time frame, sometimes two to three years. As a result, seasonal weather conditions can have a significant impact on construction phasing. In recent years, abnormally large rainfall totals have significantly impacted many construction projects, causing delays and other scheduling issues. Because of the rapid placement of RCC, some of these types of issues could be avoided. For example, aggregate base/subbase construction may require stabilization of some sort, which can be a rather lengthy process when the weather conditions are not conducive to steady working schedules. When a base or subbase is prepared and then becomes wet or frozen, additional steps are necessary to bring the material back to proper conditions. If an RCC base were used in place of a stabilized aggregate base, and assuming that the subgrade was properly prepared, the RCC could be placed in a short amount of time, and would then serve to protect the subgrade during subsequent weather events or to “winterize” the project during the winter months when HMA paving is not allowed. In this case, a project could significantly benefit from savings of both money and time.

Review of AHTD Projects

A review of AHTD construction projects for the last 10 years was performed in order to assess the extent to which RCC could be used in Arkansas. Projects from eighteen counties representing all quadrants of the state were evaluated, and those listed in the categories of reconstruction, rehabilitation, major widening, and new location were considered. A summary of project information is given in Table 9, as well as comments pertaining to the potential application of RCC. Of the 219 projects reviewed, a total of 83 were identified as appropriate for RCC use. Although more than 100 projects fit the general conditions for RCC (specifically interstates and passing lanes), not all were included. Interstate rehabilitation projects were eliminated from the list because of the inherent risk associated with applying a new technology to an interstate roadway. Passing lanes were omitted in some cases if the pavement width added was not at least 8 feet, and this was true in several instances where the added lane was split so that half was added to one side of the existing roadway and half was added to the other. Although, RCC can be placed in narrow sections, the pavement width must accommodate appropriate paving and compaction equipment. Since this would create a special situation during the construction process, it was felt that this situation would not be optimal in the early implementation stages of RCC. More projects may have also been appropriate for RCC use, but were eliminated due to unavailable documentation/plans/information. In total, 83 of 219 jobs could have benefitted from the use of RCC, which comprises a little more one-third of all new construction, reconstruction, rehabilitation, and major widening projects.

Job #	County	Description	Length (mi.)	Year Designed	ADT	Design Speed	% Trucks	Pvmt Structure	Comments	Use RCC?
009659	Baxter	Base & Surfacing	na	na	na	na	na	na	Insufficient data	No
090001	Boone	Base & Surfacing	na	na	na	na	na	na	Insufficient data	No
090003	Boone	Base & Surfacing	6.00	2007	10300	60	11	7"Cl7, 5"HMA base, 3"HMA binder, 2"HMA surf		Yes
R70027	Bradley	Base & Surfacing	na	na	na	na	na	na	Insufficient data	No
R50021	Cleburne	Base & Surfacing	na	na	na	na	na	na	Insufficient data	No
110206	Crittenden	Frontage Road	na	na	na	na	na	na	Insufficient data	No
R20010	Ashley	Major Widening	na	na	na	na	na	na	Insufficient data	No
020399	Ashley	Major Widening	2.36	2007	4000	60	10	7.5"Cl7, 4"HMA binder, 2"HMA surf	Notch & Widen	Yes
020322	Ashley	Major Widening	1.24	2007	14350	40	9	6.5"HMA base, 3"HMA binder, 2"HMA surf	Notch & Widen	Yes
020323	Ashley	Major Widening	0.96	2002	5175	38	15	6.5"HMA base, 3"HMA binder, 2"HMA surf	Notch & Widen	Yes
R20010	Ashley	Major Widening	na	na	na	na	na	na	Insufficient data	No
009942	Baxter	Major Widening	0.32	2002	16212	40	5	6"HMA base, 3"HMA binder, 4"HMA surf	Notch & Widen	Yes
090226	Baxter	Major Widening	1.72	2006	8450	45	10	6"Cl7, 4.5"HMA base, 3"HMA binder, 4"HMA susrf	Notch & Widen	Yes
R90092	Baxter	Major Widening	na	na	na	na	na	na	Insufficient data	No
R90093	Baxter	Major Widening	na	na	na	na	na	na	Insufficient data	No
090027	Benton	Major Widening	na	na	na	na	na	na	Insufficient data	No
090165	Benton	Major Widening	0.60	2005	13600	40	7	5"HMA base, 4"HMA binder, 4"HMA surf		Yes
090147	Benton	Major Widening	2.48	2005	6025	40	8	5"HMA base, 3"HMA binder, 2"HMA surf	Notch & Widen	Yes
090148	Benton	Major Widening	3.01	2007	10780	60	10	4"HMA base, 3"HMA binder, 2"HMA surf	Notch & Widen	Yes
090154	Benton	Major Widening	2.99	2006	11100	60	11	4"HMA base, 3"HMA binder, 2"HMA surf	Notch & Widen	Yes
009889	Benton	Major Widening	na	na	na	na	na	na	Insufficient data	No
090064	Benton	Major Widening	5.06	2002	14434	60	15	7"Cl7, 5"HMA base, 3"HMA binder, 4"HMA surf	Notch & Widen	Yes
R90014	Benton	Major Widening	na	na	na	na	na	na	Insufficient data	No
R90072	Benton	Major Widening	2.76	2003	18100	40	13	7"HMA base, 3"HMA binder, 4"HMA surf	Notch & Widen	Yes
090178	Benton	Major Widening	1.58	2007	13600	40	5	5"HMAbase, 4"HMA binder, 2"HMA surf	Notch & Widen	Yes
009985	Benton	Major Widening	3.20	2003	10350	40	10	6.5"HMA base, 3"HMA binder, 4"HMA surf	Notch & Widen	Yes
090179	Benton	Major Widening	2.34	2006	17150	40	9	8"Cl7, 6"HMA binder, 2"HMA surf	Notch & Widen	Yes
009921	Benton	Major Widening	na	na	na	na	na	na	Insufficient data	No
090241	Benton	Major Widening	1.61	2009	29500	40	10	8"HMA base, 3"HMA binder, 2"HMA surf	Notch & Widen	Yes
009947	Boone	Major Widening	na	na	na	na	na	na	Insufficient data	No
R90021	Boone	Major Widening	na	na	na	na	na	na	Insufficient data	No
070077	Bradley	Major Widening	na	na	na	na	na	na	Insufficient data	No
070196	Bradley	Major Widening	0.58	2002	2000	40	12	7"Cl7, 4"HMA binder, 4"HMA surf	Notch & Widening	Yes
171230	Bradley	Major Widening	0.54	2004	4275	40	21	6.5"Cl7, 4"HMA base, 3"HMA binder, 2"HMA surf	Notch & Widening	Yes
070077	Bradley	Major Widening	na	na	na	na	na	na	Insufficient data	No

Job #	County	Description	Length (mi.)	Year Designed	ADT	Design Speed	% Trucks	Pvmt Structure	Comments	Use RCC?
070150	Bradley	Major Widening	3.14	2000	5550	60	20	6”HMA base, 5”HMA binder, 2”HMA surf	Notch & Widening	Yes
070268	Calhoun	Major Widening	3.90	2007	4350	60	19	4”HMA base, 3”HMA binder, 2”HMA surf	Notch & Widening	Yes
R70051	Calhoun	Major Widening	na	na	na	na	na	na	Insufficient data	No
090149	Carroll	Major Widening	2.07	2005	8075	60	9	6”Cl7, 4”HMA base, 3”HMA binder, 2”HMA surf	Notch & Widening	Yes
090229	Carroll	Major Widening	1.67	2008	8200	60	9	9”Cl7, 4.5”HMA binder, 4”HMA surf	Notch & Widening	Yes
020239	Chicot	Major Widening	5.75	2001	7808	60	13	6”CTB, 5”HMA base, 5”HMA binder, 2”HMA surf	Notch & Widening	Yes
020426	Chicot	Major Widening	2.28	2010	9300	55	23	6”CTB, 5”HMA base, 3”HMA binder, 2”HMA surf	Notch & Widening	Yes
R20095	Chicot	Major Widening	na	na	na	na	na	na	Insufficient data	No
R20096	Chicot	Major Widening	na	na	na	na	na	na	Insufficient data	No
070180	Clark	Major Widening	0.45	2003	11950	40	6	6”HMA base, 3”HMA binder, 2”HMA surf	Notch & Widening	Yes
050175	Cleburne	Major Widening	0.77	2009	15500	30	3	6”PCCBase, 2”HMA surf	Notch & Widening	Yes
070177	Columbia	Major Widening	0.63	2004	4720	30	13	6.5”HMA base, 3”HMA binder, 2”HMA surf	Notch & Widening	Yes
100136	Craighead	Major Widening	na	na	na	na	na	na	Insufficient data	No
100303	Craighead	Major Widening	3.68	2005	10300	60	11	8”HMA base, 3”HMA binder, 2”HMA surf	Notch & Widening	Yes
100306	Craighead	Major Widening	2.60	2005	9400	60	18	6”Cl7, 4”HMA base, 3”HMA binder, 2”HMA surf	Notch & Widening	Yes
100312	Craighead	Major Widening	na	na	na	na	na	na	Insufficient data	No
100212	Craighead	Major Widening	4.35	2001	11972	60	7	6.5”HMA base, 4”HMA binder, 4”HMA surf	Notch & Widening	Yes
100194	Craighead	Major Widening	na	na	na	na	na	na	Insufficient data	No
R00081	Craighead	Major Widening	na	na	na	na	na	na	Insufficient data	No
R00020	Craighead	Major Widening	na	na	na	na	na	na	Insufficient data	No
100611	Craighead	Major Widening	3.29	2006	6730	60	8	6”Cl7, 4”HMA base, 3”HMA binder, 2”HMA surf	Notch & Widening	Yes
100454	Craighead	Major Widening	3.00	2001	9700	40	13	6”HMA base, 4”HMA binder, 4”HMA surf	Notch & Widening	Yes
100417	Craighead	Major Widening	2.73	2002	16099	40	9	6.5”HMA base, 4”HMA binder, 4”HMA surf	Notch & Widening	Yes
100461	Craighead	Major Widening	3.41	2002	9743	45	8	6.5”HMA base, 4”HMA binder, 4”HMA surf	Notch & Widening	Yes
100293	Craighead	Major Widening	na	na	na	na	na	na	Insufficient data	No
100294	Craighead	Major Widening	2.99	2001	11550	60	19	7.5”HMA base, 4”HMA binder, 4”HMA surf	Notch & Widening	Yes
100642	Craighead	Major Widening	3.93	2010	2500	60	20	9”Cl7, 4.5”HMA binder, 4”HMA surf	Notch & Widening	Yes
040290	Crawford	Major Widening	0.96	2003	16600	40	5	5”HMA base, 3”HMA binder, 2”HMA surf	Notch & Widening	Yes
040226	Crawford	Major Widening	na	na	na	na	na	na	Insufficient data	No
110225	Crittenden	Major Widening	na	na	na	na	na	na	Insufficient data	No
110337	Crittenden	Major Widening	5.76	2004	10100	60	14	6”CTB, 4.5”HMA base, 3”HMA binder, 4”HMA surf	Notch & Widening	Yes
110303	Crittenden	Major Widening	na	na	na	na	na	na	Insufficient data	No
110173	Crittenden	Major Widening	na	na	na	na	na	na	Insufficient data	No
110342	Crittenden	Major Widening	1.52	2005	4940	30	10	10”Cl7, 4”HMA binder, 4”HMA surf	Notch & Widening	Yes
110505	Crittenden	Major Widening	0.84	2010	7600	40	39	8”Cl7, 5”HMA base, 4”HMA binder, 4”HMA surf	Notch & Widening	Yes

Job #	County	Description	Length (mi.)	Year Designed	ADT	Design Speed	% Trucks	Pvmt Structure	Comments	Use RCC?
110506	Crittenden	Major Widening	2.24	2009	7800	60	39	8”Cl7, 5”HMA base, 4”HMA binder, 4”HMA surf	Notch & Widening	Yes
110070	Crittenden	Major Widening	na	na	na	na	na	na	Insufficient data	No
R70123	Bradley	Widening	1.91	2001	1350	52	25	8.5”HMA base, 3”HMA binder, 2”HMA surf	Notch & Widening	Yes
020325	Arkansas	New Location	2.51	2004	2165	55	25	6.5”Cl7, 6”HMA base, 3”HMA binder, 2”HMA surf		Yes
R20077	Arkansas	New Location	na	na	na	na	na	na	Not used	No
R90081	Baxter	New Location	na	na	na	na	na	na	Insufficient data	No
090099	Benton	New Location	0.83	2006	4996	40	10	5”HMA base, 3”HMA binder, 4”HMA surf		Yes
070034	Bradley	New Location	na	na	na	na	na	na	Insufficient data	No
070117	Bradley	New Location	na	na	na	na	na	na	Insufficient data	No
070049	Calhoun	New Location	na	na	na	na	na	na	Insufficient data	No
R20080	Chicot	New Location	na	na	na	na	na	na	Insufficient data	No
100134	Clay	New Location	na	na	na	na	na	na	Insufficient data	No
100240	Clay	New Location	na	na	na	na	na	na	Insufficient data	No
001934	Cleveland	New Location	9.65	2007	20100	70	20	8”Cl7, 7”HMA base, 4”HMA binder, 2”HMA surf	New	Yes
R70053	Columbia	New Location	na	na	na	na	na	na	Insufficient data	No
R70074	Columbia	New Location	na	na	na	na	na	na	Insufficient data	No
080113	Conway	New Location	1.24	2003	2450	40	6	8.5”Cl7, 4”HMA binder, 2”HMA surf	New Construction	Yes
100661	Craighead	New Location	0.29	2008	6970	40	7		Too short for RCC	No
100662	Craighead	New Location	0.18	2009	7080	40	7		Too short for RCC	No
100444	Craighead	New Location	3.31	2002	11875	60	19	7”Cl7, 5”HMA base, 4”HMA binder, 4”HMA surf	New Construction	Yes
110233	Crittenden	New Location	na	na	na	na	na	na	Insufficient data	No
110251	Crittenden	New Location	1.37	2007	9000	40	20	8”Cl7, 10”PCC	New Construction	Yes
110284	Crittenden	New Location	na	na	na	na	na	na	Insufficient data	No
110285	Crittenden	New Location	na	na	na	na	na	na	Insufficient data	No
110096	Crittenden	New Location	na	na	na	na	na	na	Insufficient data	No
110154	Crittenden	New Location	na	na	na	na	na	na	Insufficient data	No
020339	Ashley	Passing Lanes	3.53	2005	4300	55	15	4”HMA base, 4”HMA binder, 3”HMA surf	Passing Lane	No
020415	Ashley	Passing Lanes	3.64	2006	4370	55	21	6”Cl7 base, 3”HMA binder, 2”HMA surf	Passing Lane	No
070197	Bradley	Passing Lanes	3.08	2002	1300	55	34	8.5”HMA base, 3”HMA binder, 2”HMA surf	Widening	No
090167	Carroll	Passing Lanes	1.17	2004	2930	55	9	9”Cl7, 4”HMA binder, 2”HMA surf	Passing lanes	Yes
090202	Carroll	Passing Lanes	na	na	na	na	na	na	Insufficient data	No
R00084	Clay	Passing Lanes	na	na	na	na	na	na	Insufficient data	No
R00119	Clay	Passing Lanes	2.42	2001	1350	55	24	7.5”HMA base, 3”HMA binder, 2”HMA surf	Passing lane	Yes
050067	Cleburne	Passing Lanes	5.52	2002	3100	55	18	6”Cl7, 4”HMA binder, 2”HMA surf	Notch & Widening	Yes
050039	Cleburne	Passing Lanes	2.37	2006	4330	55	10	8”Cl7, 4.5”HMA binder, 2”HMA surf	Passing Lane	No

Job #	County	Description	Length (mi.)	Year Designed	ADT	Design Speed	% Trucks	Pvmt Structure	Comments	Use RCC?
R70095	Cleveland	Passing Lanes	na	na	na	na	na	na	Insufficient data	No
R70107	Cleveland	Passing Lanes	na	na	na	na	na	na	Insufficient data	No
070204	Cleveland	Passing Lanes	3.72	2002	3500	55	14	7”Cl7, 6.5”HMA base, 3”HMA binder, 2”HMA surf	Passing Lane	Yes
001942	Cleveland	Passing Lanes	7.8	2004	5245	60	20	6”Cl7, 4”HMA base, 3”HMA binder, 2”HMA surf	Passing Lane	Yes
RX0028	Cleveland	Passing Lanes	8.17	2002	5150	55	17	7”Cl7, 5.5”HMA base, 3”HMA binder, 2”HMA surf	Passing Lane	Yes
070301	Columbia	Passing Lanes	2.47	2010	3300	55	12	8.5”Cl7, 4.5”HMA binder, 2”HMA surf	Notch & Widening	Yes
RX0027	Columbia	Passing Lanes	10.14	2002	5500	55	21	9.5”HMA base, 3”HMA binder, 1.5”HMA surf	Notch & Widening	Yes
100526	Craighead	Passing Lanes	5.03	2001	8850	60	12	7”HMA base, 3”HMA binder, 2”HMA surf	Passing Lanes	Yes
110409	Crittenden	Passing Lanes	1.99	2001	6200	55	24	6”Cl7, 4”HMA base, 3”HMA binder, 4”HMA surf	Passing Lane	Yes
110334	Crittenden	Passing Lanes	2.9	2001	6200	55	24	6”Cl7, 4”HMA base, 3”HMA binder, 4”HMA surf	Passing Lane	Yes
FA0106	Arkansas	Reconstruction	na	na	na	na	na	na	Inaccessible data	No
FA0107	Arkansas	Reconstruction	1.18	2007	130	40	8	7”Cl5 agg base, 2”HMA surf		Yes
SA0127	Arkansas	Reconstruction	1.40	2001	305	40	10	8.5”Cl7 agg base, 2”HMA surf		Yes
001701	Arkansas	Reconstruction	7.9km	1999	2850	100km/hr	17	Cl7 base, 6”HMA base, 3”HMA binder, 2”HMA surf	Metric Job	Yes
R20081	Arkansas	Reconstruction	na	na	na	na	na	na	Overlay?	No
FA0210	Ashley	Reconstruction	na	na	na	na	na	na	Overlay?	No
001941	Ashley	Reconstruction	7.51	2004	1700	53	11	Cl7 base, 6.5”HMA base, 3”HMA binder, 2”HMA surf	Narrow sections	No
R20021	Ashley	Reconstruction	na	na	na	na	na	na		No
020241	Ashley	Reconstruction	1.45	2001	7700	30	18	10”HMA base, 3”HMA binder, 2”HMA surf		Yes
FA0311	Baxter	Reconstruction	1.64	2000	340	30	7	7”Cl7 base, 2”HMA surf	Low Volume	Yes
009973	Baxter	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R90029	Baxter	Reconstruction	na	na	na	na	na	na	Insufficient data	No
009984	Benton	Reconstruction	na	na	na	na	na	na	Insufficient data	No
009612	Benton	Reconstruction	na	na	na	na	na	na	Insufficient data	No
009956	Benton	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R90025	Benton	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R90026	Benton	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R90027	Benton	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R90056	Benton	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R90050	Benton	Reconstruction	na	na	na	na	na	na	Insufficient data	No
FA0615	Bradley	Reconstruction	1.31	2003	120	40	11	7”Cl7 base, 2”HMA surf in future	Low Volume	Yes
FA0616	Bradley	Reconstruction	1.14	2004	330	40	22	Cl1 base, HMA surf in future	Low Volume	Yes
FA0619	Bradley	Reconstruction	1.17	2008	330	40	22	Cl1 base, HMA surf in future	Low Volume	Yes
FA0620	Bradley	Reconstruction	0.79	2009	330	40	22	Cl1 base, HMA surf in future	Low Volume	Yes
001941	Bradley	Reconstruction	7.51	2004	1700	53	11	7”Cl7, 7”HMA base, 3”HMA binder, 2”HMA surf	Notch & Widen	Yes

Job #	County	Description	Length (mi.)	Year Designed	ADT	Design Speed	% Trucks	Pvmt Structure	Comments	Use RCC?
007714	Bradley	Reconstruction	na	na	na	na	na	na	Insufficient data	No
007715	Bradley	Reconstruction	na	na	na	na	na	na	Insufficient data	No
090098	Carroll	Reconstruction	0.42	2001	8080	na	4	6"Cl7, 9"PCCP (non-reinforced)	New roadway	Yes
090081	Carroll	Reconstruction	na	na	na	na	na	na	Insufficient data	No
090092	Carroll	Reconstruction	0.39	2002	8080	na	5	6"Cl7, 9"PCCP (non-reinforced)	New roadway	Yes
R90017	Carroll	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R90028	Carroll	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R90104	Carroll	Reconstruction	5.09	2005	4400	55	20	7"Cl7, 5"HMA base, 3"HMA binder, 2"HMA surf	Passing lanes	Yes
070141	Clark	Reconstruction	na	na	na	na	na	na	Insufficient data	No
070215	Clark	Reconstruction	3.26	2004	1500	54	9	6"HMA base, 3"HMA binder, 2"HMA surf	Notch & Widening	Yes
070063	Clark	Reconstruction	na	na	na	na	na	na	Insufficient data	No
070064	Clark	Reconstruction	2.84	2001	1550	54	15	7"HMA base, 3"HMA binder, 2"HMA surf	Notch & Widening	Yes
070052	Clark	Reconstruction	na	na	na	na	na	na	Insufficient data	No
070245	Clark	Reconstruction	4.71	2005	1385	55	14	10"HMA base, 2"HMA surf		Yes
100528	Clay	Reconstruction	1.84	2010	50	30	3	7"Cl7 base, 2"HMA surf	Low Volume	Yes
R00125	Clay	Reconstruction	na	na	na	na	na	na	Insufficient data	No
100316	Clay	Reconstruction	na	na	na	na	na	na	Insufficient data	No
070067	Cleveland	Reconstruction	na	na	na	na	na	na	Insufficient data	No
008895	Conway	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R80070	Conway	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R00041	Craighead	Reconstruction	na	na	na	na	na	na	Insufficient data	No
040233	Crawford	Reconstruction	na	na	na	na	na	na	Insufficient data	No
040293	Crawford	Reconstruction	0.63	na	na	na	na	12"Cl7, 6"HMA binder, 3"HMA surf	Too short for RCC?	No
040351	Crawford	Reconstruction	0.78	2006	140	40	3	10"Cl7, 2"HMA surf	Too short for RCC?	No
FA1708	Crawford	Reconstruction	na	na	na	na	na	na	Insufficient data	No
FA1709	Crawford	Reconstruction	1.04	2003	1300	40	13	7"Cl7, 2"HMA surf	Total reconstruct	Yes
FA1710	Crawford	Reconstruction	0.85	2005	1200	40	7	7"Cl7, 2"HMA surf	Total reconstruct	Yes
R40014	Crawford	Reconstruction	na	na	na	na	na	na	Insufficient data	No
040206	Crawford	Reconstruction	na	na	na	na	na	na	Insufficient data	No
040207	Crawford	Reconstruction	na	na	na	na	na	na	Insufficient data	No
040149	Crawford	Reconstruction	1.72	2000	290	40	6	7"Cl7, 2"HMA surf		Yes
110121	Crittenden	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R10008	Crittenden	Reconstruction	na	na	na	na	na	na	Insufficient data	No
110467	Crittenden	Reconstruction	0.69	2004	2700	40	35	12"CTB, 6"HMA base, 4"HMA binder, 2"HMA surf	Too short for RCC?	No
110522	Crittenden	Reconstruction	0.62	2009	6000	30	5	6"lime st. sub, 5" asph. Stab base, 9"PCC	Too short for RCC?	No

Job #	County	Description	Length (mi.)	Year Designed	ADT	Design Speed	% Trucks	Pvmt Structure	Comments	Use RCC?
110492	Crittenden	Reconstruction	1.26	2006	37200	65	26	6”CSB, 1”HMA surf, 14”PCC	High-Vol Road	No
110153	Crittenden	Reconstruction	na	na	na	na	na	na	Insufficient data	No
R10046	Crittenden	Reconstruction	na	na	na	na	na	na	Insufficient data	No
020494	Arkansas	Rehabilitation	3.11	na	na	na	na	Cold mill & 2” overlay	Overlay	No
020380	Arkansas	Rehabilitation	3.07	2004	na	na	na	6”CTB, 6.5”HMA base, 3”HMA binder, 2”HMA surf		Yes
020493	Ashley	Rehabilitation	na	na	na	na	na	na	Overlay?	No
020240	Ashley	Rehabilitation	12.66km	1999	4600	90km/hr	10	4”HMA base, 3”HMA binder, 2”HMA surf	Metric job	Yes
090266	Benton	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
090267	Boone	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
070057	Bradley	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
070332	Calhoun	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
090048	Carroll	Rehabilitation	0.54	2000	7600	na	4	6”Cl7, 9”PCCP (non-reinforced)	New roadway	Yes
090052	Carroll	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
020492	Chicot	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
B70100	Clark	Rehabilitation	5.76	2002	24900	70	54	HMA over rubblized PCC	Interstate Rehab.	No
B70101	Clark	Rehabilitation	6.18	2000	21000	70	54	HMA over rubblized PCC	Interstate Rehab.	No
B70102	Clark	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
BX0100	Clark	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
BX0102	Clark	Rehabilitation	7.88	2002	26900	70	49	HMA over rubblized PCC	Interstate Rehab.	No
RX0007	Clark	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
100692	Clay	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
050204	Cleburne	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
070331	Cleveland	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
B80101	Conway	Rehabilitation	6.61	2001	25450	70	36	HMA over rubblized PCC	Interstate Rehab.	No
B80102	Conway	Rehabilitation	5.81	2000	31350	70	28	HMA over rubblized PCC	Interstate Rehab.	No
B80106	Conway	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
B80107	Conway	Rehabilitation	5.29	2001	32400	70	28	HMA over rubblized PCC	Interstate Rehab.	No
100588	Craighead	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
100697	Craighead	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
R40011	Crawford	Rehabilitation	9.07	na	na	na	na	na	Interstate Rehab	No
B40100	Crawford	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
B40102	Crawford	Rehabilitation	9.82	2002	29000	70	35	HMA over rubblized PCC	Interstate Rehab	No
B40105	Crawford	Rehabilitation	7.38	2001	24900	70	25	HMA over rubblized PCC	Interstate Rehab	No
040543	Crawford	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
110252	Crittenden	Rehabilitation	na	na	na	na	na	na	Insufficient data	No

Job #	County	Description	Length (mi.)	Year Designed	ADT	Design Speed	% Trucks	Pvmt Structure	Comments	Use RCC?
B10101	Crittenden	Rehabilitation	2.15	2000	36450	65	47	6"Cl7, 4"Op-Gr Base, 13" PCC	High-Vol Road	No
B10103	Crittenden	Rehabilitation	12.75	2001	36000	70	44	6"PCCBase, 6.5"HMA base, 3"HMA binder,4"HMA surf	High-Vol Road	No
B10106	Crittenden	Rehabilitation	2.97	2003	41500	65	34	6"Cl7, 6"CSB, 1"HMA surf, 14"PCC	Interstate Rehab	No
B10107	Crittenden	Rehabilitation	7.99	2002	29300	70	34	4"HMA binder, 2"HMA surf	Resurfacing	No
B10108	Crittenden	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
BX0101	Crittenden	Rehabilitation	11.98	2001	29600	70	32	HMA over rubblized PCC	Interstate Rehab	No
110521	Crittenden	Rehabilitation	na	na	na	na	na	na	Insufficient data	No
R20097	Chicot	Tourist Info Ctr	2.64	2005	8950	40	9	6"CTB, 5"HMA base, 3"HMA binder, 2"HMA surf	Notch & Widening	Yes
090131	Benton	na	na	na	na	na	na	na	Insufficient data	No

Table 9. Summary of AHTD Projects Reviewed for RCC Use

Conclusions Regarding Feasibility of RCC

In the first phase of the project, RCC features were identified that would be advantageous to AHTD, and highlights of the experiences of other agencies with respect to the implementation of this material were documented. Estimated costs were developed for the purpose of comparing pavement sections composed of a variety of paving materials. In nearly every case, the RCC alternative demonstrated the lowest initial material costs, while providing adequate structure for a given set of performance conditions.

RCC is not recommended for all pavement applications. Specifically, evidence exists which suggests the potential for less than desirable features when RCC is used as a surface course on high-speed roadways unless diamond grinding is used. Although many of these issues can be overcome through experience and familiarity, it is recommended that the initial use of this material be restricted to sub-surface pavement layers or used for roadways with low to medium traffic levels. Specific applications that could benefit most from the advantages of RCC include:

- Wearing course for new construction, reconstruction, or rehabilitation (only if diamond-ground)
- Base course for new construction, reconstruction, or rehabilitation
- Base material for notch and widening projects
- Base course for intersection rehabilitation
- Rest areas
- Parking areas
- Weigh stations
- Construction Staging

By combining the procedural efficiencies of the asphalt paving process with the structural advantages of concrete materials, the review indicated that RCC pavements present a viable alternative with significant economic benefits for roadway construction.

PHASE 2 – LABORATORY INVESTIGATION OF RCC

In the second phase of the project, a laboratory study was conducted to assess RCC mix design methods and mixture performance. The first portion of the investigation involved a consideration of the available mix design methods. Of the methods reviewed in the literature review, two were identified as most commonly used for RCC – the Vebe and Proctor methods. Of these methods, the Vebe method is most often used for RCC in dam construction, while the Proctor method is most commonly used to design roadway paving RCC mixes. The Proctor method is based on traditional methods used for soil and cement products, which is believed to be more appropriate for roadway applications. Thus, the Proctor method was chosen for further investigation. However, the process used to construct RCC pavements is most like that for asphalt pavements. Thus, it seemed reasonable that laboratory design methods should also possess similarities to the design of asphalt mixtures. It was previously noted that one of the difficulties associated with RCC mixtures was the lack of consistency between laboratory and field constructed specimens with regard to expected performance. The Superpave Gyratory Compactor used to design asphalt mixes was developed in an effort to mimic the compaction process for asphalt pavements. Since RCC mixes are compacted like asphalt mixes in the field, the design of RCC mixtures could also significantly benefit from the use of this device during the mix design process. Gyratory compaction was the second design method included in the study.

Four aggregate sources from within the state of Arkansas were used in the laboratory portion of this study. These sources represented the mineral types that are typical of roadway construction in the state, including sandstone, limestone, syenite, and dolomite. The locations of each source are shown in Figure 2.

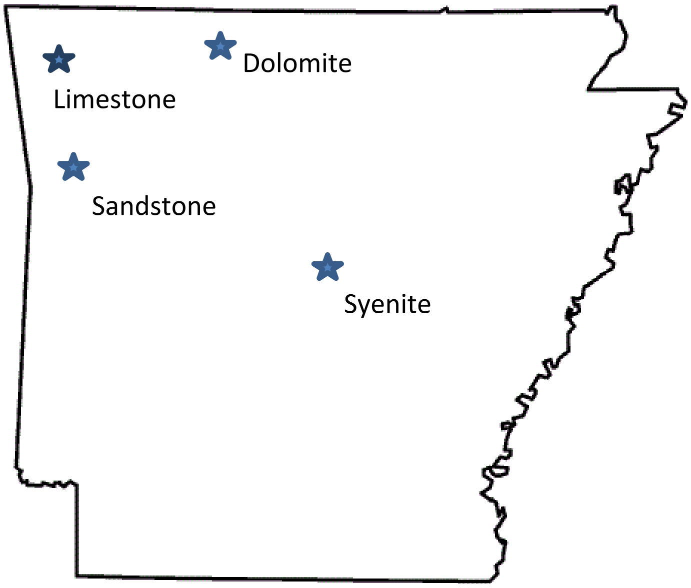

Figure 2. Location of Aggregate Sources

The Proctor Design Method

For RCC designed by the Proctor method, ASTM D 1557 (AASHTO T 180) is usually specified, which is the Modified Proctor method. For this type of design, an aggregate structure and trial cement content are chosen, and RCC samples are compacted using a series of moisture contents to develop the 'Proctor' curve. Based on the parabolic relationship of density and moisture content, the optimum moisture content is chosen as that which corresponds with the maximum dry density (i.e., the peak of the parabola). After the optimum moisture content is determined, RCC cylinders are prepared using a range of cement contents. The minimum cement content that is capable of generating the desired compressive strength is selected, and the optimum moisture content is then verified (or adjusted) for that cement content. In Figure 3, an example of an RCC mix design by the Proctor method is shown. In this illustration, the proctor compaction relationship formed a typical parabolic shape such that the optimum moisture content was approximately 7.3 percent, and the corresponding maximum dry density was 141 pcf. The strength relationship is such that increasing the cement content increases the compressive strength. For a target design strength of 4500 psi, a cement content of approximately 14 percent would be selected.

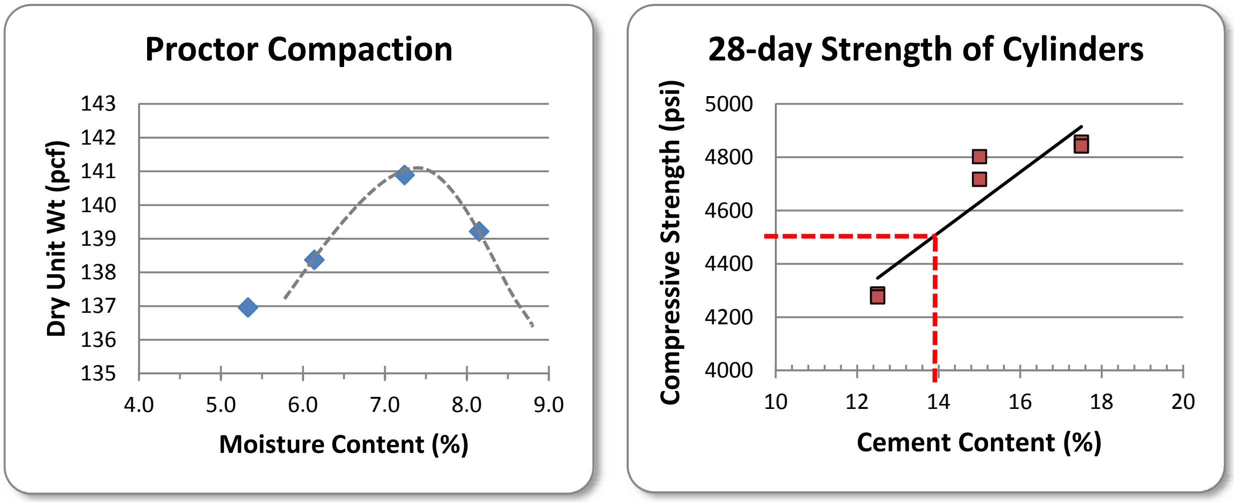

Figure 3. Sample RCC Mix Design by the Proctor Method

Gradation

Compressive strength is the primary design factor for conventional concrete mixes, however the performance of an RCC mixture is largely assessed by its density. Mixture density is greatly affected by the gradation and workability of the mixture, making the blend gradation of an RCC mixture a critical design factor. Conventional concrete mixtures are often gap-graded, including a source of coarse aggregate and a source of fine aggregate, but lesser amounts of middle-sized aggregate. RCC, however, contains less paste than conventional concrete, making the aggregate structure of the mix an even more important feature of the design process. For this reason, a number of gradation design methods were investigated.

Conventional concrete mixes have often been designed using individual gradation specifications for coarse aggregate and fine aggregate. However, little emphasis was placed on the interactions of these aggregates, as the gradation of the entire aggregate blend was not considered. This does not allow for the optimization of the mixture's blend gradation. However, Shilstone stated that the combined gradation curve for the blend of aggregates was much more important than the aggregate source (Shilstone, 1990), and revolutionized the methods for optimizing concrete mixtures. Following similar principles, the 0.45 power chart has been used for many years and was developed for the purpose of determining the ideal combined gradation for asphalt mixtures. On this chart, a straight line from the origin to 100 percent passing the maximum aggregate size is called the maximum density line (MDL), and represents the densest gradation possible for the aggregate blend. In order to optimize the concrete aggregate combination, the gradation curve should closely follow the MDL, although this sometimes results in excessive sand content. Most guidance available regarding the Shilstone method is intended for conventional concrete mixtures, and may or may not be appropriate for RCC.

The Shilstone method is similar to procedures used for designing aggregate blends in asphalt mixtures. The asphalt industry also uses the 0.45 power chart and MDL, but specifies a set of control points between which the blend gradation must pass. In order to meet the volumetric requirements for asphalt mixtures, it is often recommended that the blend gradation not follow the MDL too closely, and that a somewhat coarse gradation can often be beneficial. The strength of an asphalt mixture depends heavily upon the strength of the aggregate interlock. Since RCC has a low paste content and the aggregate structure is an important feature, these same principles may apply. Thus, the aggregate gradation requirements for asphalt mixtures were chosen for further study.

Aggregate packing characteristics have also been used successfully for designing asphalt mixtures, specifically the Bailey method (Vavrik et. al., 2002). The Bailey method is a systematic approach that focuses on creating a densely packed aggregate structure by optimizing the coarse aggregate structure, and then iteratively filling the remaining spaces with smaller aggregate sizes. This method is yet another technique for maximizing the volume of space in a mixture that is filled by aggregate particles, and has also been used in conjunction with the concept of locking point in gyratory compaction. This idea was also evaluated.

To investigate the effects of different gradation types on RCC mixtures, two aggregate types (sandstone and syenite) were used to develop fine, dense, and coarse gradations similar to the way that gradations would be defined by the Superpave system in the asphalt industry. Some of the blends were difficult to achieve, and it was noted that using at least three aggregate components provided greater flexibility in making adjustments to the blend gradation. The sandstone blends are illustrated in Figure 4, and the syenite blends are shown in Figure 5. On each graph, the PCA-recommended gradation band for RCC aggregate blends is denoted by the dashed lines, and the MDL is shown as the thin straight line. The fine gradations are primarily above the MDL, the dense gradations are very near (and/or parallel to) the MDL, and the coarser gradations pass below the MDL. As is typical for asphalt gradations, these features are most evident in the smaller sieve size range (i.e., #4 sieve and smaller). None of the gradations clearly fit within the PCA gradation band, having a slightly finer gradation than that recommended by PCA.

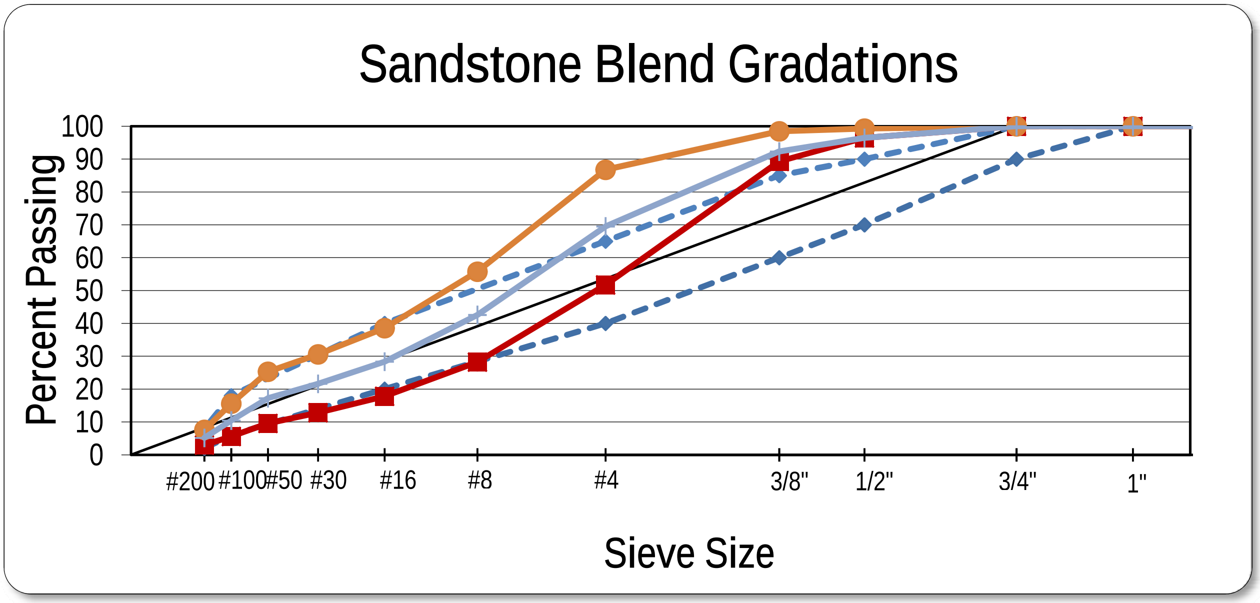

Figure 4. Fine, Dense, and Coarse Sandstone Blend Gradations

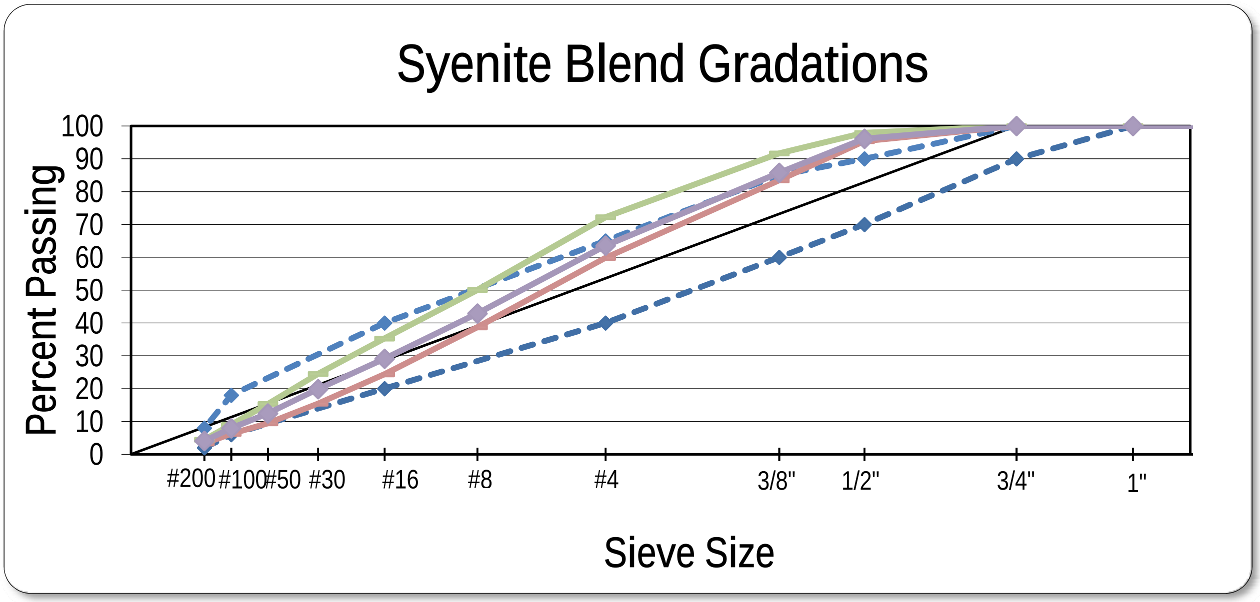

Figure 5. Fine, Dense, and Coarse Syenite Blend Gradations

Each gradation was used to produce a mix design according to the Proctor method, using the Proctor curve to determine optimum moisture content, and strength specimens to determine cement content. All specimens were batched and mixed according to ASTM C192, and specimens for strength testing were prepared according to ASTM C 1435, 'Standard Practice for Molding Roller-Compacted Concrete in

Cylinder Molds Using a Vibrating Hammer' using 6 x 12 inch cylinders. A Proctor curve for the coarse-graded syenite mix design is shown in Figure 6 and the strengths for various cement contents are shown in Figure 7. Based on the Proctor curve, an optimum moisture content of 5.2 percent was selected, and the cement content was chosen to be 13 percent in order to achieve the design strength at 28 days of 4500 psi. The Proctor curve was then verified for a cement content of 13 percent.

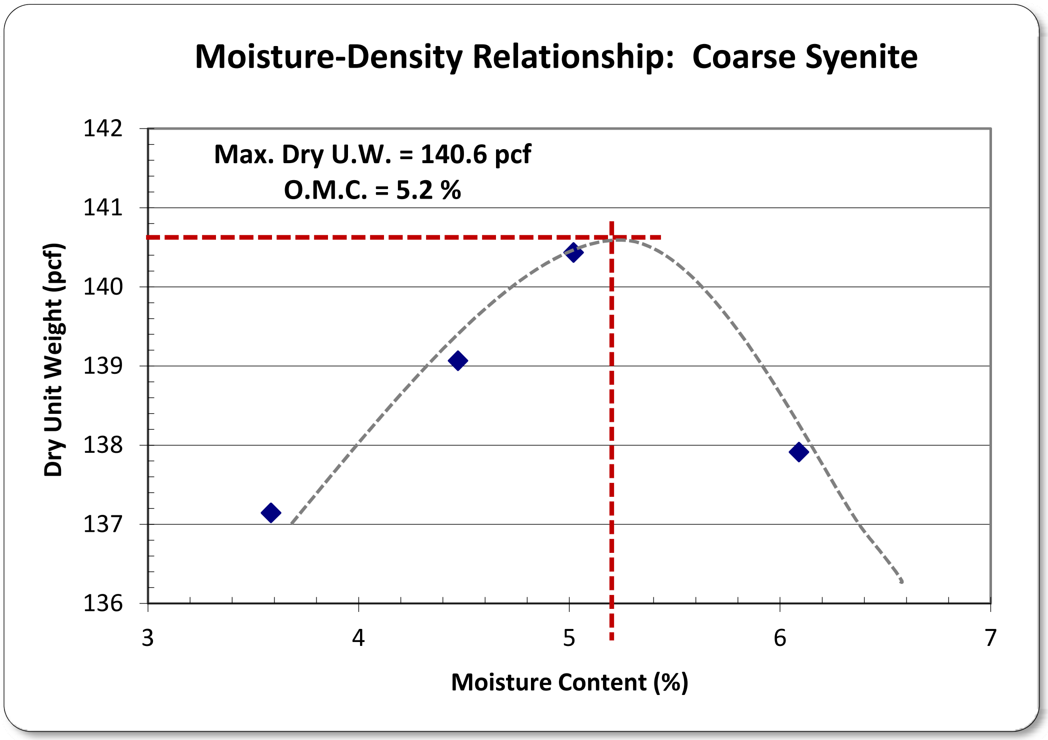

Figure 6. Proctor Curve for Coarse Syenite Blend

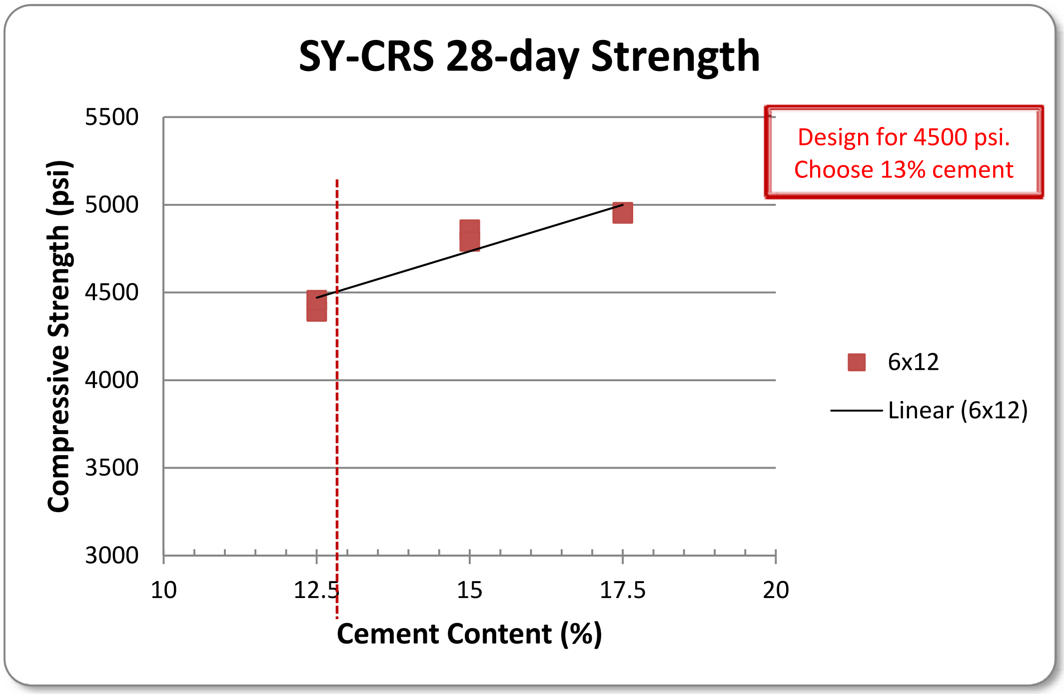

Figure 7. Cement Content vs. Strength for Coarse Syenite Blend

A mix design summary for the six mixtures with a target design strength of 4500 psi is given in Table 10.

Table 10. Summary of Mix Designs Based on Proctor Design Method

	Sandstone			Syenite		
	Coarse	Fine	Dense	Coarse	Fine	Dense
Maximum Dry Density (pcf)	133.0	136.4	134.6	140.6	137.3	139.3
Optimum Moisture Content (%)	7.0	7.7	8.1	5.2	5.7	4.5
Cement Content (%)	17	18	17	13	14	12
Water/Cement (w/c) Ratio	0.39	0.40	0.44	0.38	0.39	0.36
Percent Paste by Weight (%)	24	25	25	18	19	16

The syenite mixes possessed greater densities than the sandstone, and required less cement to achieve a compressive strength of 4500 psi. A trial cement content of 12 percent was used for the initial Proctor curve development, and it was noted that if an increase in cement content was necessary for achieving adequate strength, then the Proctor curve used to validate the design required an increase in optimum moisture content. Higher water contents were required for the sandstone mixes, primarily because higher cement contents were needed to generate the desired compressive strengths.

To further evaluate measures of strength for the coarse, fine, and dense blending techniques, density and strength were measured for replicate specimens of each combination of experimental factors, as shown in Table 11. Specimens for this portion of testing were prepared according to ASTM C 1435, using both 6-in. x 12-in. and 4-in. x 8-in. inch cylinders. Densities were determined, as well as strengths at 24 hours and at 28 days. Although 28-day strengths are typically used for concrete design, RCC pavements can be opened to traffic in as little as 24 hours, making the early strength of the mix an important factor. Thus, both measures were calculated for this analysis.

Table 11. Summary of Experimental Factors to Compare Aggregate Gradations Using Superpave Blending Techniques.

Experimental Factors	Number of Levels	Description
Aggregate Type	2	Sandstone Syenite
Blend Gradation Shape	3	Coarse Fine Dense
Cement Content (%)	3	12.5% 15% 17.5
Cylinder Size	2	6 x 12, 4 x 8
Response Variables	2	Density (pcf) Compressive Strength (psi)

A summary of average density results is shown in Table 12. The syenite aggregates generated greater densities than the sandstone aggregates. Again, this was anticipated because the relative densities of the syenite aggregates were greater than those of the sandstone aggregates. Regarding gradation, the aggregate blends that most closely followed the maximum density line (i.e., Dense blends) most often displayed the highest densities. For the combined dataset, the average density of the dense blends was 146.4 pcf, the average density of the coarse blends was 145.8 pcf, and that of the fine blends was 145.2 pcf.

Table 12. Summary of Density Data for Coarse, Fine, and Dense Blends

Specimen Density (pcf)							
		6x12 Cylinders			4x8 Cylinders		
		%Cement					
Aggregate	**Blend**	12.5	15	17.5	12.5	15	17.5
Sandstone	CRS	143.34	143.31	143.32	144.76	144.67	144.49
	FIN	143.39	143.38	143.49	143.38	143.40	143.42
	DNS	144.54	144.47	144.53	144.83	144.52	144.99
Syenite	CRS	147.33	148.85	147.61	147.13	147.15	147.22
	FIN	147.11	148.04	147.20	146.45	146.49	146.63
	DNS	148.53	146.65	148.14	148.47	148.33	148.46

Statistical analyses, summarized in Table 13, proved that the differences between each of the three gradation shapes were statistically significant. As expected, aggregate type also significantly affected specimen densities. Significant interactions were present between blend gradation shape and cement content, as well as blend shape and cylinder size. Regarding blend shape and cement content, no notable trends were identified, as an increase in cement content did not consistently provide an increase or decrease in density. As for the relationship of blend shape and cylinder size, slightly higher densities were noted for the coarse and dense blends prepared in a 4 x 8 cylinder, while the fine blend exhibited a slightly higher density when compacted in the 6 x 12 cylinder. However, these differences were 0.5 pcf or less, and were determined to be practically insignificant.

Table 13. Statistical Results for Analysis of Density (ANOVA, $\alpha = 0.05$)

Source	DF	F Value	Pr > F	Significant?
AGG	1	1464.68	**<.0001**	**Yes**
BLEND	2	53.71	**<.0001**	**Yes**
CEM	2	0.02	0.9771	No
BLEND*CEM	4	4.30	**0.0029**	**Yes**
CYL	1	0.91	0.3422	No
BLEND*CYL	2	9.60	**0.0001**	**Yes**
CEM*CYL	2	0.35	0.7049	No
BLEND*CEM*CYL	4	2.22	0.0720	No
DAY	1	0.05	0.8195	No
BLEND*DAY	2	0.34	0.7140	No
CEM*DAY	2	0.01	0.9886	No
BLEND*CEM*DAY	4	0.19	0.9421	No
CYL*DAY	1	0.11	0.7367	No
BLEND*CYL*DAY	2	0.16	0.8534	No
CEM*CYL*DAY	2	0.02	0.9768	No
BLEND*CEM*CYL*DAY	4	0.08	0.9880	No

Because there were statistically significant effects due to cylinder size, an additional analysis was performed to assess the individual effects of cylinder size on density. A paired t-test was used to complete the analysis, and no statistically significant difference was present (p-value = 0.45). Figure 8 shows the relationship, in which no significant trends were present with respect to specimen size, and most paired differences were 2 pcf or less. The results are grouped according to high and low density, which are consistent with the higher and lower densities of the syenite and sandstone mixes, respectively. For the sandstone mixes, there is some evidence that the 4 x 8 cylinders generally had higher densities than their companion 6 x 12 cylinders. However, for the syenite mixes, data points fall on both sides of the line of equality, indicating no consistent trend.

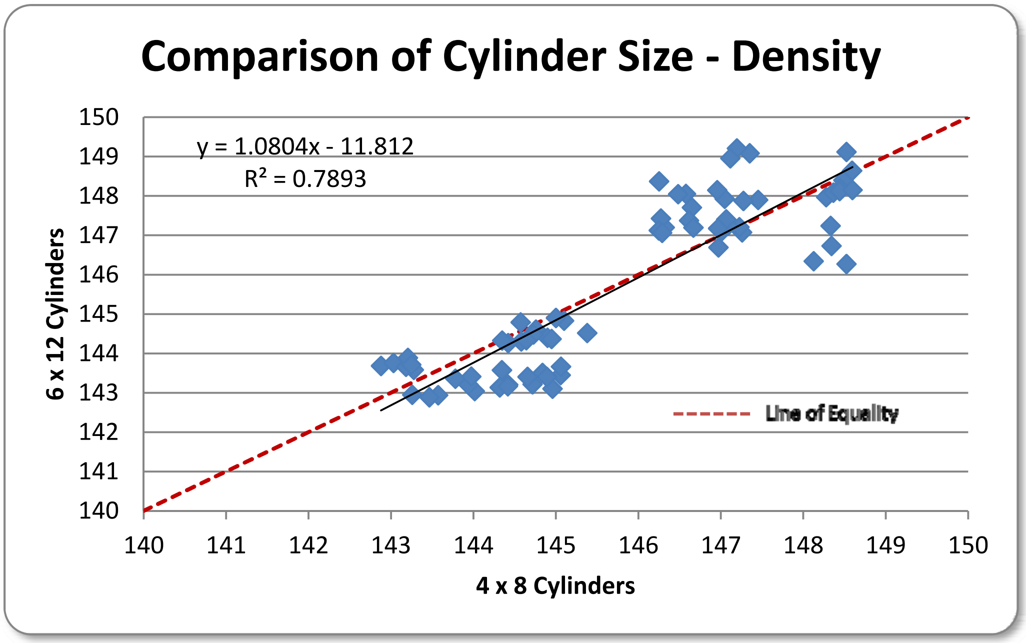

Figure 8. Comparison of Cylinder Size with Respect to Density

Next, each of the gradation types was analyzed based on compressive strength at 24 hours and at 28 days. The average results are shown in Table 14, and a complete data summary is shown graphically in Appendix A. Design cement contents for each blend were chosen as the cement content providing a minimum 28-day compressive strength of 4500 psi. Most existing specifications require a minimum of 4000 to 5000 psi, and so 4500 psi was chosen for this study.

Clearly, the 28-day strengths were greater than the 24-hour strengths, as expected. Compressive strengths for the syenite blends were greater than those for the sandstone blends. Also, the strengths of 6 x 12 cylinders were greater than those of the 4 x 8 cylinders, though the similar trends were evident regarding rate of strength gain with increasing cement content. Overall, the 6 x 12 specimens gained strength at a higher rate than the 4 x 8 specimens when cement content was increased. Relative to gradation blend shape, the dense-graded mixes had the highest compressive strengths, followed by the coarse-graded blends, and finally the fine-graded blends.

Table 14. Summary of Strength Data for Coarse, Fine, and Dense Blends

		24-hour Compressive Strength (psi)					
		6x12 cylinders			4x8 Cylinders		
		%Cement					
Aggregate	**Blend**	12.5	15	17.5	12.5	15	17.5
Sandstone	CRS	940	1070	1204	807	866	988
	FIN	896	1035	1115	801	819	964
	DNS	982	1082	1276	815	875	1041
Syenite	CRS	1087	1221	1266	957	1090	1193
	FIN	1139	1175	1183	927	1035	1117
	DNS	1177	1245	1302	1019	1107	1296

28-day Compressive Strength (psi)							
		6x12 cylinders			4x8 Cylinders		
		%Cement					
Aggregate	**Blend**	12.5	15	17.5	12.5	15	17.5
Sandstone	CRS	3263	4307	4397	3425	3930	4123
	FIN	3196	4195	4237	3308	3644	3723
	DNS	3461	4419	4460	3627	3982	4189
Syenite	CRS	4425	4825	4954	4233	4563	4754
	FIN	4282	4760	4850	4102	4489	4558
	DNS	4597	4831	5128	4426	4628	4789

Statistical analyses (ANOVA, $\alpha=0.05$), shown in Table 15, revealed that aggregate source was significant, with the syenite aggregates generating greater strengths. This trend is consistent with that of density. Blend gradation was statistically significant with all three blend shapes indicating individual statistical significance. The dense blends generated the highest strengths, followed by the coarse blends, and then the fine blends. Cylinder size was also a significant factor, such that the 6 x 12 specimens displayed higher strengths than the 4 x 8 specimens. These differences were statistically significant. Cement content and cylinder age displayed a significant interaction in that the increase from 12 to 15 percent cement had a greater effect on the 28-day strengths than on the 24-hour strengths. The incremental increases in cement content significantly increased compressive strength.

Table 15. Statistical Results for Analysis of Strength (ANOVA, $\alpha = 0.05$)

Source	DF	F Value	Pr > F	Significant?
AGG	1	200.62	**<.0001**	**Yes**
BLEND	2	10.07	**<.0001**	**Yes**
CEM	2	62.95	**<.0001**	**Yes**
BLEND*CEM	4	0.40	0.8110	No
CYL	1	34.73	**<.0001**	**Yes**
BLEND*CYL	2	0.19	0.8313	No
CEM*CYL	2	2.86	0.0617	Marginal
BLEND*CEM*CYL	4	0.02	0.9993	No
DAY	1	10016.9	**<.0001**	**Yes**
BLEND*DAY	2	2.77	0.0673	Marginal
CEM*DAY	2	21.25	**<.0001**	**Yes**
BLEND*CEM*DAY	4	0.16	0.9587	No
CYL*DAY	1	1.52	0.2200	No
BLEND*CYL*DAY	2	0.20	0.8153	No
CEM*CYL*DAY	2	2.73	0.0701	No
BLEND*CEM*CYL*DAY	4	0.07	0.9898	No

Compressive strength values were significantly affected by cylinder size (p-value <0.0001), with the 6 x 12 cylinder size producing an increase in strength of 188 psi, on average. Although this difference may not appear extreme, it was quite consistent, making even minor differences more statistically detectable. The relationship had an R^2 value of 0.99 and is shown in Figure 9, in which the trendline closely follows the line of equality.

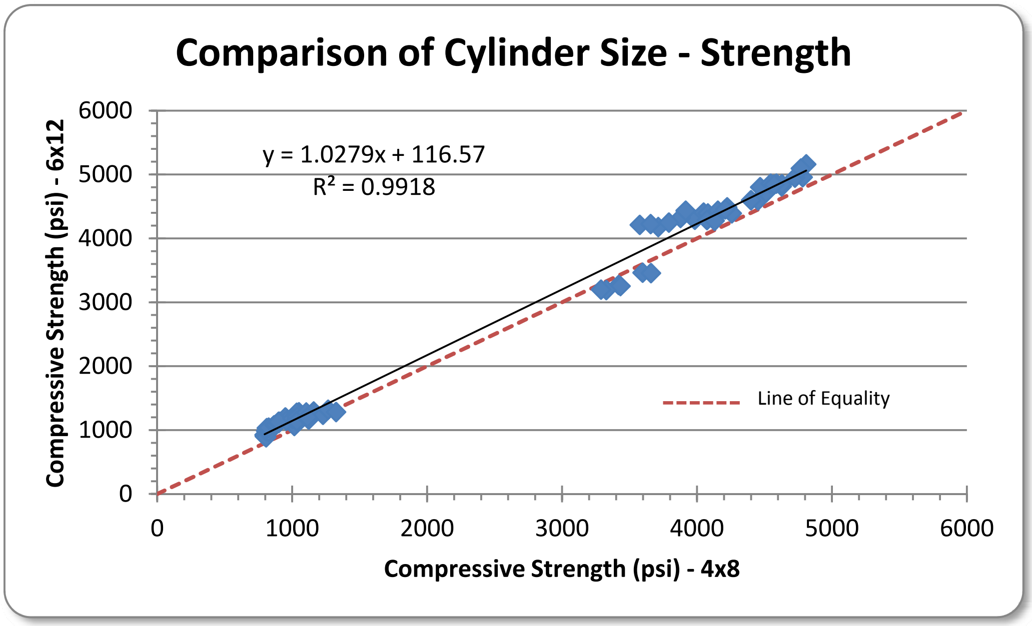

Figure 9. Comparison of Cylinder Size with Respect to Compressive Strength

Density and strength are both important properties of RCC. While conventional concrete relies primarily upon measures of strength, the density of RCC is a key parameter that is monitored during construction, and serves as a real-time indicator of pavement quality. It is generally accepted that strength and density are related properties of a concrete mixture, such that increases in density correlate with increased compressive strength. In order to confirm this, the relationships of strength and density were plotted in Figure 10. While the trends are certainly evident, the relationships are not strong enough to be used for predictive purposes, particularly for the 24-hour compressive strength relationship (R^2=.30).

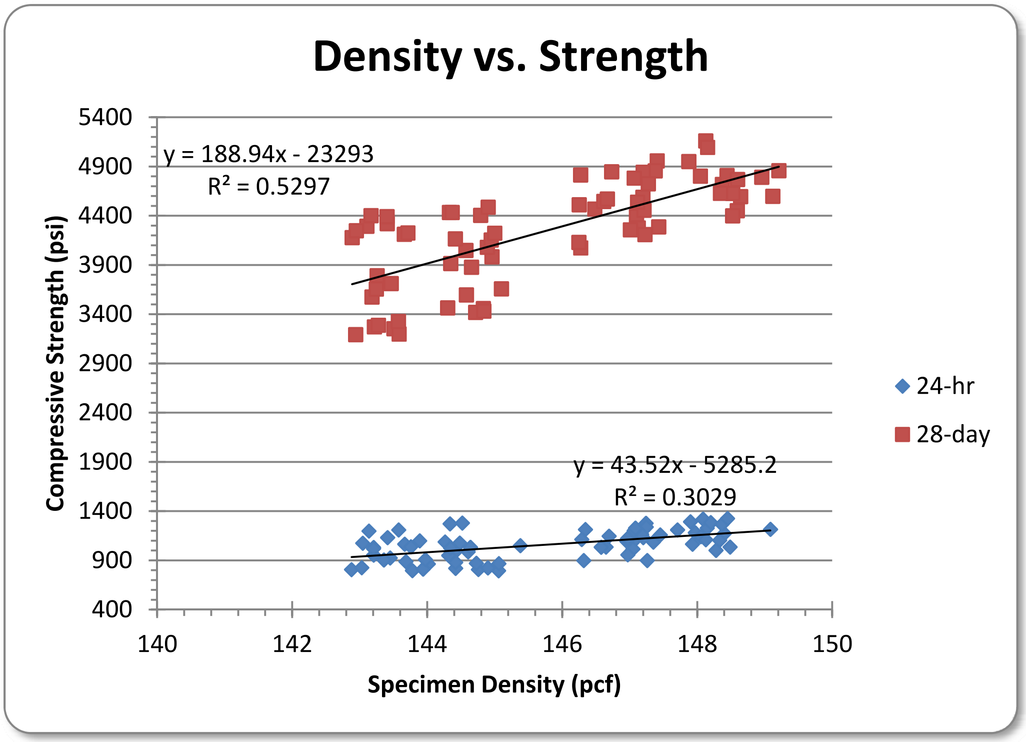

Figure 10. Comparison of Density and Strength for 24-hr and 28-day Compressive Strengths

In summary, specimen size did not significantly affect density, but did affect compressive strength. Due to the high level of consistency in the relationship between the two specimen sizes, it was decided that further investigations could be completed using 4 x 8 specimens without affecting the relative density or strength characteristics, allowing for greater efficiency in the laboratory investigation.

Natural Sand

Based on the results of the gradation comparison, it appeared that RCC mixtures gained the greatest benefit from well-graded dense gradations that closely followed the maximum density line of the 0.45 power chart. Because the Shilstone method is based on these principles, it was investigated next using three aggregate sources (sandstone, syenite, and limestone), and the resulting specimens were used to compare the densities and strengths achieved when the shape of the gradation curve was varied. Natural sand was added to create these changes, and was used for two purposes. First, sand-sized particles were effective in creating the desired gradation blend shapes. Second, natural sand has a rounded shape and increases the workability of the mixture. For asphalt mixtures this is not desirable, as natural sand can significantly increase the rutting potential of the asphalt mixture. However, rutting is not a typical distress associated with RCC, and so natural sand used to add workability could be advantageous for generating additional mixture density.

For each aggregate type, multiple crushed aggregate components (both coarse and fine) were combined with varying percentages of natural sand, and the shape of the gradation curve was adjusted to vary the distances from the maximum density line, with the goal of at least one gradation matching the MDL as closely as possible. The gradations for the sandstone aggregate are illustrated in Figure 11, in which the dashed line represents the maximum density line (MDL) and the individual points represent the recommended gradation band as suggested by the Portland Cement Association (Harrington, et.al, 2010). This figure demonstrates that as adjustments were made to the blend to increase the percentage of natural sand to 15 percent, the gradation curve gradually moved closer to the MDL. As the sand content increased to 20 percent, the gradation curve became coarser and moved away from the MDL slightly.

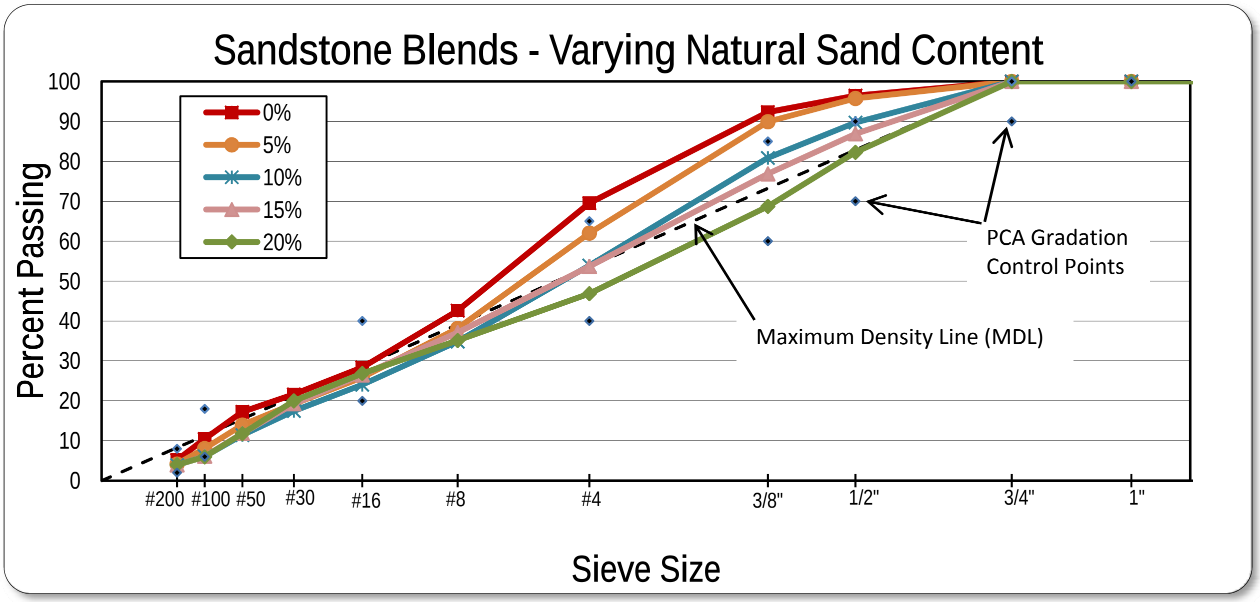

Figure 11. Blend Gradations for Sandstone Aggregate Source with Varying Percentages of Natural Sand

Gradations for the syenite and limestone aggregate sources are shown in Figures 12 and 13, respectively. For the syenite blend, the addition of natural sand was effective in moving the finer portion of the gradation curve nearer to the MDL. However, a change was made to the coarse aggregate for the 10 and 15 percent sand blends to more closely approach the MDL.

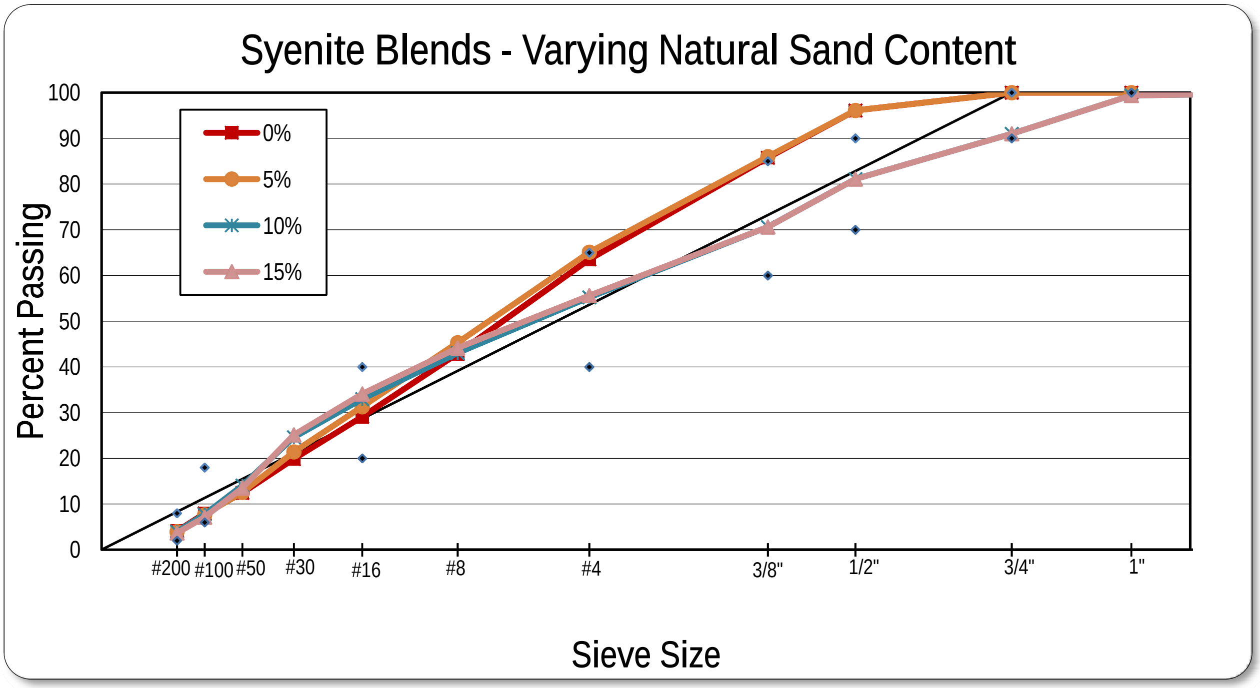

Figure 12. Blend Gradations for Syenite Aggregate Source with Varying Percentages of Natural Sand

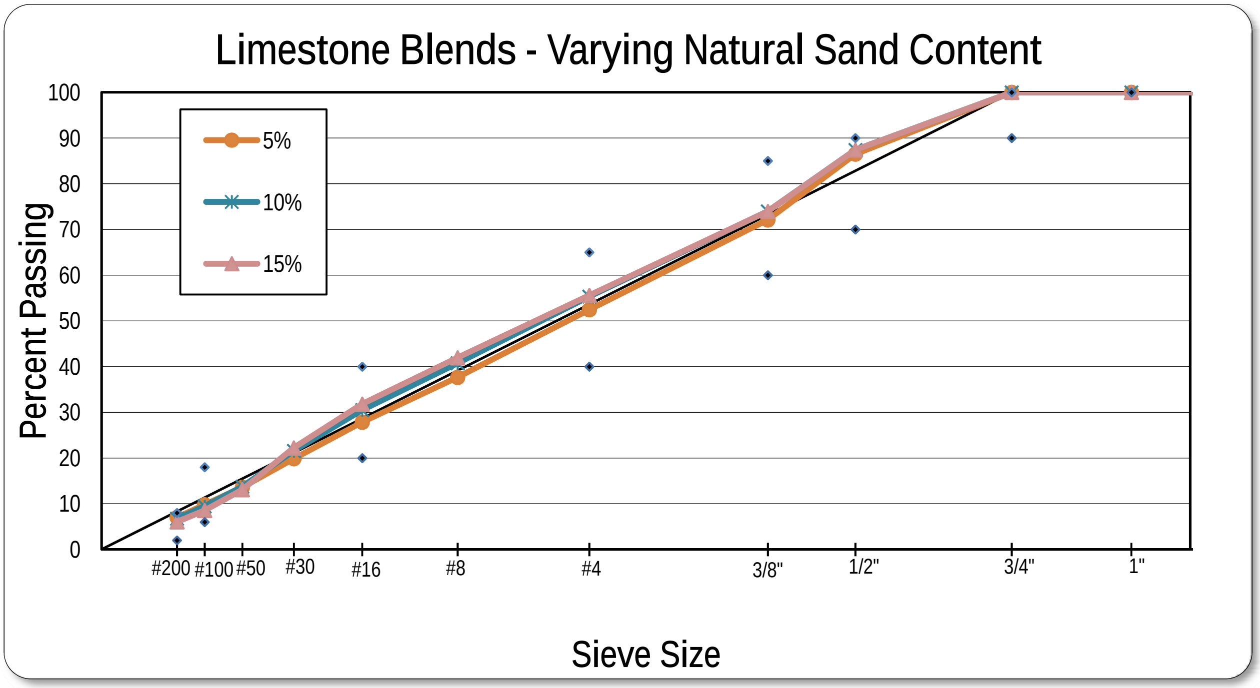

Figure 13. Blend Gradations for Limestone Aggregate Source with Varying Percentages of Natural Sand

For each trial blend, an RCC mix design was performed using the Proctor method to determine the optimum moisture content and maximum dry density. A summary of density results is shown in Figure 14, in which the blend gradation from each aggregate source that was closest to the MDL is denoted by a patterned bar. For the sandstone source, the 15 percent sand mix was closest to the MDL, and also provided a higher maximum dry density than the other sand contents, though only slightly greater than that of the 10 and 20 percent sand blends. For the syenite blends, the 15 percent sand mix was closest to the MDL. While the maximum density for this mix was higher than for the lower sand contents, the 20 percent blend yielded an even higher maximum density. For the limestone mixes, the 5 percent blend most closely matched the MDL, and also yielded the highest density.

In general, both the blend gradation shape and the aggregate particle shape affected RCC mixture density. As the blend gradation curve moved closer to the maximum density line, the density of the mixtures increased. Also, as the percentage of natural sand increased, the density of the mixture also increased due to the increased workability created by the rounded natural sand particles. Thus, in order to increase the density of an RCC paving mixture, the percentage of natural sand should be maximized, while also making sure that the blend gradation follows the maximum density line as closely as possible.

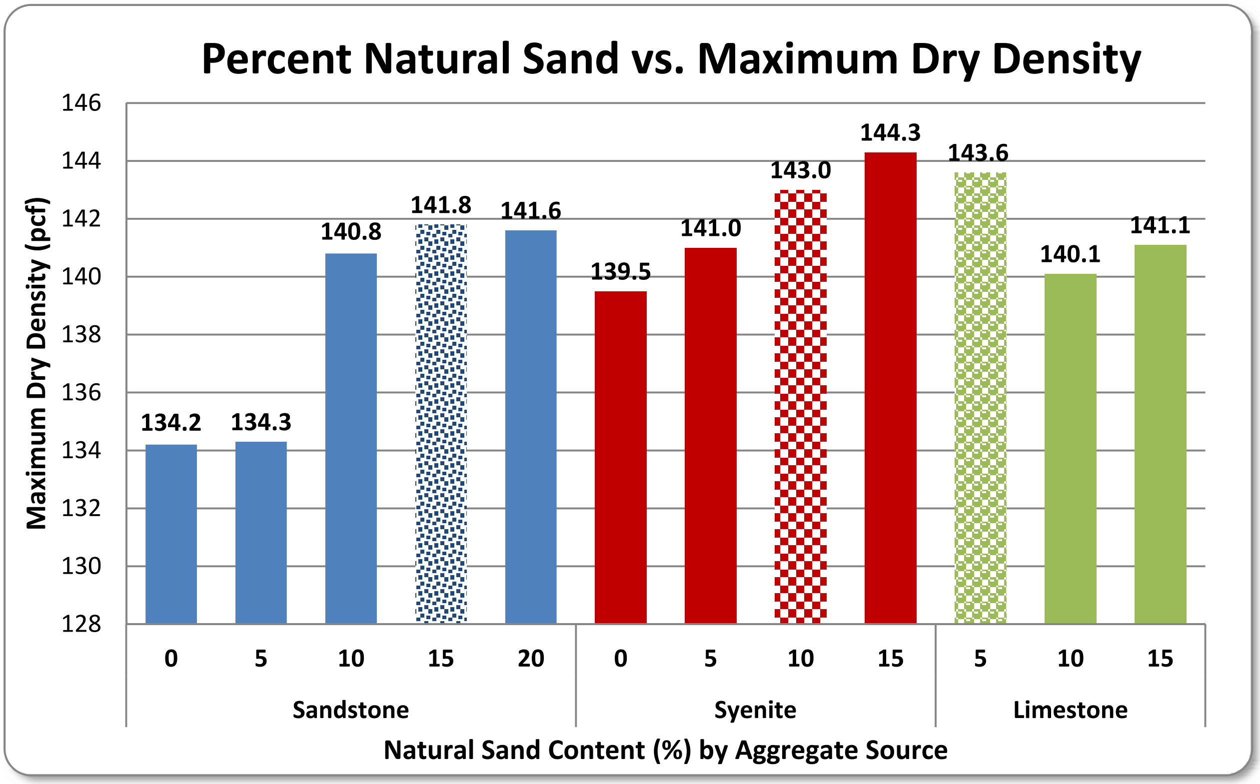

Figure 14. Percent Natural Sand vs. Maximum Dry Density for Sandstone, Syenite, and Limestone Blends

In order to validate this conclusion, one additional blend gradation was created using these principles. A well-graded dolomite aggregate source was combined with 25 percent natural sand, such that the gradation blend closely followed the MDL, as shown in Figure 15. The resulting maximum density by the Proctor method was 143.7 pcf. This density was among the highest in the study, confirming the success of the method.

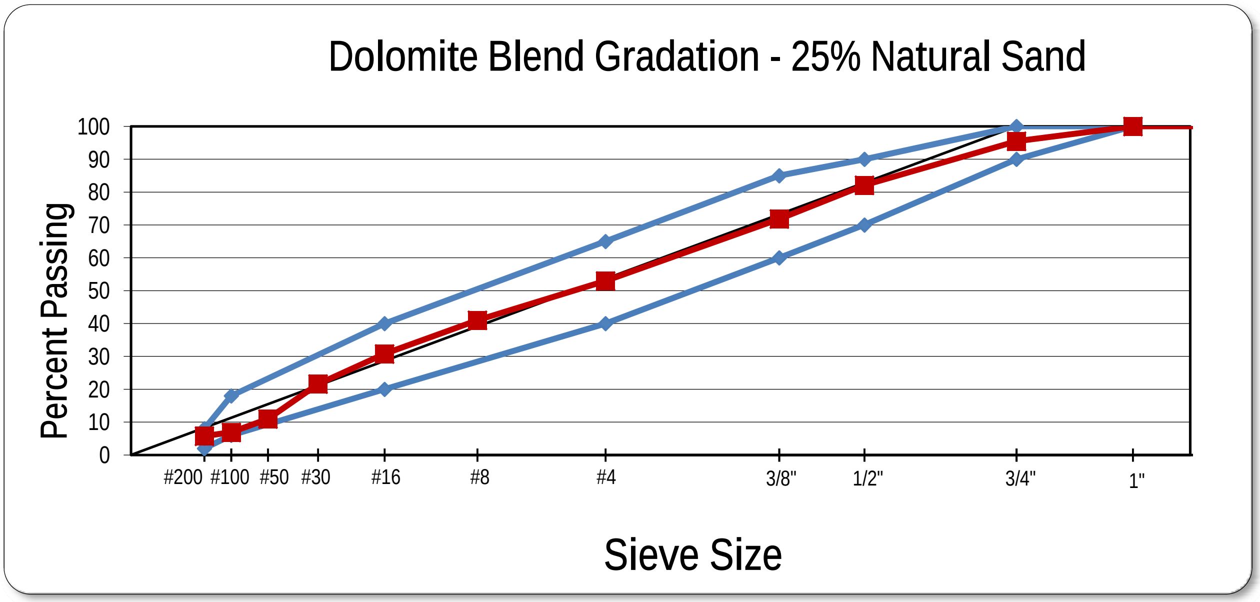

Figure 15. Blend Gradation for Dolomite Aggregate Source with 25 percent Natural Sand

Compressive Strength

In order to more fully characterize the factors affecting compressive strength of RCC, cylindrical strength specimens were also prepared for a subset of the mixes in the sand study. Compressive strengths were determined for these mixes containing varying sand contents, cement contents, and curing times. In this testing matrix, six mixtures were chosen, and 32 cylinders were prepared for each. The details of this experiment are shown in Table 16.

Table 16. Experimental Design for Effects of Sand Content, Curing Time and Cement Content on Compressive Strength

Factor	Levels
Aggregate Type	3 (SS, SY, LS)
Sand Content	2 (Low = 10%, High = 20% for SS mixes, 15% for SY and LS mixes)
Curing Time	4 (1, 3, 7, and 28 days)
Cement Content	4 (11%, 13%, 15%, and 17% for SS and LS mixes, 10%, 12%, 14%, and 16% for SY mixes)

Based on the ANOVA results, shown in Table 17, no interactions between factors were significant. However, the main effects of aggregate type, curing time, and cement content were statistically significant. Sand content did not significantly affect compressive strength.

Table 17. ANOVA Results for Effects of Sand Content, Curing Time, and Cement Content on Compressive Strength

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Significant?
AGG	2	26812017.9	13406009	14.28	<.0001	Yes
SAND	1	1047105	1047105	1.12	0.2926	No
CURE	3	267898753.1	89299584.4	95.11	<.0001	Yes
SAND*CURE	3	1216651.6	405550.5	0.43	0.7304	No
CEMENT	3	76359054.7	25453018.2	27.11	<.0001	Yes
SAND*CEMENT	3	555636.8	185212.3	0.2	0.8981	No
CURE*CEMENT	9	5385742.3	598415.8	0.64	0.7638	No
SAND*CURE*CEMENT	9	9232646.8	1025849.6	1.09	0.3713	No

Aggregate type, curing time, and cement content were statistically significant factors affecting the compressive strength of RCC, such that increased curing times and cement contents produced higher compressive strengths. It was expected that as cement content and curing time increased, compressive strengths would also increase. These features are demonstrated in Figures 16 and 17, in which the mean and distribution of strength values for each grouping is shown.

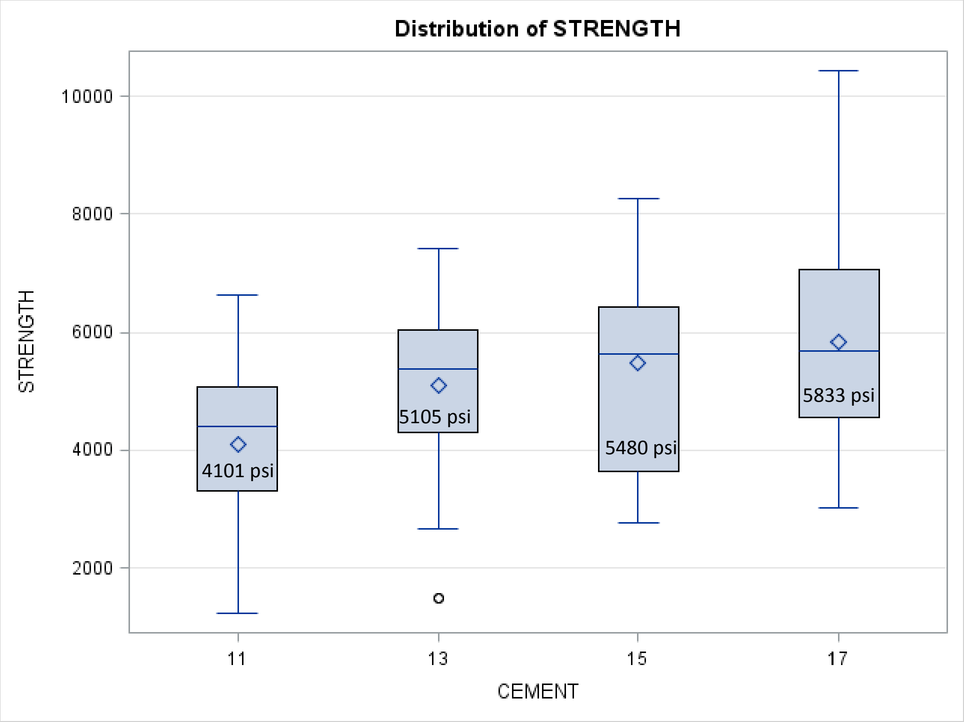

Figure 16. Mean and Distribution of Compressive Strengths for Various Cement Contents

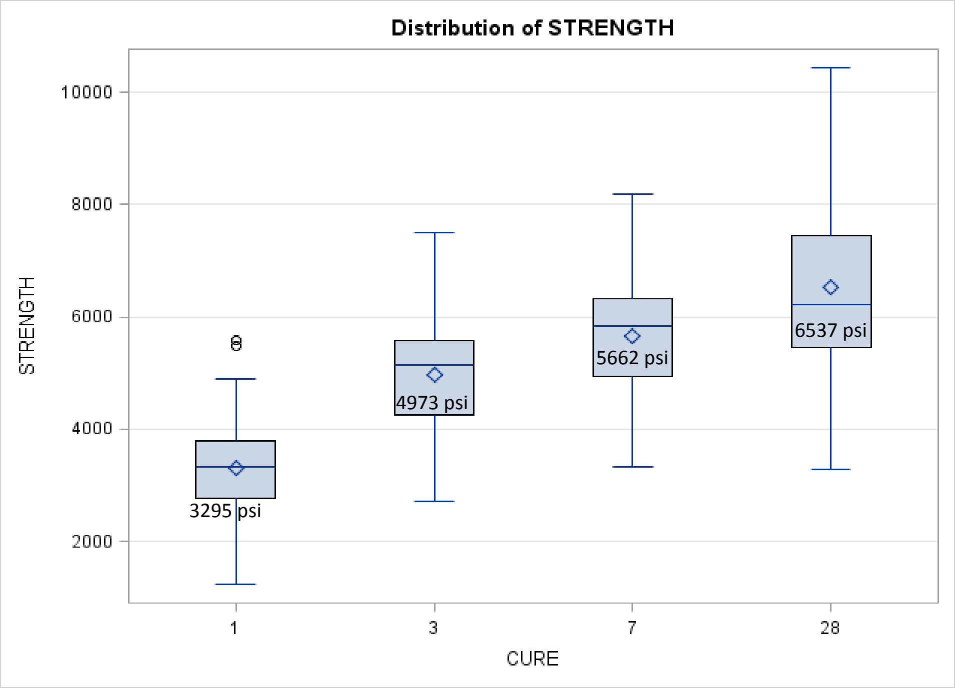

Figure 17. Mean and Distribution of Compressive Strengths for Varied Curing Times

The most important conclusion of this analysis is that the individual factors of cement content and curing time operated independently and did not depend on one another to generate a desired outcome. In other words, the rate of strength gain was not dependent upon cement content.

Of particular interest was the effect of increasing the natural sand content of an RCC mixture. Previously, it was shown that adjusting the natural sand content to create a gradation that closely followed the MDL would, in fact, generate higher specimen densities, and increases in density are generally associated with increases in compressive strength. However, sand content did not significantly affect compressive strength. The mean compressive strength of the low sand contents was 5211 psi, while that of the high sand content was 5042 psi, as shown in Figure 18. Thus, increasing the cement content was the most effective method for adding compressive strength, while density increases were most adequately addressed by changes in the blend gradation shape. Furthermore, since sand content did not affect strength, changes can be made in sand content to create desired effects in the density and workability of the RCC mix without adversely affecting the strength of the mix.

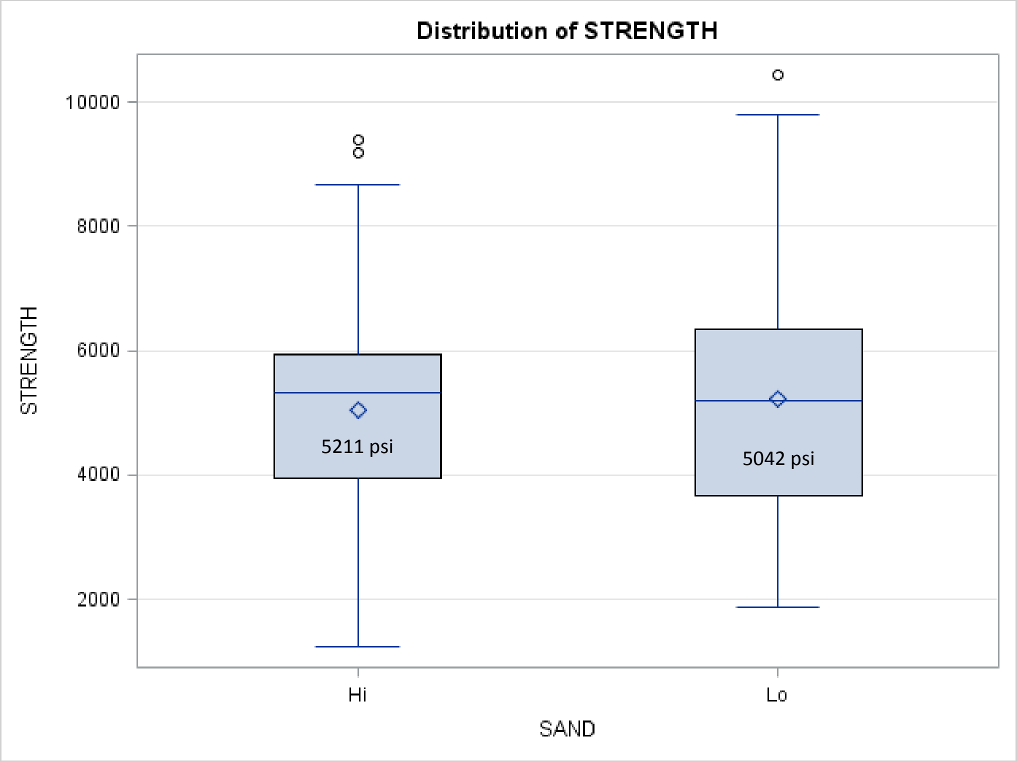

Figure 18. Mean and Distribution of Compressive Strengths for High and Low Natural Sand Contents

Strength Gain

Strength gain is another important factor for RCC pavements. While conventional concrete and RCC paving mixtures are designed based on 28-day strengths, RCC is much more dependent upon early strength gain because one of its key advantages is the fact that it can usually be opened to traffic within 1 to 3 days. Thus, it is reasonable that the strengths of RCC specimens should be analyzed with respect to strengths at shorter curing times. In order to more fully characterize these properties, 7 mixtures were used to model the strength gain of RCC. For each mixture, strengths were plotted with respect to curing time. A logarithmic relationship most accurately described the correlations, as shown in Figure 19. Graphs for all mixtures are given in Appendix B.

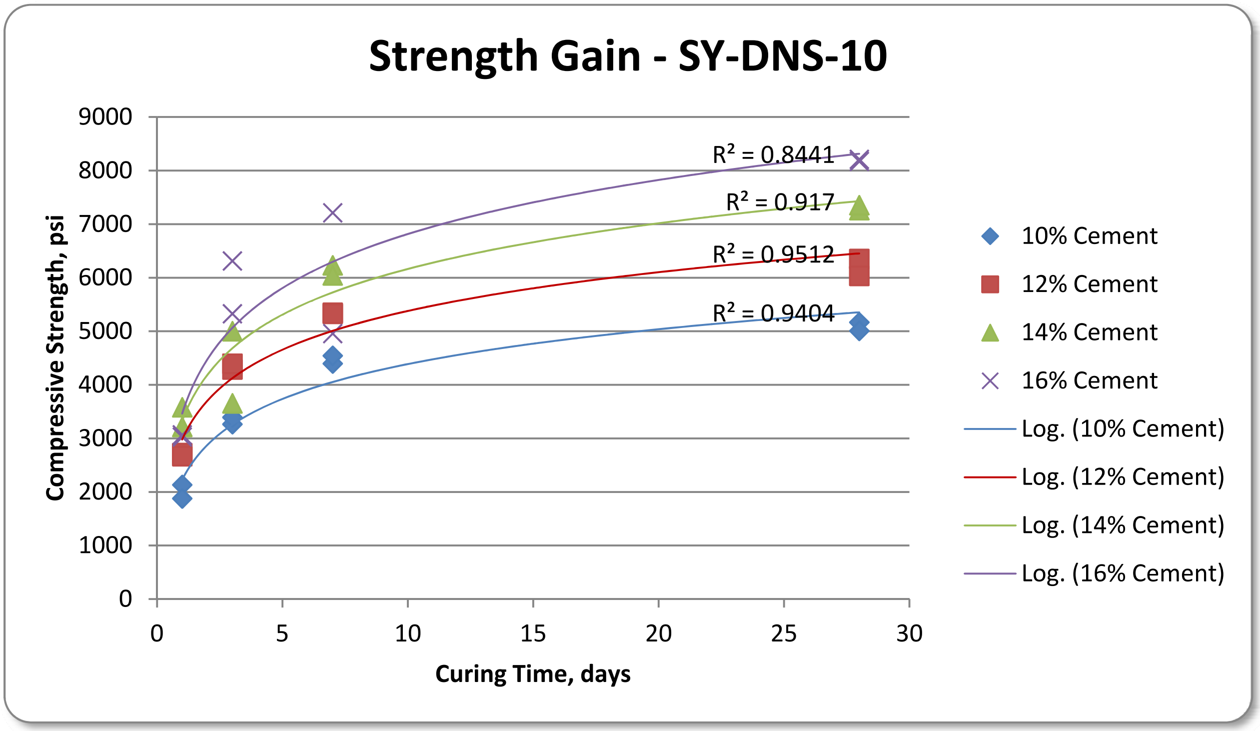

Figure 19. Strength Gain for SY-DNS-10 Mixture for Varying Cement Contents

These relationships demonstrate a fairly common strength gain rate, similar to that of conventional concrete. Since the design process is based on 28-day strength, but early performance and opening to traffic is based on earlier measures of strength, strengths were calculated in terms of the percentage of 28-day strength. A data summary is shown in Table 18.

Table 18. Percent of 28-day Strength for Various Curing Times

	Percent of 28-day Strength at Given Cure Time		
Mix Design	**1-day**	**3-day**	**7-day**
SS-DNS-10	62	82	95
SS-DNS-20	62	83	97
SY-DNS-10	42	66	83
SY-DNS-15	33	69	76
LS-DNS-10	55	75	87
LS-DNS-15	60	84	88
DL-DNS-25	42	79	83
Average for All Mixes	**51**	**77**	**87**

On average, approximately 50 percent of the 28-day strength was gained within the first 24 hours, 77 percent in 3 days, and 87 in 7 days. This is important because strength gain rate can significantly affect lane closure times during construction. For example, if specifications state that unrestricted traffic is allowed on the compacted roadway after a strength of 2500 psi has been achieved, and the design 28-day strength of the mix is 5000 psi, then the roadway can be expected to be opened to traffic after 24 hours. If the design 28-day strength of the mix is only 4000 psi, then a 2 to 3 day lane closure can be expected. Thus, the design strength for a mixture can be adjusted to accommodate not only the structural requirements, but also to aid in minimizing lane closures associated with construction.

Gyratory Design Method

Although the Proctor design method is used most commonly for the design of RCC pavements, the method of field compaction for RCC could be more accurately modeled by laboratory compaction using the Superpave gyratory compactor. The kneading action of the gyratory compactor is intended to mimic the forces applied by the roller during field compaction. For the gyratory method, there is no stated RCC design procedure, although work is currently underway to establish a standard ASTM method for compacting an RCC sample in a Superpave Gyratory Compactor (SGC) (Williams, 2012). The gyratory compactor places a sample under 600 kPa of load, while applying a 0.16 degree angle (internal) to the sample and rotating it at a rate of 30 gyrations per minute. This style of compactor is shown in Figure 20.

Figure 20. Pine Model G2 Superpave Gyratory Compactor

The first step in assessing gyratory compaction for RCC was to determine whether or not this type of sample could actually be produced in the laboratory in a practical manner. Aggregate blends were batched and mixed according to ASTM C 192 using a trial cement content and varying water contents, similar to the Proctor design method, and then compacted in the SGC. Because of the dry nature of the RCC mixture, samples were able to be extruded immediately and intact, as shown in Figure 21. However, for samples containing higher moisture contents, excess paste was squeezed from the sample during compaction. This paste escaped from the mold during compaction through the gap created between the mold and bottom plate while the angle was applied. Because of this, it was quickly realized that great care must be taken to ensure that any visible paste is immediately cleaned and does not contact any of the sensitive electronics in the compactor, or harden on the internal surfaces of the compactor.

Figure 21. Extruding a Compacted RCC Specimen from the Gyratory Compactor

It was anticipated that gyratory compaction would provide a parabolic relationship similar to that of the Proctor method, allowing for the optimum moisture content to be readily identified. However, this was not the case. In gyratory compaction, the density increased with increasing moisture content, but did not decrease as moisture content continued to increase past an optimum value. Instead, excess moisture was compressed from the sample, which meant that for higher target moisture contents, the actual moisture content after compaction was less (sometimes significantly) than the target moisture content. For example, a target moisture content of 8.5 percent may result in an actual specimen moisture content of only 6.5 percent due to the moisture/paste loss during compaction. In effect, the gyratory compaction method resulted in a maximum achievable moisture content, which generally coincided with the maximum achievable density. The gyratory relationships were not parabolic and did not “break over”, but instead exhibited continual positive correlation. An example of the moisture density relationship developed by the gyratory compaction method is shown in Figure 22. In this graph, the maximum achievable moisture content, or ‘terminal’ moisture content was approximately 6.6 percent.

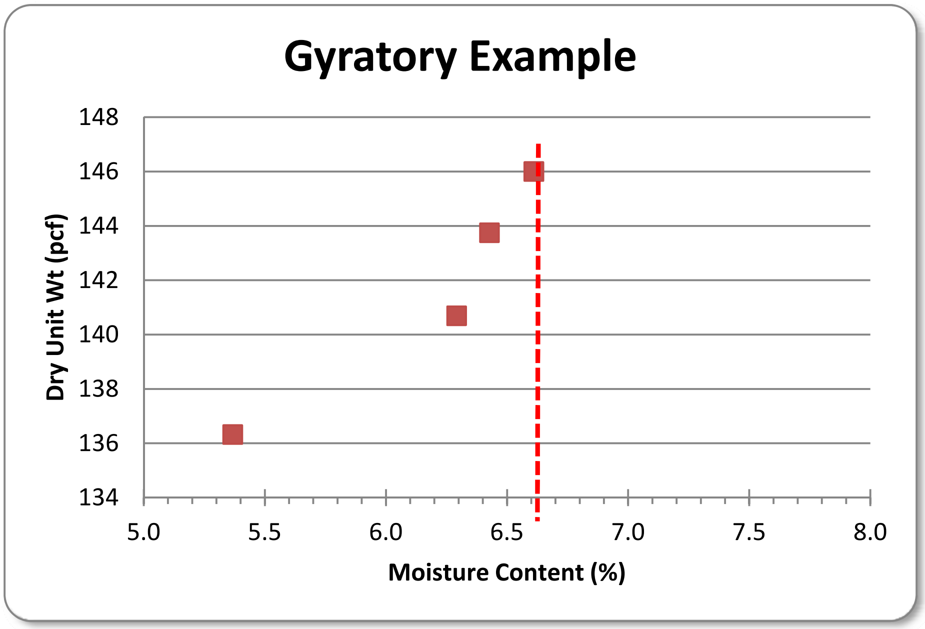

Figure 22. Moisture-Density Relationship of RCC by the Gyratory Method

Comparison of Proctor and Gyratory Compaction

For the seventeen mix designs previously developed using the Proctor compaction method, corresponding designs were developed using the SGC in order to provide a direct comparison of results. These mix designs represented 4 different aggregate sources, varying gradation shapes, and contained various percentages of natural sand. A summary of blend gradations is given in Table 19.

Table 19. Summary of Gyratory Blend Gradations

Aggregate Type	Gradation Type	Natural Sand Content (%)
Sandstone (SS)	Coarse (CRS)	0
Sandstone (SS)	Fine (FIN)	0
Sandstone (SS)	Dense (DNS)	0
Syenite (SY)	Coarse (CRS)	0
Syenite (SY)	Fine (FIN)	0
Syenite (SY)	Dense (DNS)	0
Sandstone (SS)	Dense (DNS)	5
Sandstone (SS)	Dense (DNS)	10
Sandstone (SS)	Dense (DNS)	15
Sandstone (SS)	Dense (DNS)	20
Syenite (SY)	Dense (DNS)	5
Syenite (SY)	Dense (DNS)	10
Syenite (SY)	Dense (DNS)	15
Limestone (LS)	Dense (DNS)	5
Limestone (LS)	Dense (DNS)	10
Limestone (LS)	Dense (DNS)	15
Dolomite (DL)	Dense (DNS)	25

Each of the blend gradations was mixed with varying water contents and then mixed and compacted to determine the optimum water content and maximum density. Gyratory compaction was performed using a Pine G2 model compactor, a 150 mm diameter mold, and 50 gyrations. A summary of results is shown in Table 20. In this table, density and moisture content data are shown for each specimen compacted by each method. Target moisture contents were the intended moisture contents, while the actual moisture contents were the measured moisture contents taken from each specimen after compaction. In some cases, the specimens containing high target moisture contents were not able to be completed due to excessive moisture loss during compaction.

Table 20. Moisture Content and Density Comparison for Proctor and Gyratory Compacted Specimens

Mix Design	Target Moisture Content (%)	Proctor Actual Moisture Content (%)	Proctor Dry Density (pcf)	Gyratory Actual Moisture Content (%)	Gyratory Dry Density (pcf)
SS-CRS-0	6	5.5	133.9	5.5	126.2
	7	6.2	135.0	6.6	132.9
	8	7.4	135.9	6.7	136.9
	9	8.4	133.7	--	--
SS-FIN-0	6	5.6	133.3	5.5	131.9
	7	6.5	134.3	5.7	134.9
	8	7.5	133.7	6.5	137.4
	9	8.7	132.7	--	--
SS-DNS-0	6	5.2	132.6	6.4	135.8
	7	6.5	133.2	6.3	139.1
	8	7.5	134.1	6.3	140.9
	9	8.4	131.8	--	--
SY-CRS-0	5	5.0	136.2	5.4	138.7
	6	6.0	137.9	5.2	143.2
	7	7.0	138.8	5.1	146.9
	8	7.8	137.4	--	--
SY-FIN-0	5	4.8	135.0	4.8	137.8
	6	5.8	135.6	5.5	142.5
	7	6.9	136.7	5.6	143.6
	8	7.7	134.4	--	--
SY-DNS-0	5	4.8	139.0	5.1	137.6
	6	5.6	139.4	5.0	142.3
	7	6.7	138.3	5.4	144.8
	8	7.6	133.3	--	--
SS-DNS-5	6.5	6.2	130.0	6.3	132.7
	7.5	7.2	131.1	7.2	137.9
	8.5	8.4	134.1	8.2	135.2
	9.5	9.2	133.8	8.4	137.6
SS-DNS-10	6	5.6	135.5	5.1	136.4
	7	6.0	140.4	5.3	140.4
	8	7.6	139.8	6.7	141.9
	9	8.6	137.6	7.3	142.0
SS-DNS-15	6	5.6	137.3	5.7	137.3
	7	6.2	141.7	5.8	141.1
	8	7.1	139.4	6.5	143.0
	9	8.9	135.5	6.9	143.4
SS-DNS-20	6	5.2	140.5	5.5	140.3
	7	6.9	141.3	6.3	142.3
	8	7.2	139.1	6.3	144.2

	9	8.2	136.5	--	--
SY-DNS-5	5.5	5.3	137.0	5.4	136.3
	6.5	6.1	138.4	6.3	140.7
	7.5	7.2	140.9	6.4	143.8
	8.5	8.1	139.2	6.6	146.0
SY-DNS-10	5	6.1	139.4	5.2	141.3
	6	5.3	142.3	5.3	146.6
	7	6.1	142.6	4.8	150.1
	8	7.0	142.9	5.5	150.3
SY-DNS-15	5	4.7	142.1	4.8	143.1
	6	4.9	143.2	4.9	147.1
	7	6.1	144.1	4.7	149.7
	8	7.4	144.3	5.1	151.0
LS-DNS-5	6	5.7	137.4	5.6	135.1
	7	5.4	143.4	5.3	141.9
	8	7.7	142.2	6.2	145.9
	9	8.3	140.2	6.4	146.5
LS-DNS-10	6	5.3	135.6	5.5	137.3
	7	6.2	139.3	6.2	141.0
	8	7.2	139.7	6.8	144.9
	9	7.7	140.0	6.9	146.6
LS-DNS-15	6	5.6	135.8	5.3	139.1
	7	6.5	140.2	6.0	144.4
	8	7.2	141.0	6.1	147.0
	9	8.1	138.8	6.7	147.2
DL-DNS-25	6	6.6	142.6	5.5	142.2
	7	7.8	143.6	5.8	146.7
	8	8.3	142.2	6.0	150.8
	9	8.2	141.2	6.0	151.6

Note: Missing gyratory data indicates that too much water and/or paste was present and further increases in water content were not pursued.

Next, the gyratory method was used to determine optimum moisture content and maximum dry density for each of the RCC designs. In this method, the optimum moisture content was determined as the ‘terminal’ moisture content, and the dry density at that moisture content was treated as the maximum value. The summary data is shown in Table 21.

Table 21. Optimum Moisture and Maximum Dry Density for Mix Designs

Mix Design	Proctor Optimum Moisture Content (%)	Proctor Maximum Dry Density (pcf)	Gyratory Optimum Moisture Content (%)	Gyratory Maximum Dry Density (pcf)
SS-CRS-0	7.2	135.9	6.7	137.0
SS-FIN-0	6.7	134.4	6.5	137.5
SS-DNS-0	7.3	134.2	6.4	139.2
SY-CRS-0	6.9	138.8	5.1	147.0
SY-FIN-0	6.7	136.8	5.6	143.8
SY-DNS-0	5.5	139.5	5.5	145.0
SS-DNS-5	8.8	134.3	7.4	138.0
SS-DNS-10	6.8	140.8	7.1	142.4
SS-DNS-15	6.4	141.8	6.9	143.5
SS-DNS-20	6.4	141.6	6.6	144.2
SY-DNS-5	7.4	141.0	6.4	143.8
SY-DNS-10	7.2	143.0	5.5	150.4
SY-DNS-15	7.2	144.3	5.1	151.2
LS-DNS-5	6.0	143.6	6.4	146.5
LS-DNS-10	8.0	140.1	6.9	146.5
LS-DNS-15	7.0	141.1	6.2	147.0
DL-DNS-25	7.5	143.7	6.0	151.6

Overall, the gyratory method produced lower optimum moisture contents and higher maximum densities than the Proctor method. Statistically, this was confirmed using the paired t-test. The gyratory design method resulted in an average of 0.75 percent less in design moisture content (p-value <0.0001), and 4.7 pcf higher in maximum dry density (p-value = 0.0019). This difference was also practically significant. Typical RCC specifications require 98 percent of maximum laboratory density, meaning that the contractor would have to achieve significantly higher in-place densities during construction. Thus, the designs generated by the gyratory method were not equivalent to those obtained by the Proctor method. For example, assume that an RCC mix designed by the Proctor method has a maximum dry density of 140 pcf and an optimum moisture content of 6.5 percent. During field compaction, the mat would be required to meet 98 percent of the maximum wet density, or 146.1 pcf. If that same mixture had been designed using the gyratory method and had a maximum dry density of 144.7 and a terminal moisture content of 5.75 percent, the mat would be required to meet a minimum density of 150.0 pcf. This would create difficulty for the contractor because the field compaction equipment would be no different, yet it would be necessary to provide 3.9 percent more compaction to meet the specifications.

Moisture content was notable in that several of the mixes were fairly sensitive to changes in moisture content, having significant changes in density when the moisture content changed by less than 1 percent. In other words, a “steep” Proctor curve was associated with some mixes. The practical effect of this concept is that RCC mixes may be more sensitive to changes in moisture content, and tighter specifications may be necessary for proper field control.

Because the Proctor and gyratory methods did not produce similar designs, the compaction process was explored further using compaction data for six mixtures at varying moisture contents. Fine, coarse, and dense mixes from the sandstone and syenite aggregate sources were compacted in the SGC at varying moisture contents. The SGC records specimen height to the nearest 0.1 mm after each gyration. Since the specimen diameter within the mold does not change, the decrease in height is a proportional representation of the increase in density. A graphical summary of the change in specimen height during compaction is presented in Figure 23.

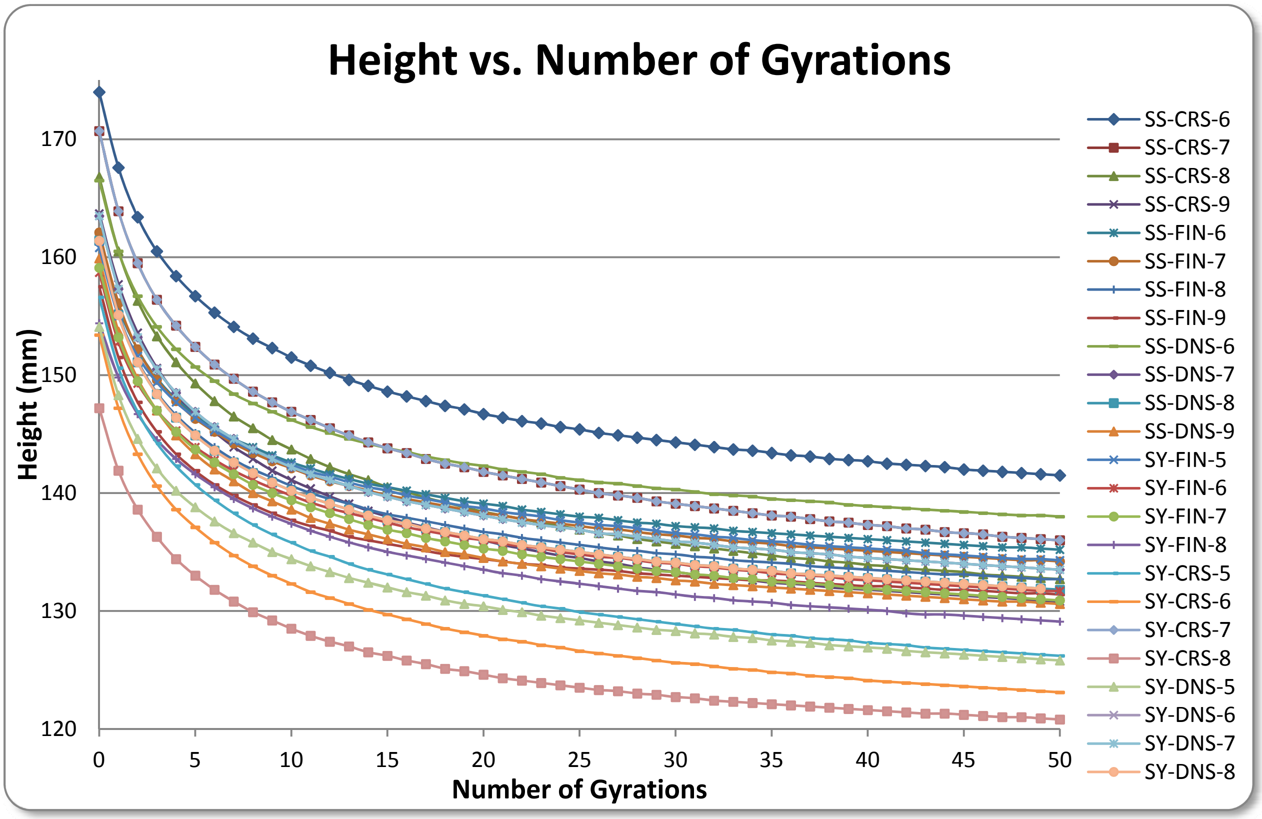

Figure 23. Specimen Heights During Compaction For Varying Gradations and Water Contents

Most of the specimen compaction occurred during the first 5 to 10 gyrations, and after approximately 15 gyrations, the rate of densification was approximately linear. The rate of densification was relatively similar for all mixes, regardless of gradation type or moisture content.

In an attempt to reconcile differences in the Proctor and gyratory methods, it was thought that lower numbers of gyrations may provide a better correlation to Proctor densities. Gyratory densities were calculated proportionally based on the heights recorded for 35, 40, 45, and 50 gyrations, and compared to the densities derived from the Proctor method. An example of such a comparison is shown in Figure

24. Overall, the differences in gyratory compactive effort did not improve the correlations, and further comparisons were not pursued. Moisture content appeared to affect the densities much more significantly than the number of gyrations. This is consistent with the fact that most of the sample densification in gyratory compaction occurred during the early stages of the compaction process.

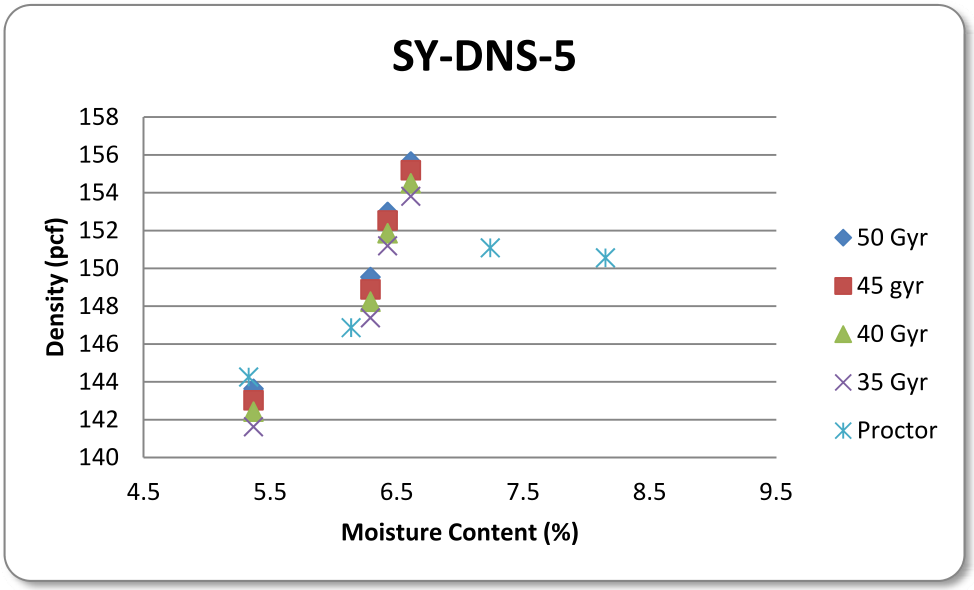

Figure 24. Moisture-Density Relationship Comparison for Proctor and Gyratory Compaction with Varying Numbers of Gyrations – Dense Syenite Mix with 5% Natural Sand.

In the Pine G2 gyratory compactor, which was used for this project, a measurement of shear is also provided for each gyration. The shear value is a representation of the stiffness of the mixture, and quantifies the resistance of a mixture that is placed on the machine during each gyration of the compaction process. These values, shown in Figure 25, were analyzed to determine whether any obvious differences could be detected with respect to aggregate gradation or moisture content.

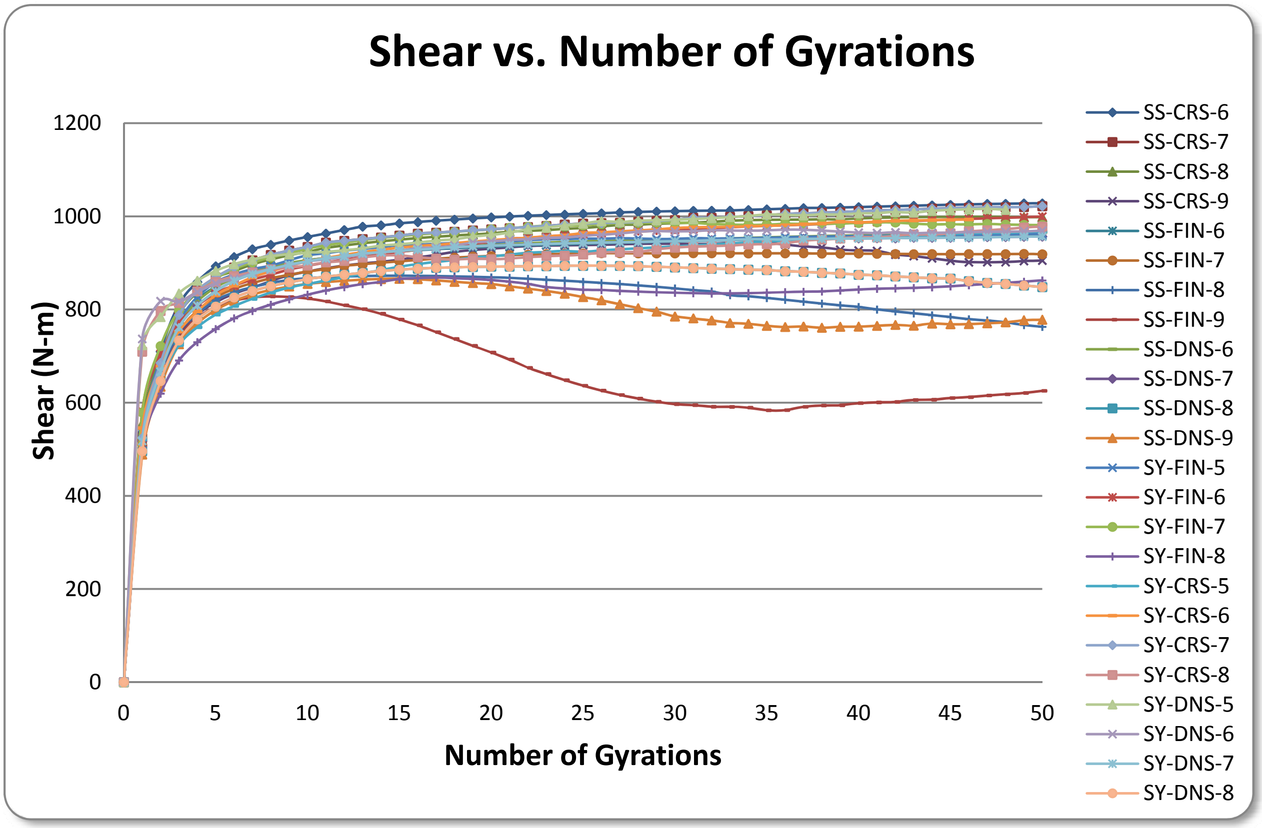

Figure 25. Specimen Heights During Compaction For Varying Gradations and Water Contents

In general, the shear increased dramatically during the first 5 gyrations, and then leveled off after about 10 or 15 gyrations. For most specimens, there was a slight linear increase in shear throughout the remainder of the compaction process. However, a few of the specimens experienced a decrease in shear during the latter stages of compaction, indicating a reduction in stiffness, or stability. These decreases indicated that a possible shift in the aggregate structure reduced the stiffness of the mixture, and suggested that the aggregate 'skeleton' did not possess the necessary aggregate interlock. In most cases, the specimens experiencing a reduction in stiffness were fine graded blends and/or high water contents. Thus, fine-graded blends may not be suitable for RCC design, and excessive moisture contents in the RCC may lead to mixture instability.

Locking Point

The Locking Point concept for gyratory compaction was developed as an alternate method for designing an aggregate structure. The Locking Point is generally defined as the point at which further compaction creates no further appreciable increase in specimen consolidation. In other words, at the locking point, the aggregate skeleton has "locked up" and additional gyrations in the compactor do not lead to substantial changes in density, which is identified by a lack of change in sample height. Locking point is defined in different ways by various agencies, but is typically stated to be the number of gyrations at which the same specimen height has been recorded for either two or three consecutive gyrations. The

Bailey Method for establishing blend gradations was based on the Locking Point concept (Li and Gibson, 2011).

In order to investigate this concept, the locking point was determined for the fine, coarse, and dense graded mixtures from two aggregate sources (sandstone and syenite). Locking point was determined to be the first of two consecutive gyrations where the same height was recorded. The locking points are shown in Table 22. If no data is shown, then the locking point was not reached within the 50 gyrations applied to the specimen.

Table 22. Locking Point for Varying Gradations

	Locking Point (gyrations) for Aggregate Type and Moisture Content							
	Sandstone				Syenite			
	6%	7%	8%	9%	5%	6%	7%	8%
Coarse	--	--	--	--	--	--	--	43
Fine	47	48	44	40	48	49	--	43
Dense	48	--	--	47	--	--	--	--

The locking point was reached for less than half of the specimens. When the locking point was not reached, it meant that the specimen was relatively stiff and required additional compactive effort to achieve its final density, or density at the locking point. When the locking point was reached, it was an indication that the final density was reached more quickly and did not require as much compactive effort; in other words, it was a more workable mixture. When locking points were achieved, they were most often associated with the fine-graded blends and the mixes containing higher moisture contents. This confirms that a coarse-graded mixture possesses more aggregate interlock than a fine-graded mixture, and that mixtures containing higher moisture contents are likely to be more workable.

If the alternative requiring three consecutive unchanged height values had been used to define locking point, none of the specimens would have reached the locking point. This could suggest that the RCC specimens needed additional compaction to reach a stable density. However, further compaction – especially for specimens containing higher moisture contents - tended to result in paste leaking from the specimen mold. Thus, an evaluation using the three-value locking point was not believed to have practical application for RCC.

Since it was established that the Proctor and gyratory compaction methods do not produce specimens of similar density, two choices are available to agencies utilizing RCC specifications:

1. one method should be chosen as the most appropriate for RCC mixture design, or
2. different specifications must govern each method of RCC mixture design.

Since fundamentally "true" values of density cannot be determined, relative densities must be used to make comparisons. Thus, it is unknown which density measure is "most correct", and other reasons must validate the preference of one method over another. In RCC mixture design, two primary properties govern the mix – density and strength. One type of compaction (either Proctor or gyratory compaction) is used to produce specimens for measuring density, while another (impact compaction) is used to generate specimens for measuring strength. It is reasonable, then, that the compaction method most closely matching the densities of the strength specimens would provide a more consistent design.

A comparison of density for the three available compaction methods was compiled for various RCC mixtures, and the results are shown in Figure 26. Gyratory compaction generated the highest densities, while the impact method yielded the lowest densities. This is reasonable given the fundamental differences in the kneading action of the gyratory compactor and the vertical forces imparted during impact compaction. The Proctor densities were mostly intermediate, and provided a more consistent match to the corresponding specimens that would be used for strength. Field compaction of RCC is most often performed using a high-density paver with a vibrating screed, providing somewhat of a combination of kneading and impact compaction. Thus, the Proctor method was chosen as the most representative of actual field compaction, and the preferred method for RCC mixture design.

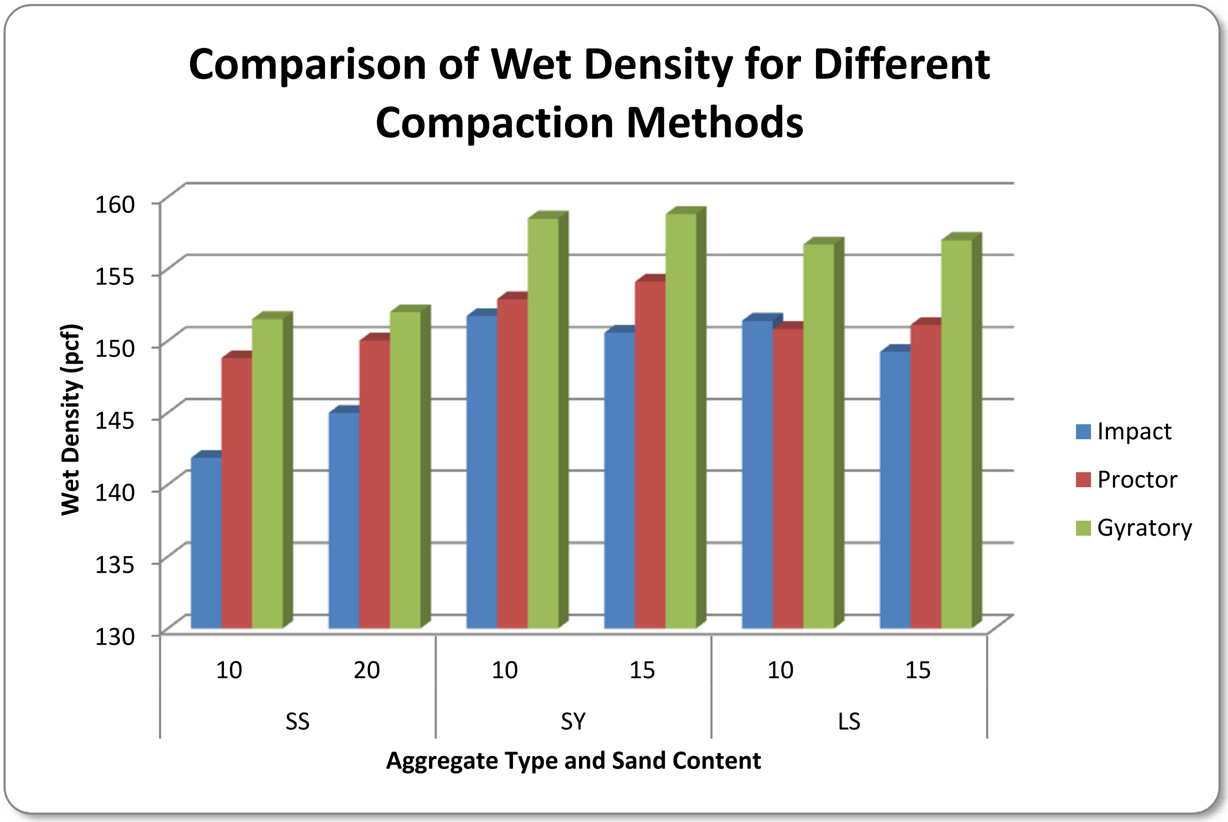

Figure 26. Comparison of Density for Specimens Compacted by Impact, Proctor, and Gyratory Methods

Specimen Geometry

If the gyratory compaction method was used for designing RCC mixes, it would be beneficial if the same type of specimens used to establish the optimum moisture content and maximum density of the RCC mixture could also be used for a determination of strength. In the current method, a Proctor or gyratory sample is prepared for determining moisture and density. Then cylinders must be prepared using an impact hammer in order to test for strength, allowing for potential differences in compaction method for the various stages of the mix design process. RCC strength specimens are most often made in 6 x 12 cylinders, but may also be formed in 4 x 8 cylinders. Traditionally, cylindrical specimens used for strength testing should have a length-to-diameter ratio (L/D) of approximately 2. If this ratio is reduced to 1.75 or less, then a correction factor must be applied to appropriately reduce the strength value of the specimen. When RCC is compacted in the gyratory compactor, the specimens are 150mm in diameter and typically no more than 150mm in height, resulting in a L/D ratio of only 1 (requiring a correction factor of 0.87. To investigate the possibility of using gyratory-compacted specimens for strength determinations, additional specimens were prepared in the gyratory compactor using two methods:

1. A 150mm x 150mm specimen was compacted in the SGC
2. A 150mm x 150mm specimen was compacted, and then a 3-inch diameter core was cut from the center of the specimen to generate a specimen with L/D equal to 2.

Additionally, 6 x 12 inch cylinders were prepared and cut in half, providing two 6 x 6 inch cylinders. This provided a direct comparison of impact and gyratory compaction for specimens having a L/D ratio of 1. Triplicate specimens were prepared using two mix designs (SS-DNS-5 and SY-DNS-5) and each of five specimen preparation methods. A summary of results is given in Table 23. Note that Proctor compaction was not used to prepare strength specimens because the final specimen height would be only 4.58 inches, which is significantly less than that required for the smallest available correction factor (L/D = 1). Because RCC pavements rely on early strength gain before opening to traffic, only 7-day strengths were used in the comparisons.

Table 23. Summary Density and Strength Data for Varying Specimen Geometry and Compaction

Specimen Geometry / Compaction Method	Density (pcf)	COV, % (density)	Strength (psi)	COV, % (strength)
6” x 12” cylinder Impact	145.69	0.12	3270	3.0
4” x 8” cylinder Impact	146.42	0.26	2972	4.1
6” x 6” cylinder Gyratory	143.20	0.62	2780	3.2
3” x 6” cylinder Gyratory	145.41	0.92	3460	3.1
6” x 6” cylinder Impact	145.60	0.11	2825	2.6

A complete randomized block ANOVA was used to analyze the effects of specimen geometry and compaction on density and strength. With respect to density, geometry/compaction was significant (p-value <0.0001) such that the densities of the gyratory-compacted 6 x 6 cylinders were significantly less than those of the other methods. All others were capable of producing similar specimen densities. The coefficient of variation for each method was very low – less than 1.0 percent in all cases. It has been shown that for asphalt specimens compacted in the gyratory compactor, a density gradient exists such that the perimeter areas of the specimen are less dense than the interior portions (Nam, 2005). Because the 3 x 6 specimens were cored from the center of 6 x 6 specimens, it is reasonable that they would demonstrate higher densities.

In terms of strength, geometry/compaction was again a significant factor (p-value <0.0001). However, none of the specimen types could be considered to produce similar strength results. The 3 x 6 gyratory-compacted specimens generated the greatest strengths, while the 6 x 6 gyratory-compacted specimens possessed the lowest strengths. Though specimen size and shape could not be separated from compaction method, compaction method did not appear to consistently affect strength values, and it was concluded that specimen shape has a greater impact on compressive strength than compaction method. Coefficients of variation were again relatively low, with all values less than 5 percent. Because significant differences were obtained for the various specimen configurations, gyratory-compacted specimens should not be used to produce specimens for measures of compressive strength.

Maximum Theoretical Density

For traditional concrete mixtures, density of the hardened concrete mixture can be measured according to ASTM C 642. This test is rather time consuming, does not provide a measure of absolute density, and is not commonly used in highway specifications. Although density can be an important parameter for traditional concrete materials, most specifications utilize strength as the primary measure of quality and basis of pay. The cement hydration process is the primary factor in strength development in concrete pavements, and may not be significantly related to density. In contrast, RCC pavements contain considerably less cement paste than traditional concrete mixtures, resulting in an increased dependence upon aggregate quality and interlock strength. Thus, aggregate quality and material density are much more critical to the overall performance of RCC mixtures than traditional concrete mixtures, and mixture density is usually a significant part of any QC/QA program for RCC pavements.

Measures of density can be generated in many ways. Different methods are specified for various types of paving materials. The density of RCC is a function of the density of its constituent materials (aggregate, cementitious materials, and water) and the workability/compactability of the mixture. Relative density, or specific gravity, is used to represent the density of aggregates, which are significant components of most paving materials. This property is calculated as a ratio of mass to volume such that the volume is determined from the difference between the weight of the material in air and in water.

For soil/aggregate mixtures, density is typically measured in the laboratory by the Proctor method (AASHTO T 99, AASHTO T 180, ASTM D 698, and ASTM D 1557) to establish the maximum dry unit weight (i.e., “Proctor” value). This value is considered to be the maximum dry density that should be achieved during field compaction. During construction, field density measures are compared to the Proctor value and reported as percent compaction. Although the Proctor value does not represent a theoretical maximum value of density, it does provide a “standard” by which to evaluate the level of field compaction, and most specifications require a minimum percent compaction for given material types or applications. Another measure of density used in soils applications is the unit weight (or density) at zero air voids (γ_{ZAV}). This value is calculated based on the assumption that no air is present in the soil mixture, and is a function of the density of the solid particles and water in the material, as shown in Equation 1. This value is a function of moisture content and varies such that γ_{ZAV} decreases with increasing moisture content. This quantity is not typically included as part of QC/QA specifications for soil compaction.

$$\gamma_{ZAV} = \frac{G_S * \gamma_{water}}{1 + \omega * G_S} \qquad \textit{Equation 1}$$

where: G_s = specific gravity of solids

γ_{water} = unit weight of water

ω = moisture content

Although concrete and asphalt mixtures possess significant differences inherent in material properties and behaviors, RCC and asphalt materials are similar in that each is significantly affected by the quality, density, and compactability of its constituent aggregate components. For asphalt materials, the in-place density of the compacted mat is measured and compared to a theoretical maximum density (TMD), and reported as percent compaction, or percent density. TMD is determined during the mixture design process and then monitored during construction. This value represents the mixture’s density when all of the air has been removed, and is essentially the apparent specific gravity of the coated aggregates. It is a theoretical value that cannot be practically achieved in the field, but is used as a baseline value for the purpose of providing a consistent relative comparison to in-place density. This value is determined by the Rice method, which is described in AASHTO T 209 and ASTM D 2041. The Rice method, developed by James Rice, employs a vacuum agitation process to enhance the basic principles of measuring weights and volumes of coated aggregate mixtures. It has been used for many years in the asphalt industry, and is relatively simple and inexpensive to perform. The Rice gravity of the asphalt mixture is calculated according to Equation 2.

$$TMD = \frac{Net\ wt.of\ sample\ in\ air}{Net\ wt.of\ sample\ in\ air - Net\ wt.of\ sample\ submerged} \qquad \textit{Equation 2}$$

The concept of theoretical maximum density has been previously explored for RCC mixtures. One such parameter was termed theoretical maximum constituent density (TMCD), and is defined as the combined density of the constituent RCC materials if all of the air were removed from the mixture. TMCD was adapted from asphalt mix design and aggregate blending concepts, and is calculated by Equation 3 (Amer, et.al., 2003 and Amer, et.al., 2004).

$$TMCD = \frac{P_c + P_f + P_{ca} + P_{fa} + P_w}{\frac{P_c}{RD_c} + \frac{P_f}{RD_f} + \frac{P_{ca}}{RD_{ca}} + \frac{P_{fa}}{RD_{fa}} + \frac{P_w}{RD_w}} \qquad \textit{Equation 3}$$

where: P_c = percent cement in total mix

P_f = percent fly ash in total mix

P_{ca} = percent coarse aggregate in total mix

P_{fa} = percent fine aggregate in total mix

P_w = percent water in total mix

RD_c = relative density of cement

RD_f = relative density of fly ash

RD_{ca} = relative density of coarse aggregate

RD_{fa} = relative density of fine aggregate

RD_w = relative density of water

When considering the use of density and/or specific gravity as a means to assess the quality of RCC, one must consider that there is no upper threshold of density at which the performance of RCC begins to decline. Thus, it is reasonable that the most appropriate measure of density by which to compare an in-place density would be the maximum theoretical density. This quantity represents the density of the material, assuming that no air is present in the mix, and that the mix contains only aggregates, cementitious materials, and water.

The Rice method, described in AASHTO T 209, was used to measure a theoretical maximum density (TMD) of six RCC mixes at varying moisture contents. Each specimen was batched and mixed according to ASTM C 192, and was then placed in a nonabsorbent container in a moist room for a period of 24 hours. Then the particles in each sample were separated such that no conglomerations greater than ¼ inch were present. The net weight of the test specimen in air was determined, and the sample was placed in a pycnometer and subjected to a vacuum of 27.5 ± 2.5mm Hg for a period of 15 ± 2 minutes under constant agitation on a vibrating table. A photograph of a sample under vacuum is shown in Figure 27. Then the sample was submerged for 10 ± 1 minutes and the net weight of the submerged sample was recorded. The TMD was calculated according to Equation 2, shown previously.

Figure 27. RCC Sample Under Vacuum – AASHTO T 209

Relative to the physical process of performing a Rice test on concrete materials, there were no major issues inhibiting completion of the testing. However, several challenges were noted. By curing the concrete mixture in the loose state for only 24 hours, it was unknown whether the curing of the loose mixture would properly mimic the curing that would be experienced in a compacted specimen, or whether enough curing had taken place to adequately measure the density. If longer curing times were to be used, the benefits of gaining somewhat "real time" information for the mixture would diminish. Also, as is evident in Figure 27, the water in the pycnometer during the vacuum process was cloudy, indicating either that some of the paste was being removed from the aggregate particles, or that small fines were separating from the sample resulting in measurement error. These fines could also create excessive wear on the testing apparatus.

For the coarse, fine and dense mixtures from the sandstone and syenite aggregate sources, three measures of maximum density were determined. They were the TMD values generated by the Rice laboratory testing method, and those derived by calculation, specifically unit weight at zero air voids

(ZAV), and TMCD. The calculated values were based on the measured densities of constituent materials and the actual moisture contents of each sample. A summary of results is given in Table 24.

Table 24. Summary of Results – Maximum Density (pcf) by 3 Methods

		Sandstone			**Syenite**		
Method	Moisture Content	Coarse	Fine	Dense	Coarse	Fine	Dense
Rice	Low	151.1	150.9	150.1	152.4	156.8	152.1
	Below Optimum	146.6	151.6	146.1	150.9	152.9	152.5
	Optimum	147.1	147.4	145.0	148.2	151.7	147.4
	Above Optimum	147.1	144.6	144.0	148.9	154.3	147.0
TMCD	Low	153.3	151.9	151.7	160.3	160.1	158.8
	Below Optimum	152.6	150.8	149.6	154.4	157.4	155.8
	Optimum	149.5	149.0	148.6	153.2	155.4	154.0
	Above Optimum	148.5	146.5	146.9	151.0	153.5	151.8
ZAV	Low	146.4	143.4	143.5	154.7	154.6	152.4
	Below Optimum	145.1	141.7	140.1	151.4	150.4	147.7
	Optimum	140.0	138.8	138.4	149.4	147.2	144.8
	Above Optimum	138.5	134.8	135.8	145.7	144.2	141.4

First, the results were plotted against moisture content to prove that the appropriate theoretical trends did exist. These results are shown in Figures 28, 29 and 30.

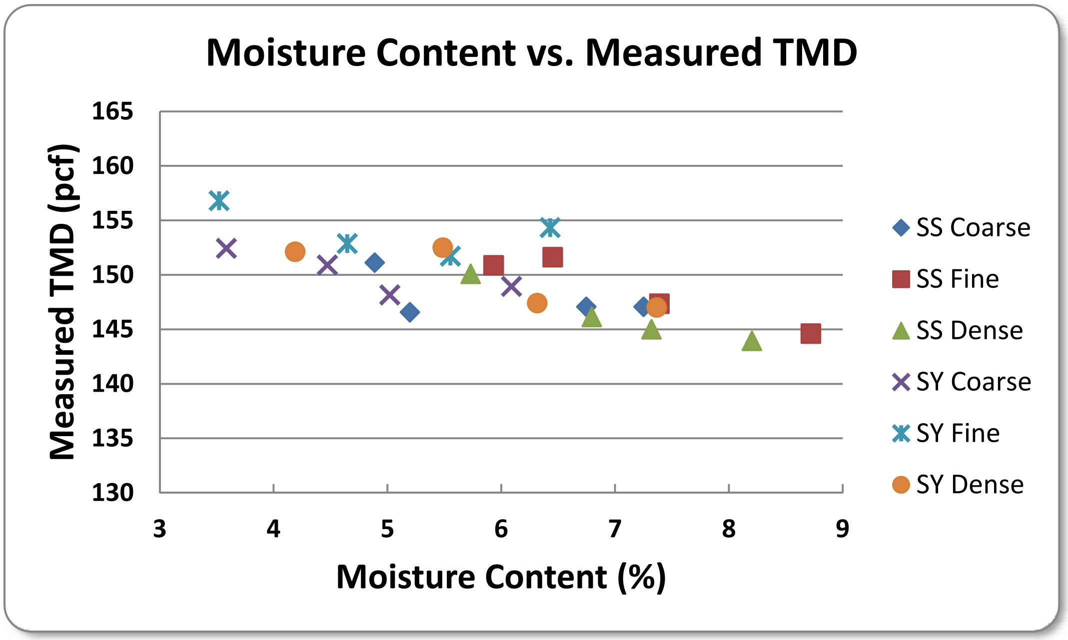

Figure 28. Relationship of Moisture Content and Measured TMD

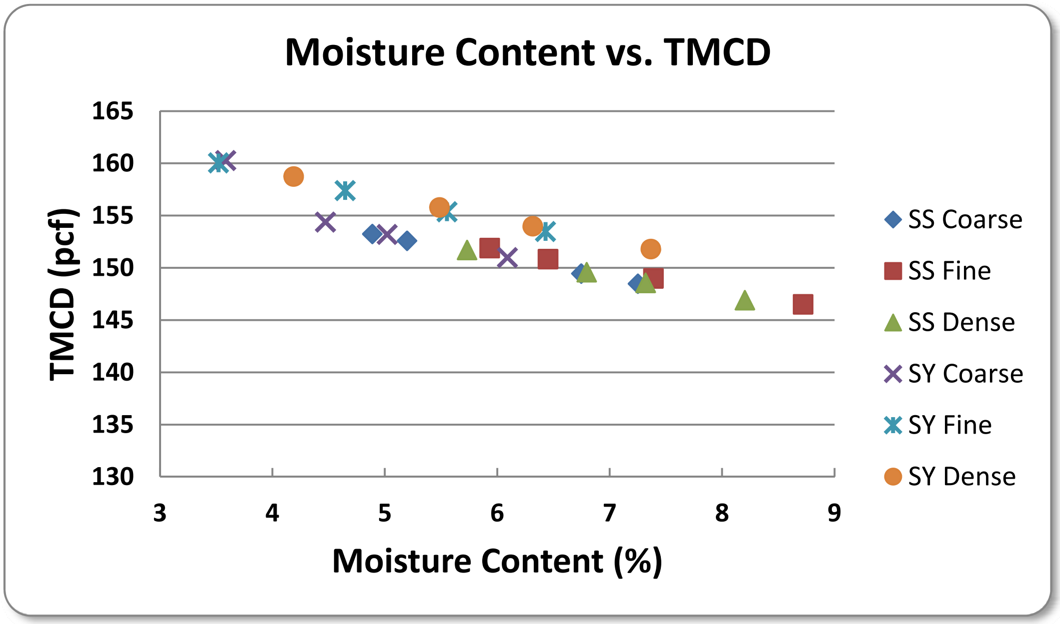

Figure 29. Relationship of Moisture Content and TMCD

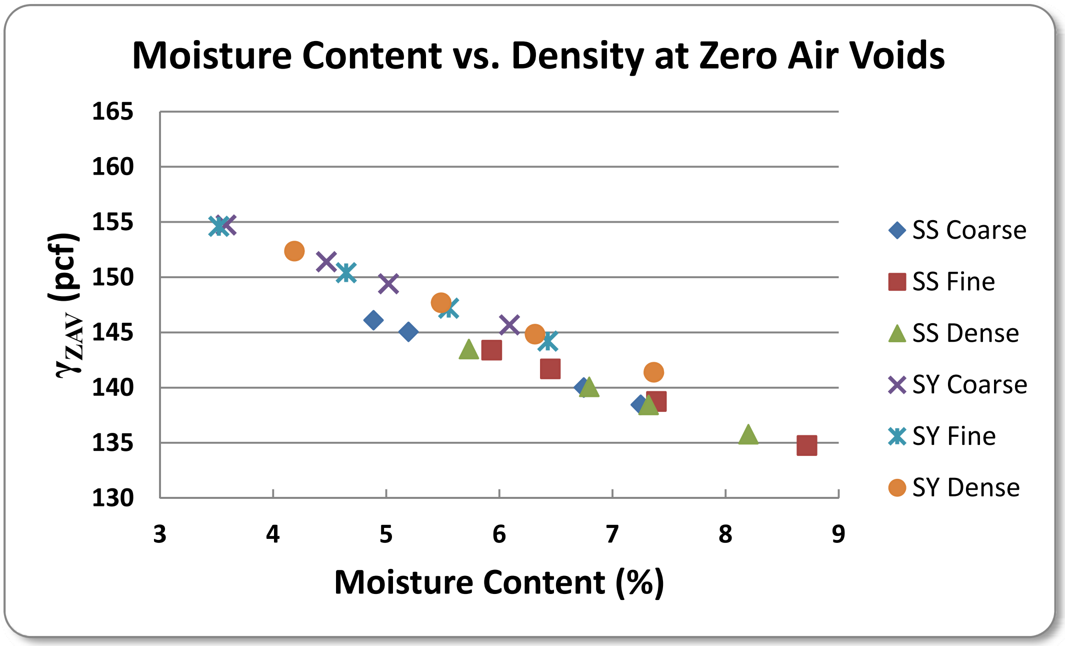

Figure 30. Relationship of Moisture Content and γ_{ZAV}

The relationships of γ_{ZAV} and TMCD showed clear linear relationships with moisture content, which was expected given that they simply represent a series of calculated values. It is interesting, however, that the γ_{ZAV} relationship showed somewhat lower values of theoretical maximum density than the TMCD method. This is most likely because the TMCD values represent a calculation based on measures of densities for the individual components of the mixture, while the ZAV calculations are based on mixture properties.

The relationship of the measured TMD by AASHTO T 209 to moisture content followed a similar relationship of decreasing density with increasing moisture content, however the trend was less defined. This is reasonable given the fact that more variability is expected from performing a laboratory test method than a calculation. Overall, the trend was reasonable, and the evident relationship supports the potential for the AASHTO T 209 method to provide measures of TMD for RCC.

Next, the measured TMD values were compared to the calculation methods, as shown in Figures 31 and 32. From these comparisons, it was evident that significant relationships existed between methods, although they were not strong enough for predictive purposes. In the relationship of γ_{ZAV} and measured TMD, the general trend did not follow the line of equality. Specifically, the γ_{ZAV} appeared to be the more sensitive of the two to changes in density, yet also tended to underestimate the measured TMD.

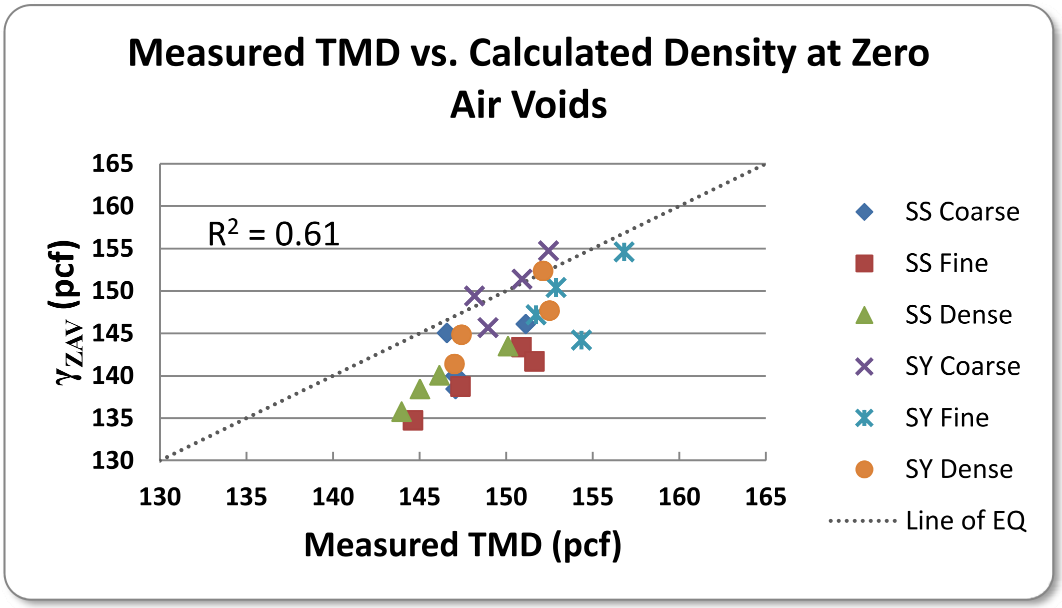

Figure 31. Relationship of Measured TMD and Zero Air Voids Density

In the relationship of TMCD and measured TMD, a slightly stronger relationship existed (R^2 = 0.68) and the general trend appeared to follow that of the line of equality, although the TMCD calculation appeared to slightly overestimate the measured values. This difference may have been due to the fact that the TMCD values are based strictly on the densities of constituent materials, while TMD is measured after mixing when a very small portion of air may have become trapped between the aggregate particles and paste coating, slightly reducing the measured density.

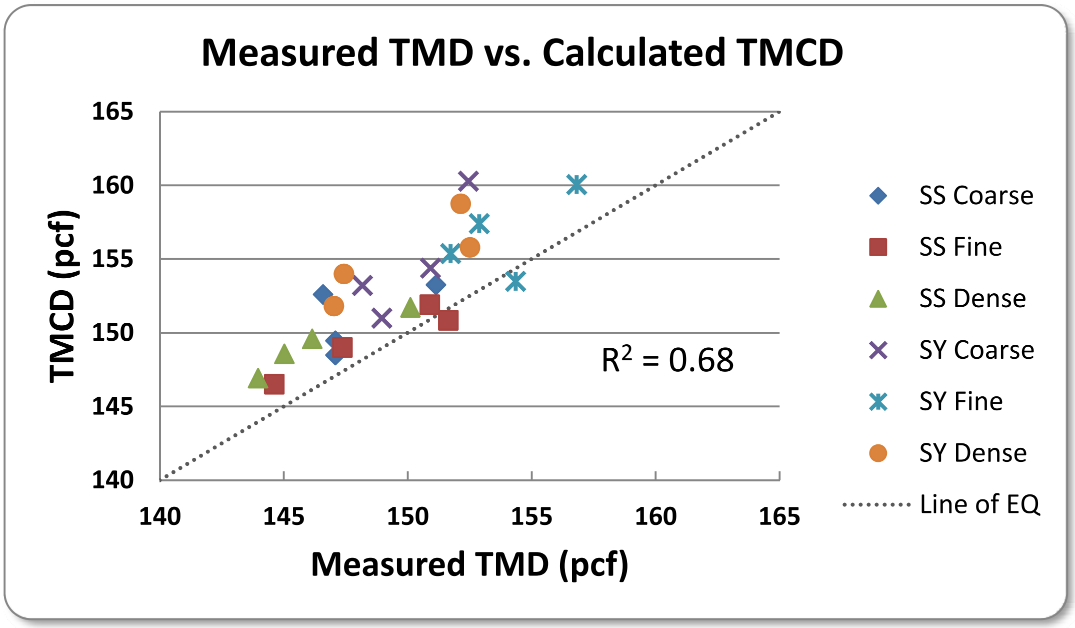

Figure 32. Relationship of Measured TMD and Calculated TMCD

Finally, the two methods for calculating a maximum density were compared. The relationship of the ZAV and TMCD methods are plotted in Figure 33. As previously noted, the TMCD method provides a higher measure of density than the ZAV calculation, with slightly greater differences for the specimens of lower density. On average, the ZAV density was 94.7 percent of the TMCD density. The consistency in the relationship of the two calculation methods was substantial, having an R^2 value of 0.91.

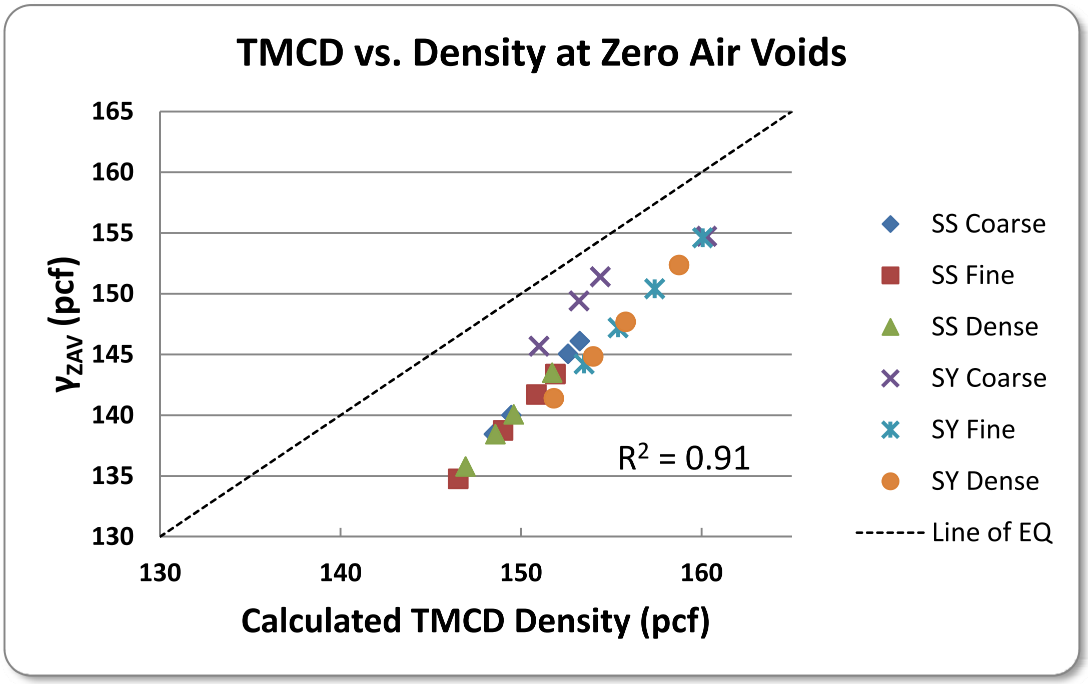

Figure 33. Relationship of TMCD and Density at Zero Air Voids (ZAV)

Overall, these relationships show that the various measures of maximum density of RCC mixtures provide similar trends but do not necessarily provide similar results. The measured TMD by AASHTO T 209 shows promise, but any chosen method must have valid application. Due to the time and effort involved in the measured values of theoretical maximum density by AASHTO T 209, along with the uncertainties encountered, this method is not recommended without further study. Though reasonable relationships were developed, the application of results was not deemed immediately applicable for routine use. Calculated measures, however, could easily be incorporated for use in assessing the extent to which an aggregate blend is able to be compacted to its maximum theoretical density. In other words, a comparison of compacted and theoretical maximum densities could be used to estimate a value of workability for an RCC mix, or used as a tool to evaluate how workable a mixture might be.

To test this theory, the TMCD was calculated for a selection of mixes from each aggregate source. From previous analyses, it was determined that designing an aggregate blend so that it closely follows the MDL should increase its density, and increasing natural sand should assist in increasing the workability of the mix, thereby aiding compaction.

For mixtures designed using the Proctor method, percent of maximum density was calculated as a percentage of ZAV and TMCD. For mixtures designed using the Gyratory method, percent density was calculated as a percentage of TMCD. Results are shown in Figure 34. For reference, the aggregate blends having gradations that most closely follow the MDL are circled. Using the ratio of maximum dry density by the Proctor method to the ZAV density, several of the mixtures possessed greater than 100 percent density. This is theoretically impossible and indicates some error in the values or concepts used for the calculations.

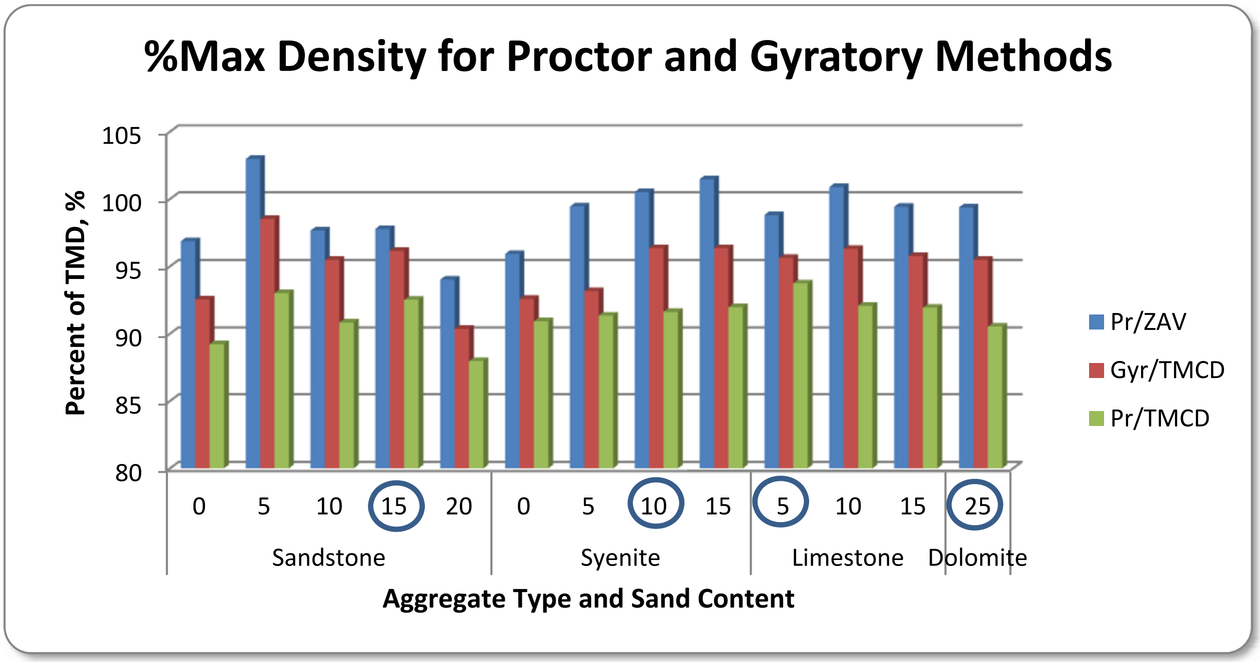

Figure 34. Percent of Maximum Density for Various Gradations and Sand Contents

Considering the combination of gyratory density and TMCD, the greatest percentages were obtained for 5 percent sandstone, 10 percent syenite, 10 percent limestone, and 25 percent dolomite. These blends did not necessarily correlate with either the blend nearest the MDL or the blend containing the greatest natural sand content.

The final combination included the ratio of Proctor density and TMCD. In this case, the blends achieving the greatest percentage of theoretical maximum density were the sandstone mixes containing 5 and 15 percent sand, the syenite mixes containing 10 and 15 percent, and the limestone mix containing 5 percent sand. In this case, the mixes that were nearest the MDL were more readily identified as also having a greater percentage of maximum density. Based on the mixes tested, a mixture may possess more desirable characteristics if the maximum dry density by the Proctor method meets a minimum threshold value of 90 percent of the TMCD. This data warrants further study, and could lead to the development of a tool for maximizing the density and workability of an RCC mixture.

RCC Performance

Performance predictions are important features of any paving mixture design procedure. Mixture proportions are focal points of the design process, but are useless if the resulting product falls prey to other factors adversely affecting long-term performance. Freeze/thaw susceptibility, skid resistance, and shrinkage were believed to be among the most likely pitfalls for RCC paving mixtures.

Freeze/Thaw Resistance

Because RCC has less paste than conventional concrete mixes, aggregates are more likely to become exposed and made susceptible to the effects of freeze/thaw damage. In the next analysis, two mixture designs were used to investigate freeze/thaw resistance. A syenite mixture was used to represent an aggregate source that has demonstrated good freeze/thaw resistance, and the dolomite mixture was selected as one that was known to be susceptible to freeze/thaw issues (Williams and Cunningham, 2012). From each aggregate source, eight replicate specimens were prepared and cured for 14 days. Then four specimens from each mix were treated as the control specimens and were cured for an additional 14 days, while the other four were saturated and subjected to five 24-hour freeze/thaw cycles. The compressive strengths were then measured when the specimens reached an age of 28 days. A summary of data is shown in Figure 35.

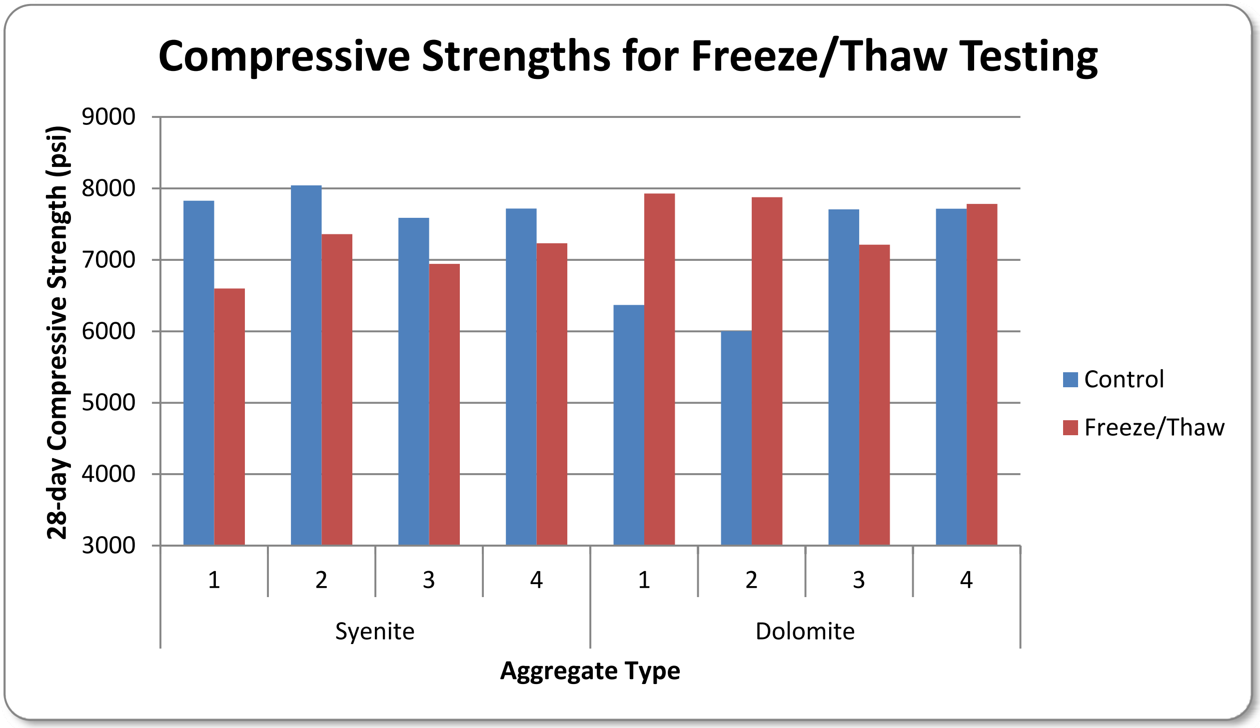

Figure 35. Effects of 5 Freeze/Thaw Cycles on RCC Cylinders Based on Strength at 28 Days

Overall, the freeze/thaw conditioning created a decrease in strength for the syenite mixtures, and mixed results for the dolomite mixtures. In two instances, a large increase in compressive strength was noted for the conditioned dolomite specimens, with one comparison yielding an increase of almost 1900 psi. Though some differences were visually evident, they were not statistically significant (p-value = 0.99) in ANOVA testing. The mean strength value for the control samples was 7271 psi, while that for the conditioned specimens was 7367. The distribution graph is shown in Figure 36. Thus, for the mixes tested, freeze/thaw conditioning did not adversely affect the compressive strengths of the RCC mixes.

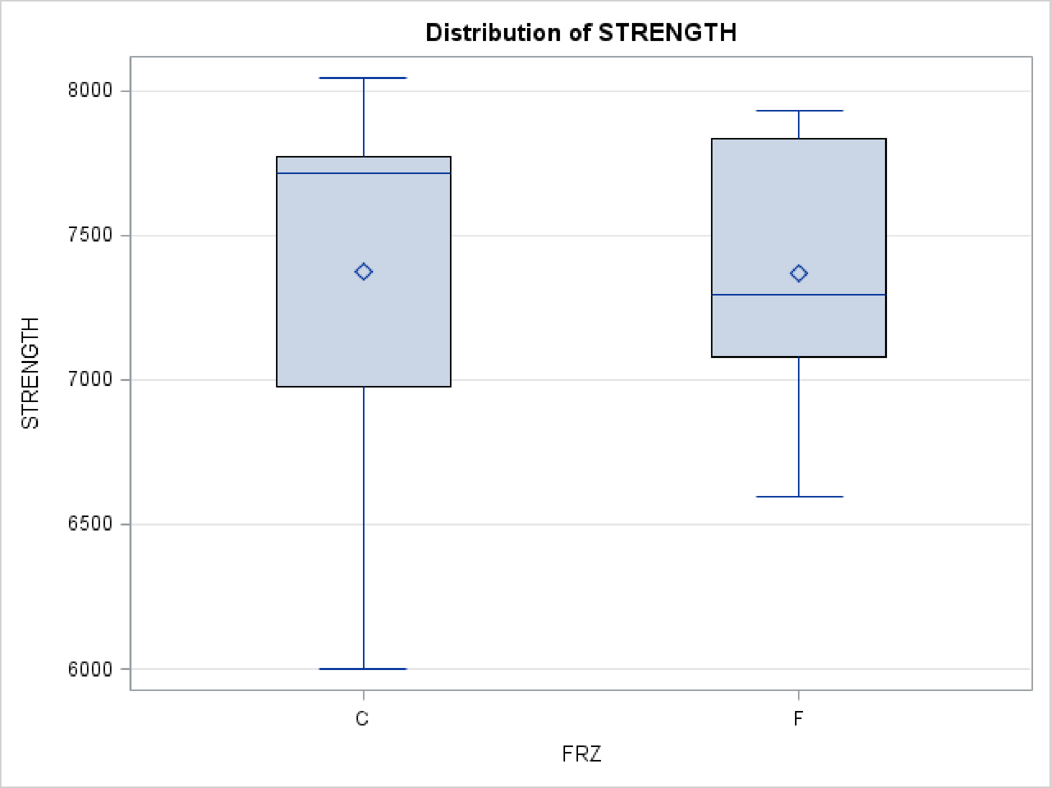

Figure 36. Distribution of Strength Values for Control (C) and Conditioned (F) Specimens

Skid Resistance

Initially, an investigation was planned that would assess the skid resistance of RCC mixtures. However, after specimen preparation methods were established, it was not felt that the laboratory prepared specimens would provide a surface representative of an actual field-constructed RCC pavement. Additionally, the literature review recommended that any medium- to high-speed roadway with an RCC wearing course would require the surface to be diamond ground in order to provide adequate smoothness. Thus, this experiment was not felt to be appropriate and was not performed.

Shrinkage

One of the stated advantages of the RCC material is that since it contains less paste, it is less likely to experience shrinkage, and shrinkage-related cracking is minimized. The research team was unable to produce specimens that were geometrically appropriate for a true shrinkage analysis. However, length change measurements were made for a sample subset, and none of the samples experienced any decrease in length. In fact, some samples developed an increase in length of approximately 1 to 1.5

mm. Thus, shrinkage was not believed to be of concern and no further investigation was performed for this property.

6. Conclusions and Recommendations

This project included a review of roller compacted concrete pavements, including the feasibility of using RCC pavements in the state of Arkansas, and a thorough investigation of RCC mixture design.

PHASE 1

The feasibility portion was completed in Phase 1 of the study, and included life-cycle cost analyses for equivalent sections of multiple pavement design parameters. To provide comparisons of typical pavement sections and comparable RCC sections, structural pavement designs for various combinations of base and wearing course alternatives were completed for the following combinations of subgrade condition and traffic level:

- Weak, poor-draining soil / low traffic
- Average soil / low to moderate traffic
- Average soil / moderately high traffic
- Good, well-draining soil / high traffic
- Average soil / high traffic
- Weak, poor-draining soil / high traffic
- Very weak, poor-draining soil / moderately high traffic
- Very weak, poor-draining soil / very high traffic

The cost of materials to construct a section for each condition was compared for each alternative, including traditional Hot Mix Asphalt (HMA) and Portland Cement Concrete (PCC) options. In most cases, the RCC alternative was the least expensive. The only exceptions were for the very weak soils, in which the full-depth HMA alternatives were slightly less costly. Next, a life-cycle cost analysis was performed to assess the relative costs over the life span of the pavement structure, and again, the RCC alternative was clearly advantageous. Based on just the initial cost of materials, the RCC alternative represented a savings of approximately 25 percent when compared to equal thicknesses of HMA.

In addition to monetary savings, RCC pavements provide efficiencies in the construction process. RCC pavements do not require reinforcing steel, dowels, forms or finishing, and can be opened to traffic in as little 24 hours after compaction. Typically, 6 to 8 inch lifts can be placed at one time, in most cases eliminating the need for multiple passes of a paver.

To date, the use of RCC has been extremely limited in the state of Arkansas, though many states in the southeastern U.S. have implemented RCC pavements with success. In a review of Arkansas projects constructed within the last decade, approximately 38 percent were identified as projects that could have benefitted from the use of RCC. Thus, substantial saving could be realized through the implementation of RCC.

Recommendation

RCC should be included as a viable alternative for pavement construction in Arkansas. The types of applications for which RCC pavement should be considered include:

- New construction and major reconstruction/rehabilitation
  - Fayetteville Shale Play Area
  - Base course for full-depth HMA
  - Alternative to PCC Base
  - As a wearing course only if diamond ground
- Notch-and-Widening projects
  - The width of the added section should be 8 feet or greater to accommodate proper compaction
- Intersection Rehabilitation
  - Cap with an asphalt wearing course or diamond grind the RCC surface
- Construction Phasing
  - To 'winterize' a project, protect the subgrade, and provide a temporary driving surface
- Rest Areas, parking lots, and weigh stations

RCC pavements are NOT recommended for use in:

- Thin overlays
- Wearing course for high-speed traffic, unless diamond grinding is performed

For roadway applications, the 1993 AASHTO guide for structural pavement design should be used to determine layer thicknesses. For composite pavement structures, the asphalt design method should be used, applying a layer coefficient of 0.50 (range of 0.47 to 0.52) for RCC. In the future, RCC should be further evaluated for the MEPDG (DARWin-ME or Pavement ME Design). For parking areas, rest areas, or weigh stations, the ACI Guide for the Design and Construction of Concrete Parking Lots (ACI 330R-08) should be used, and the design reliability level should be increased by 5 percent.

PHASE 2

In Phase 2, a critical review of RCC mix design was completed, specifically focusing on the Proctor method of design. Because of the similarities of the placement and compaction of RCC to that of asphalt mixes, the Superpave Gyratory Compactor was also evaluated as a potential design tool.

Gradation

Methods for developing RCC blend gradations were included, and particular attention was given to combinations of multiple aggregates, natural sand content, and the shape of the gradation curve. Coarse, fine, and dense gradations were compared, and the dense blends were associated with higher strengths and higher densities – both of which are desired properties. Fine-graded blends were associated with the lowest densities and strengths, discouraging further use of fine gradation shapes. Further evaluations of gradation involved using the Shilstone concept and adding natural sand to create a gradation curve that closely followed the maximum density line (MDL) on the 0.45 power chart, and it was noted that combinations of three or more aggregates provided greater flexibility in gradation adjustments.

Recommendation

> It is recommended that RCC mixtures follow the PCA-recommended guidelines for blend gradation, and employ Shilstone's concepts to maximize the density of the aggregate blend. Aggregate blends should be dense-graded, and fine-graded blends should be avoided. Excessive moisture contents could be detrimental to mix performance and should be guarded against. Moisture content fluctuations of ±0.5 percent could create significant changes in the compactability of the mixture, and fluctuations of more than ±1 percent should not be allowed.
>
> Natural sand should be used because the rounded particle shape enhances the workability of the mixture. However, the reduced paste content of RCC creates a greater dependence upon the aggregate structure; and coarse, angular aggregates provide the interlock necessary for a stable aggregate structure. Coarse aggregates used in RCC mixes should be crushed to ensure mixture stability. Depending on the aggregate sources included in the mix, natural sand percentages should be at least 10 to 15 percent, and greater when increased amounts allow the overall blend gradation to more closely match the MDL. Requiring the gradation curve to closely follow the MDL should effectively limit the natural sand content, preventing it from becoming excessive.

Mix Design

Proctor and gyratory mix design procedures did not yield equivalent designs. Increasing moisture contents beyond optimum for gyratory compacted specimens did not result in decreased densities, as is typical of the "wet" side of the Proctor curve. Rather, excess moisture and paste escaped from the sample during compaction, resulting in a maximum achievable moisture content and associated density. Gyratory-derived designs generated maximum densities of almost 5 psi greater than Proctor-derived designs. Gyratory designs also identified lower optimum moisture contents (approximately .75 percent less) than the optimum value from a Proctor design.

While either process could be used for design, the higher design maximum densities obtained by the gyratory method would require additional field compaction during the construction process. This discrepancy would necessitate an adjusted field density specification that would represent reasonably achievable levels of compaction.

Recommendation

> Until further evidence suggests that the gyratory provides more significant advantages over the Proctor method of RCC mix design, the Proctor method (according to AASHTO T 180) should be used to determine the maximum dry density and optimum moisture content of RCC mixtures.

Density

Density is a key parameter used to assess the quality of RCC pavements. Most specifications require a minimum in-place mat density of 98 percent of maximum wet density as determined by the Proctor method. The densities of the RCC mixtures evaluated in the laboratory for this study were significantly affected by:

- The densities of the constituent aggregates – greater aggregate densities generated greater mixture densities
- Particle shape – rounded particles provided additional consolidation
- Gradation shape – gradations that closely matched the maximum density line provided greater mixture densities
- Method of compaction – impact compaction (ASTM C 1435) provided the lowest densities, while gyratory compaction generated the highest densities. Proctor compaction provided intermediate results, and was believed to be most representative of field compaction

Recommendation

Density of RCC should be determined in the laboratory using the Proctor compaction method.

Theoretical Maximum Density

Theoretical maximum density (TMD) was measured for RCC mixes using the Rice method as described in AASHTO T 209. Additional values were calculated by the Zero Air Voids (ZAV) and Theoretical Maximum Constituent Density (TMCD) methods. While no method could be proven to be more correct than another, the Rice test did not provide a great enough advantage to be recommended over the calculation methods. Ratios of maximum dry density from mixture design processes were represented as percentages of TMD. The ratio of Proctor maximum dry density to TMCD was most successful in identifying stable aggregate blends. This ratio could be useful in screening trial aggregate blends for RCC mixture design.

Recommendation

The ratio of maximum dry density (by AASHTO T 180) to TMCD should be calculated during mix design. A minimum ratio of 90 percent should be used as a screening tool to identify and eliminate poor-performing RCC mixtures.

Compressive Strength

The compressive strengths of RCC specimens were measured for varying specimen configurations, gradation types, and sand contents. Overall, strengths were not affected by sand content, meaning that natural sand content can be adjusted to balance the workability and stability of a mixture without adversely affecting strength. Compressive strengths were significantly affected by the following factors:

- Cylinder dimensions - 6 x 12 cylinders yielded slightly greater strengths than their 4 x 8 companions.
- Gradation shape – dense-graded blends provided the greatest strengths
- Aggregate Type – denser aggregate components yielded specimens of greater strength
- Cement Content – Higher cement contents provided increased strengths.
- Curing Time – longer curing times generated higher strengths.

Strength Gain

Typically, 28-day strengths are used for RCC mixture design; however, early strengths are important for determining when a new RCC pavement can be opened to traffic. Thus, earlier measures of strength should be included in the RCC mixture design process. Approximately ½ of the mixture's 28-day strength was attained after 24 hours. This relationship should be considered when setting specifications for design compressive strengths so that early strengths will be adequate and lane closures can be minimized.

Gyratory Specimens

Gyratory-compacted specimens were also tested for strength, but the results were significantly different from those generated by typical RCC methods. Thus, the standard strength specimens prepared according to ASTM C 1435 should be used for compressive strength determinations.

Recommendation

> The compressive strength of RCC mixtures should be determined using specimens prepared according to ASTM C 1435. These specimens can be either 6 x 12 or 4 x 8, though the 6 x 12 specimens in this study yielded compressive strengths of almost 200 psi greater than their 4 x 8 counterparts. The 4 x 8 specimen size could be used, but may be slightly less able to meet minimum compressive strength requirements.
>
> The 28-day compressive strength of RCC paving mixtures should be set at a minimum of 5000 psi. Because RCC specimens in this study gained approximately 50 percent of their 28-day strength after 24 hours, strengths of approximately 2500 psi could then be expected after 24 hours of field curing, allowing traffic to be returned to the roadway after just 24 hours and minimizing lane closures.

Proposed Specification Language

A specification written regarding RCC mixes should include the following points. A proposed draft specification is included in Appendix C.

Aggregates

- The aggregate blend must represent a combination of 2 or more aggregates.
- Coarse aggregates used in RCC mixes shall be crushed, and should meet the quality requirements for aggregates used in HMA and PCC paving mixes.
- One of the fine aggregates must be a natural, rounded sand.
- The blend gradation must meet the requirements of Table 25, and should closely follow the maximum density line (MDL).

Table 25. PCA Recommended Gradation Specification (Harrington, 2010)

Sieve Size	Percent Passing by Weight
1" (25 mm)	100
¾" (19 mm)	90 – 100
½" (12.5 mm)	70 – 90
3/8" (9.5 mm)	60 – 85
No. 4 (4.75 mm)	40 – 60
No. 16 (1.18 mm)	20 – 40
No. 100 (150 mm)	6 – 18
No. 200 (75 mm)	2 - 8

Cement

- All cementitious materials must meet the requirements of Section 501.02 of the latest edition of the AHTD Standard Specifications for Highway Construction.

Mix Design

- Maximum density and optimum moisture content shall be determined using the Proctor method as described in AASHTO T 180 for a trial cement content.
- The optimum moisture content shall be used to prepare a set of strength specimens for a range of cement contents. The cement content shall be adequate to meet the minimum required design 28-day compressive strength.
- The Proctor relationship shall then be confirmed using the selected cement content, adjusting the optimum moisture content if necessary.
- The mix design report shall provide graphs for the initial moisture-density relationship, the cement content – strength relationship, and the final moisture-density relationship (using the selected cement content)
- Strengths at 24-hours, 3 days, and 7-days shall be submitted with the mix design.
- Theoretical Maximum Constituent Density (TMCD) shall be calculated and reported on the mix design, according to the following Equation:

$$TMCD = \frac{P_c + P_{ca} + P_{fa} + P_w}{\frac{P_c}{RD_c} + \frac{P_{ca}}{RD_{ca}} + \frac{P_{fa}}{RD_{fa}} + \frac{P_w}{RD_w}}$$

where: P_c = percent cementitious materials in total mix

P_{ca} = percent coarse aggregate in total mix

P_{fa} = percent fine aggregate in total mix

P_w = percent water in total mix

RD_c = relative density of cementitious materials

RD_{ca} = relative density of coarse aggregate

RD_{fa} = relative density of fine aggregate

RD_{w} = relative density of water

- The ratio of maximum wet density (from the final Proctor curve) to the calculated TMCD should not be less than 0.90.

Strength

- Compressive strength specimens for mixture design shall be prepared according to ASTM C 192 and ASTM C 1435, using either 6 x 12 or 4 x 8 cylinders.
- The minimum design 28-day compressive strength shall be 5000 psi.

Construction

- During construction, the compacted wet density must be at least 98 percent of the maximum density obtained by the final Proctor relationship (AASHTO T 180) during the mix design.
- Moisture content shall be maintained at the optimum percentage ± 1 percent.

7. Acknowledgments

This document contains a summary of results and recommendations for the implementation of research conducted by the University of Arkansas for the Arkansas State Highway and Transportation Department (AHTD) under project TRC 1005, Roller Compacted Concrete for Roadway Paving. The author gratefully acknowledges the assistance of the students and employees who helped make this project a success. The diligent efforts of University of Arkansas students T. Brett Gilbert, Thomas Moss, and Sanjay Selvam are sincerely appreciated.

The views expressed in this report are solely the responsibility of the author, and do not necessarily represent the official views of the sponsoring agencies. This report does not constitute a standard, specification, or regulation.

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APPENDIX A

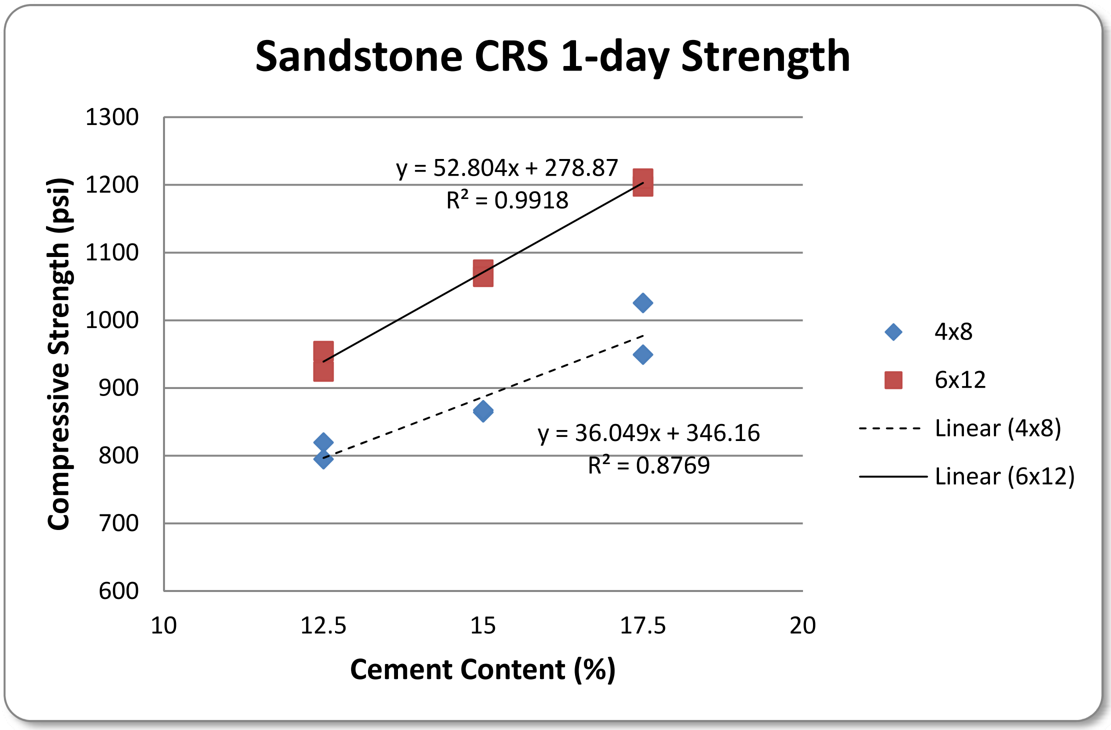

Figure A-1. 1-Day Strength Relationships for Coarse Sandstone Mixture

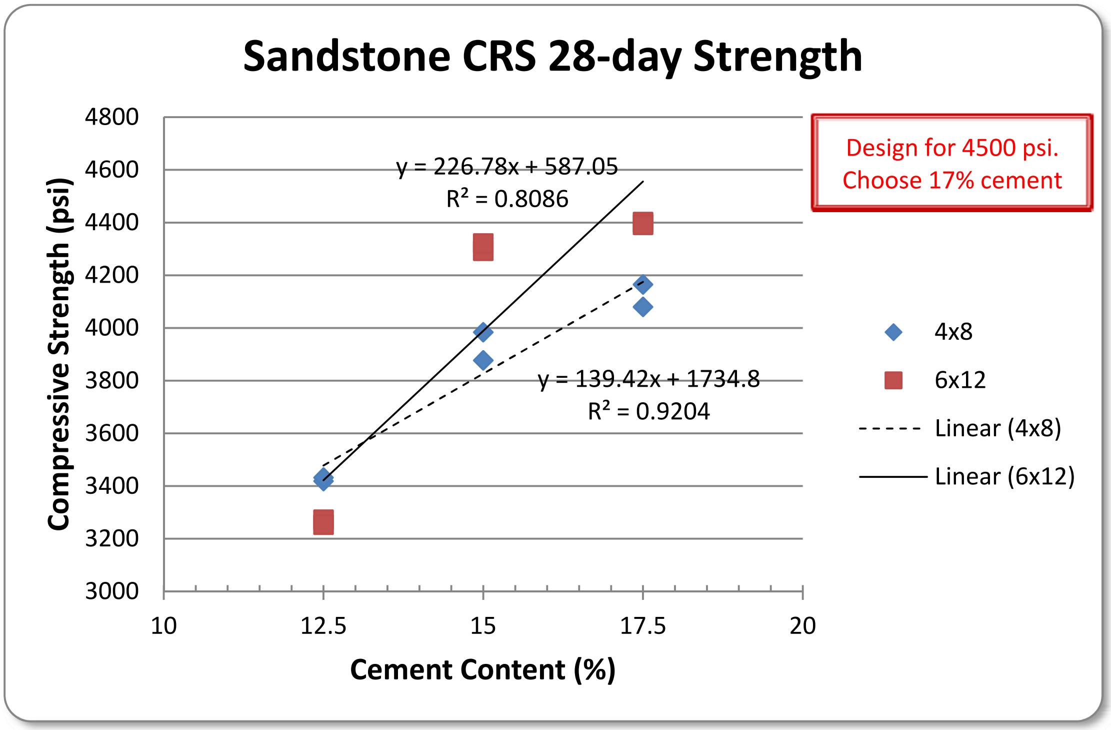

Figure A-2. 28-Day Strength Relationships for Coarse Sandstone Mixture

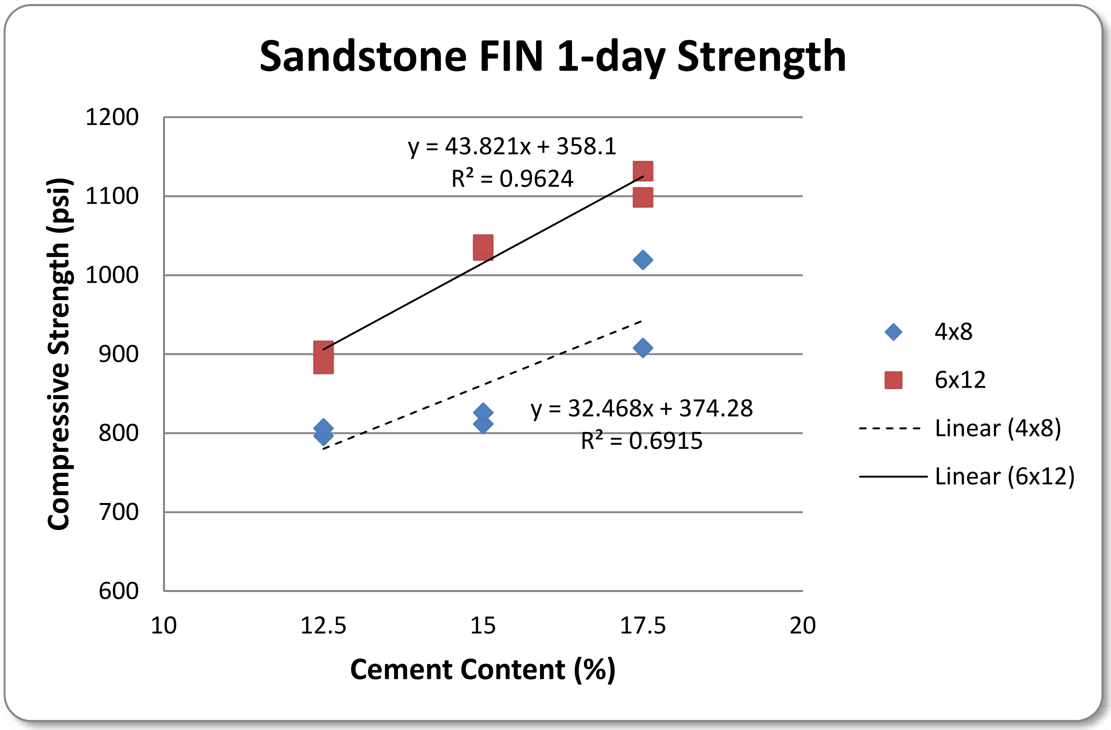

Figure A-3. 1-Day Strength Relationships for Fine Sandstone Mixture

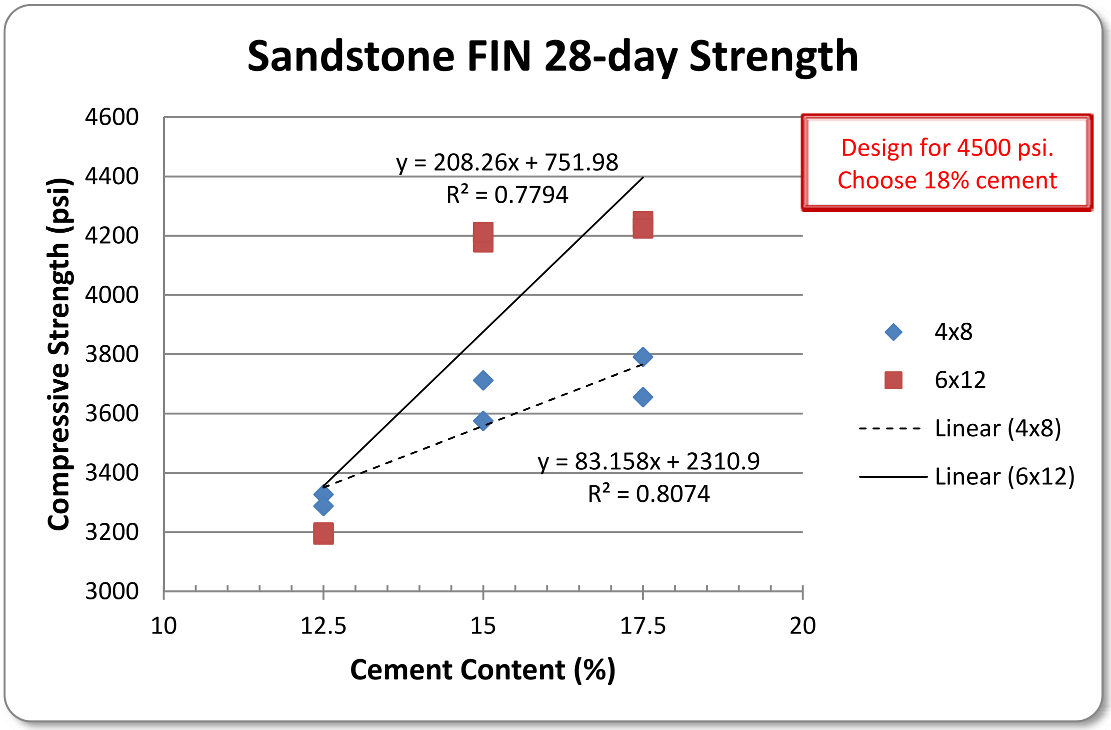

Figure A-4. 28-Day Strength Relationships for Fine Sandstone Mixture

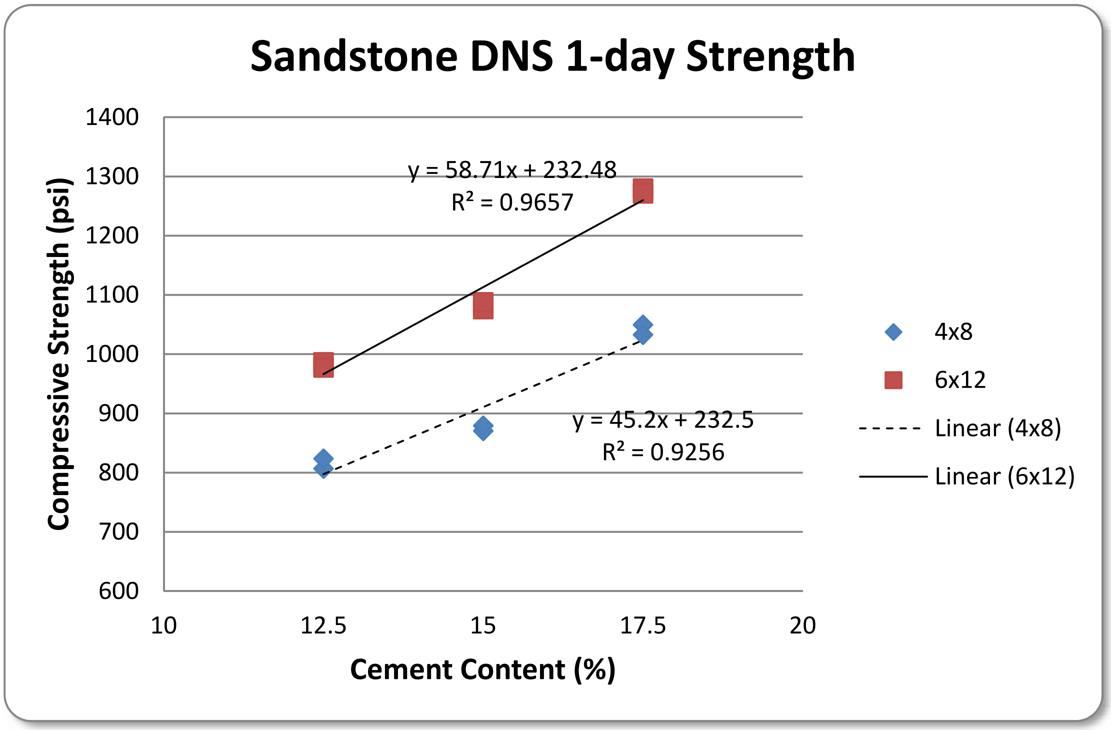

Figure A-5. 1-Day Strength Relationships for Dense Sandstone Mixture

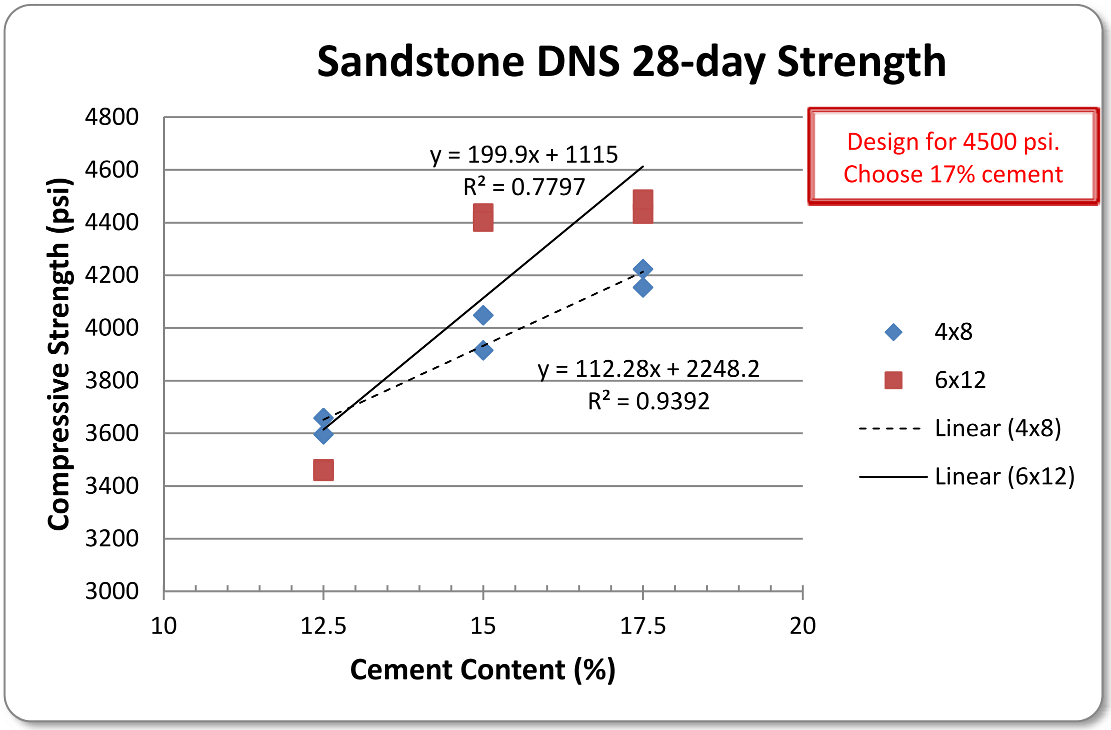

Figure A-6. 28-Day Strength Relationships for Dense Sandstone Mixture

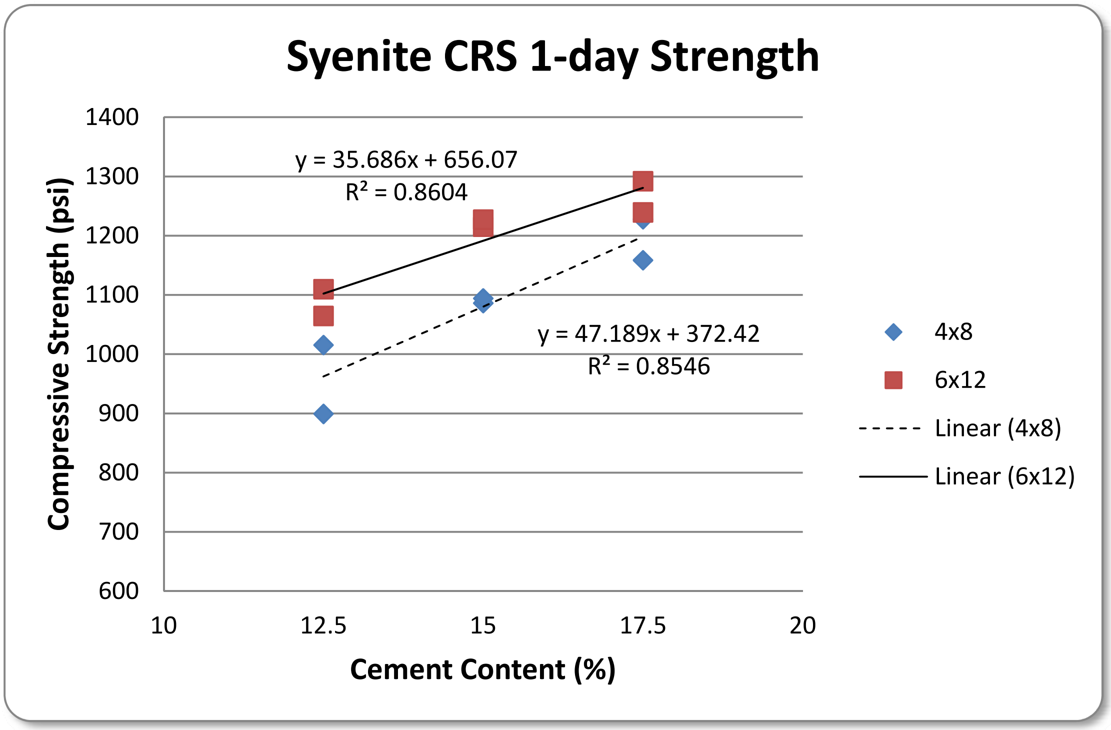

Figure A-7. 1-Day Strength Relationships for Coarse Syenite Mixture

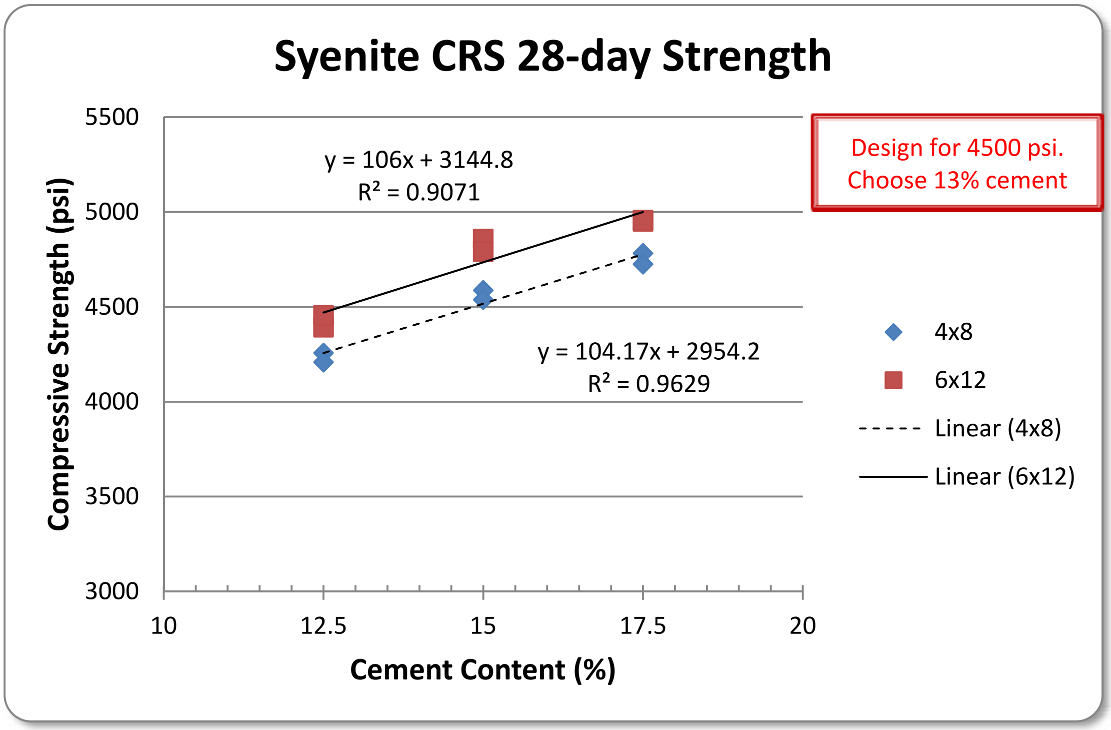

Figure A-8. 28-Day Strength Relationships for Coarse Syenite Mixture

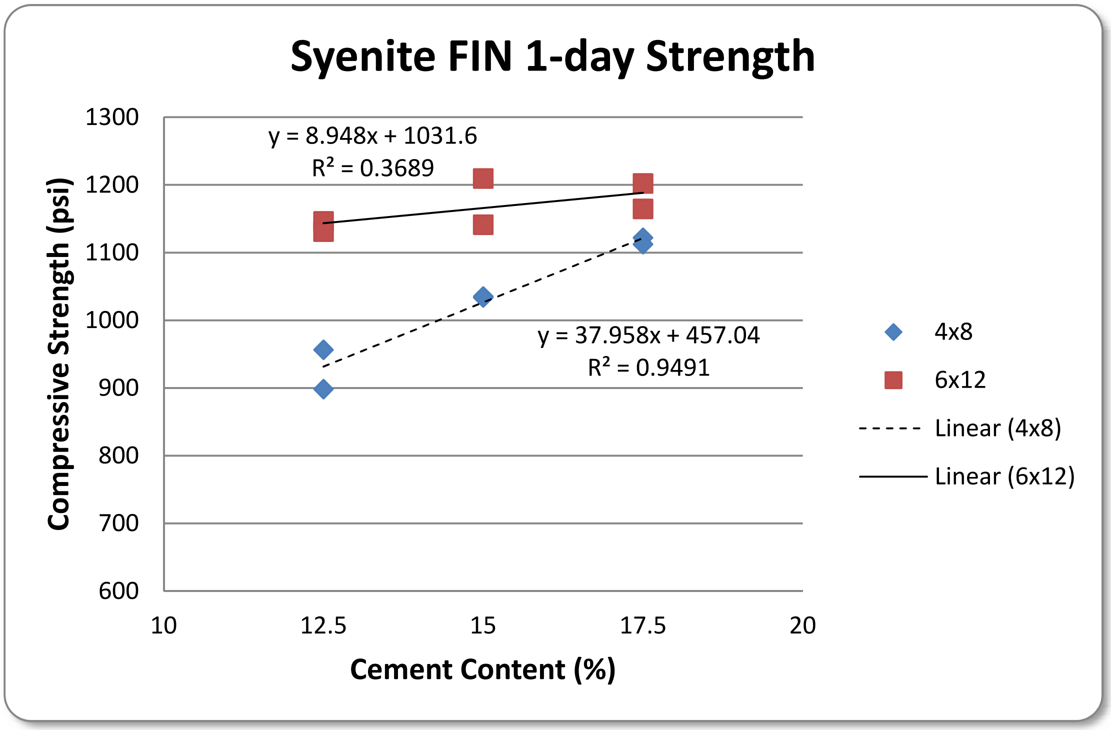

Figure A-9. 1-Day Strength Relationships for Fine Syenite Mixture

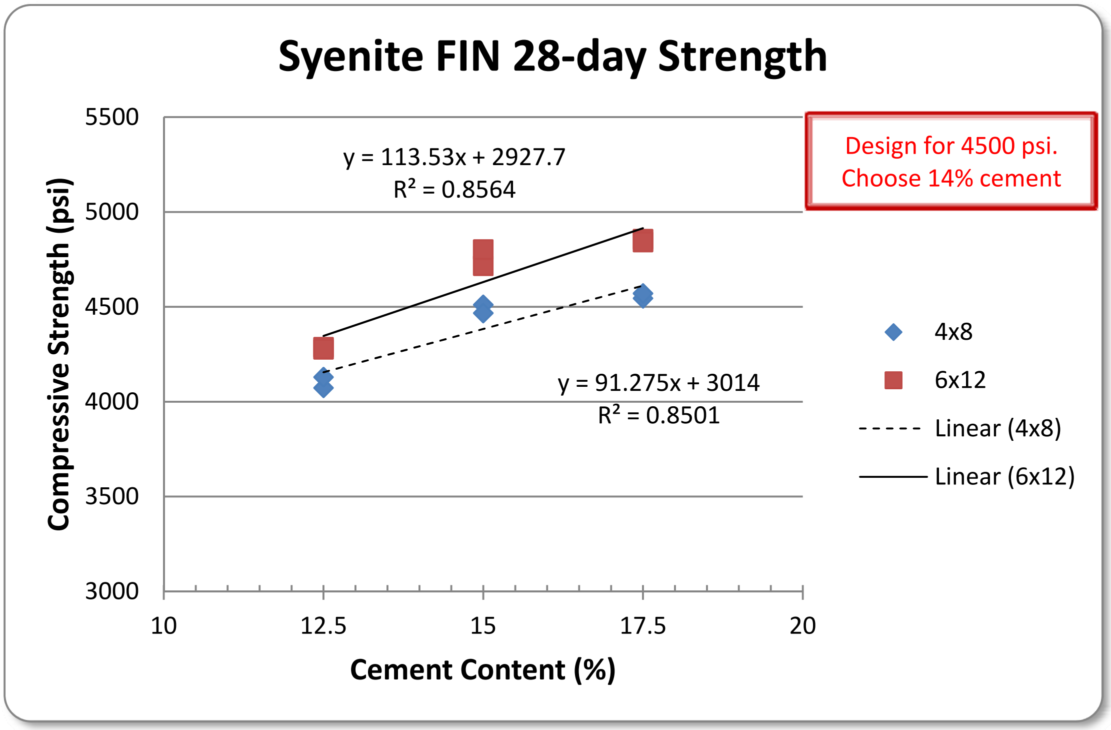

Figure A-10. 28-Day Strength Relationships for Fine Syenite Mixture

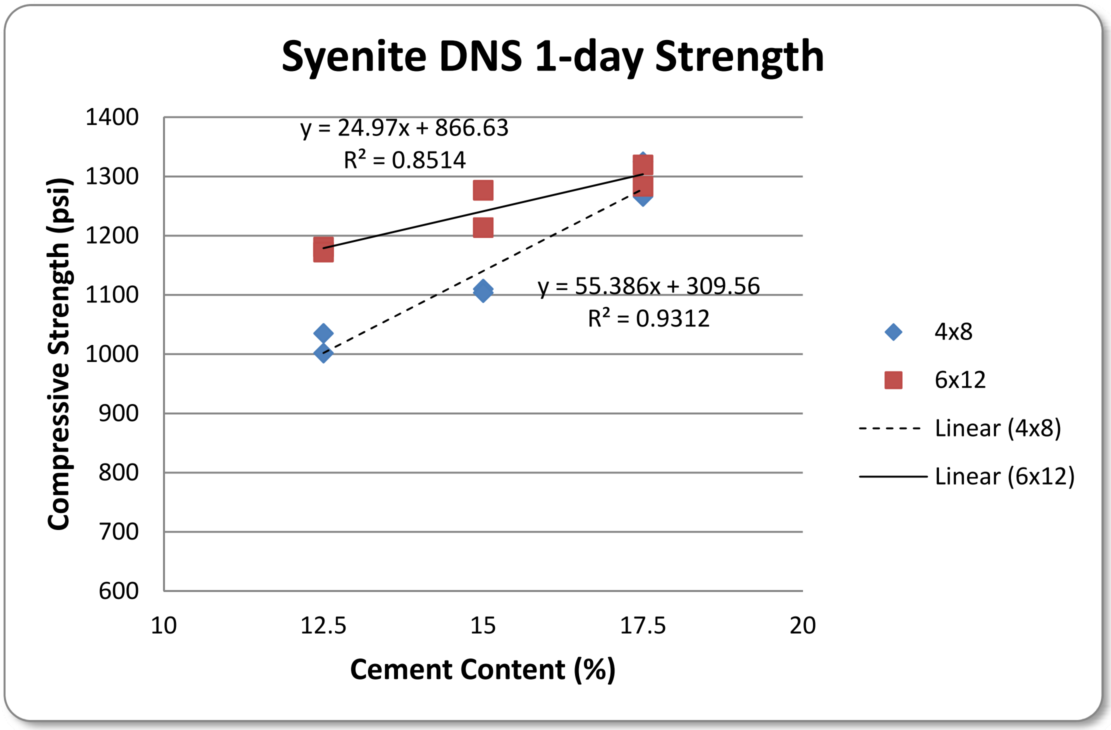

Figure A-11. 1-Day Strength Relationships for Dense Syenite Mixture

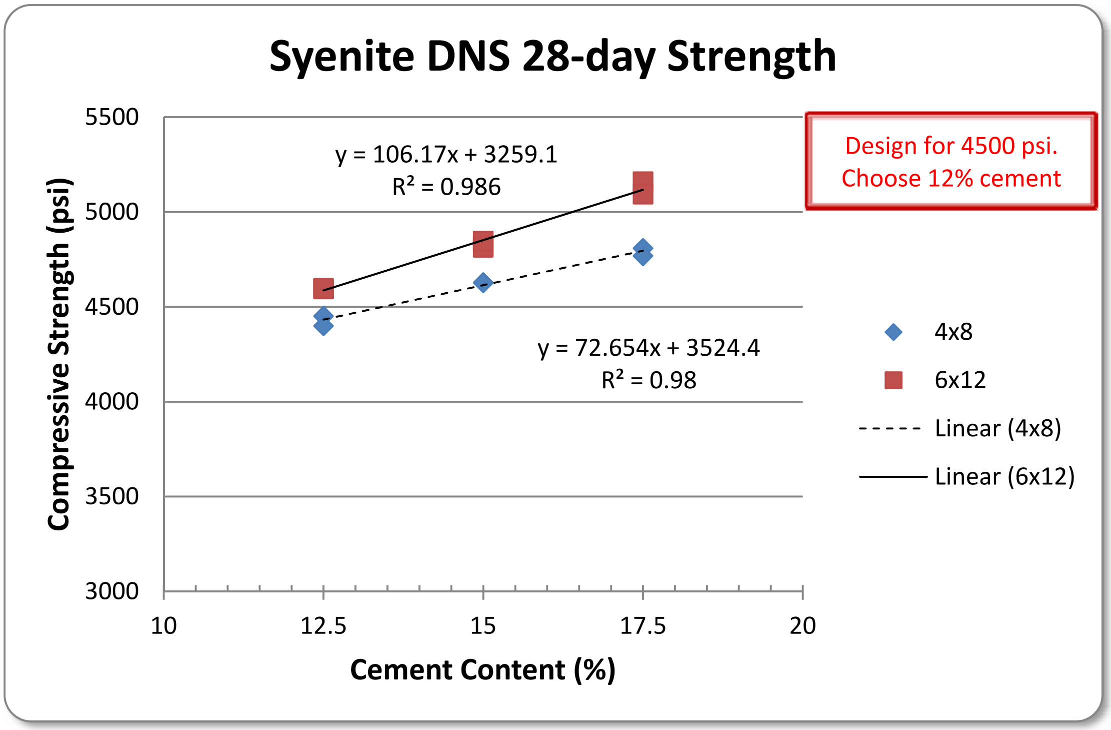

Figure A-12. 28-Day Strength Relationships for Dense Syenite Mixture

APPENDIX B

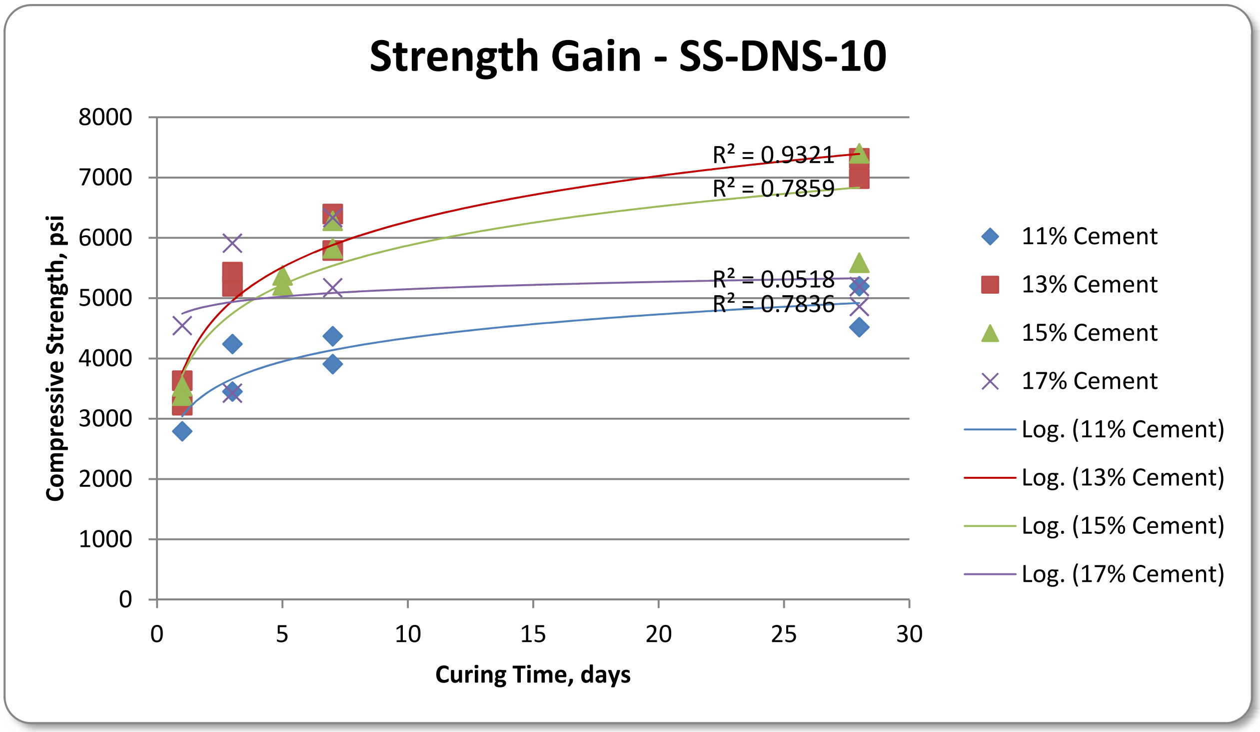

Figure B-1. Strength Gain vs. Time for Sandstone Mixture (SS-DNS-10) at Varying Cement Contents

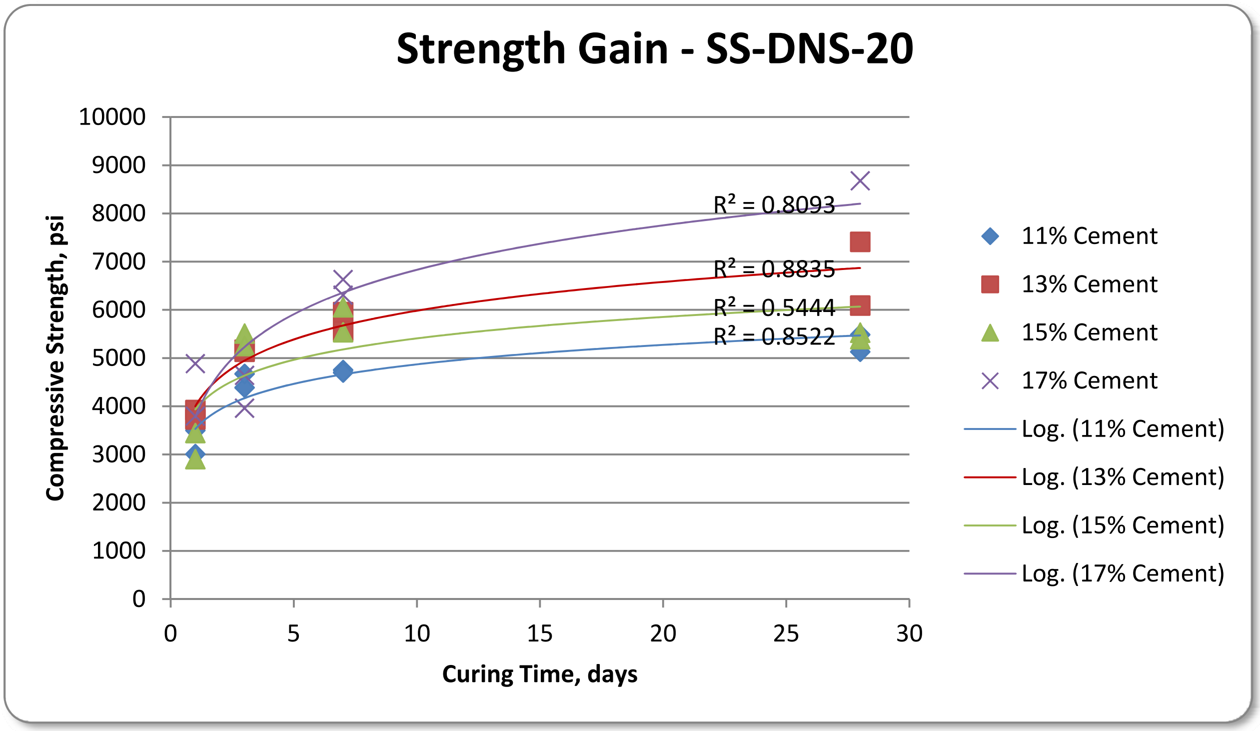

Figure B-2. Strength Gain vs. Time for Sandstone Mixture (SS-DNS-20) at Varying Cement Contents

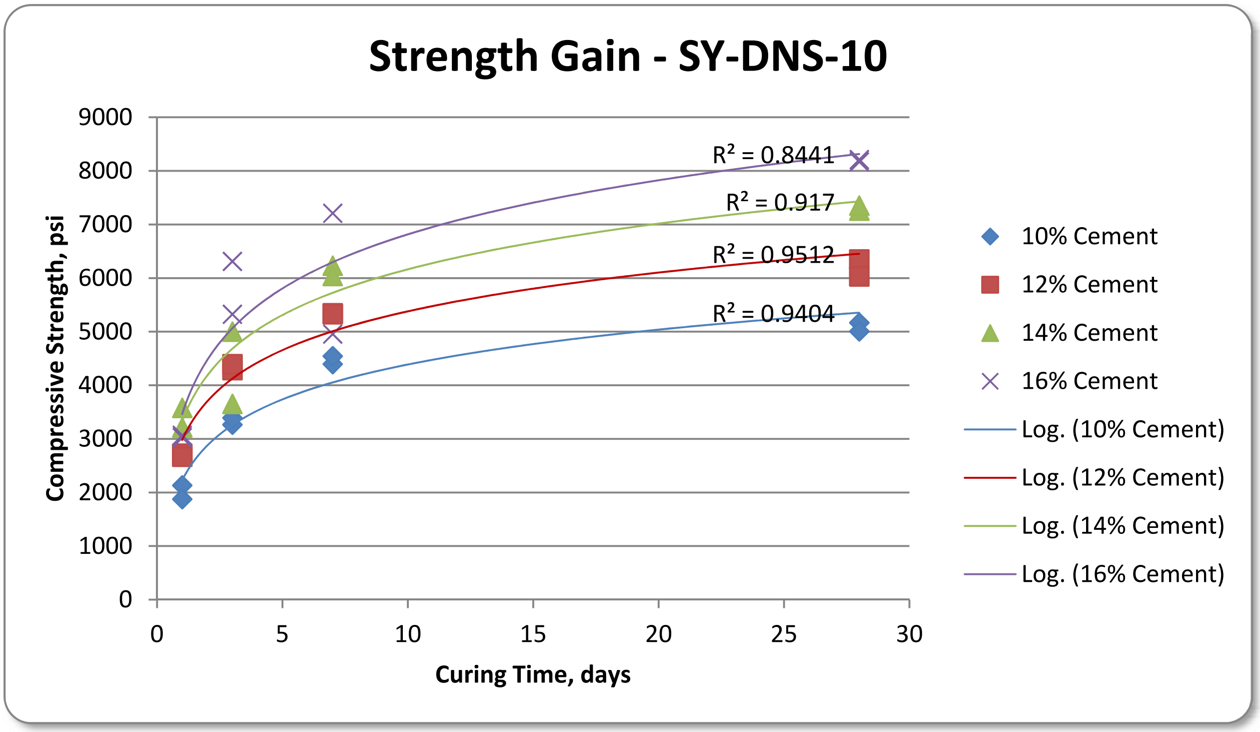

Figure B-3. Strength Gain vs. Time for Syenite Mixture (SY-DNS-10) at Varying Cement Contents

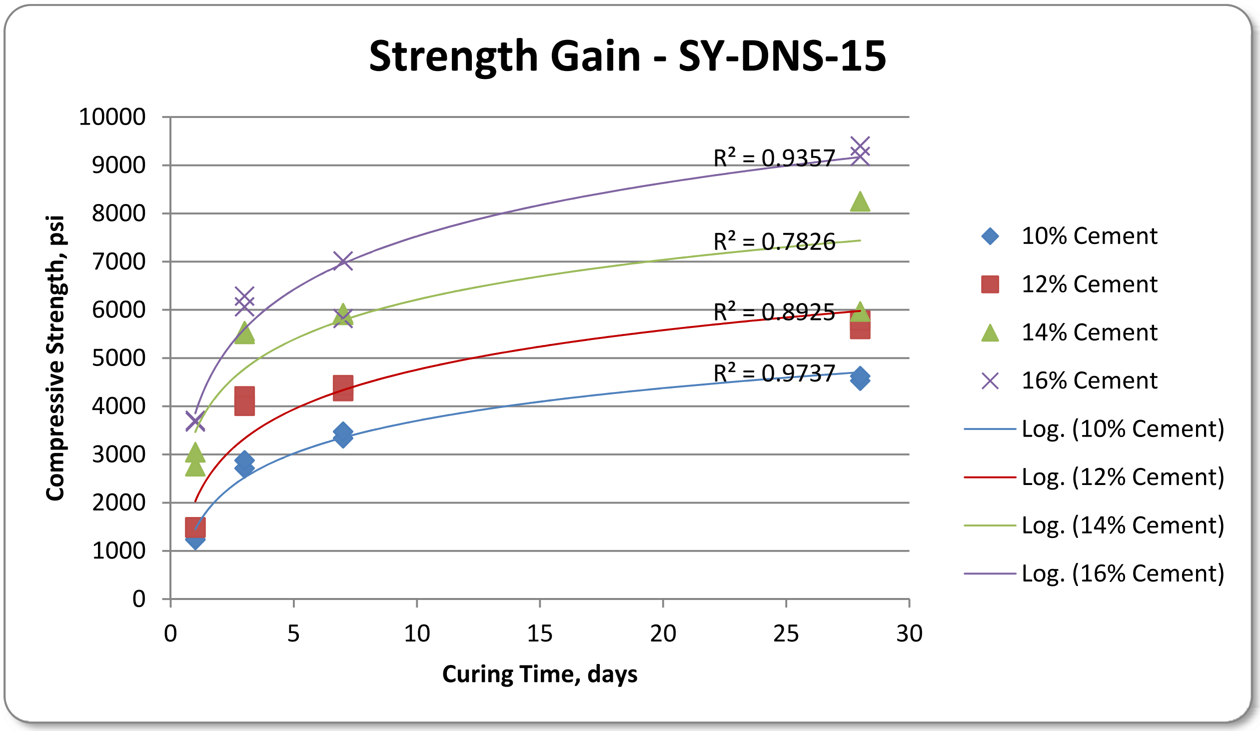

Figure B-4. Strength Gain vs. Time for Syenite Mixture (SY-DNS-15) at Varying Cement Contents

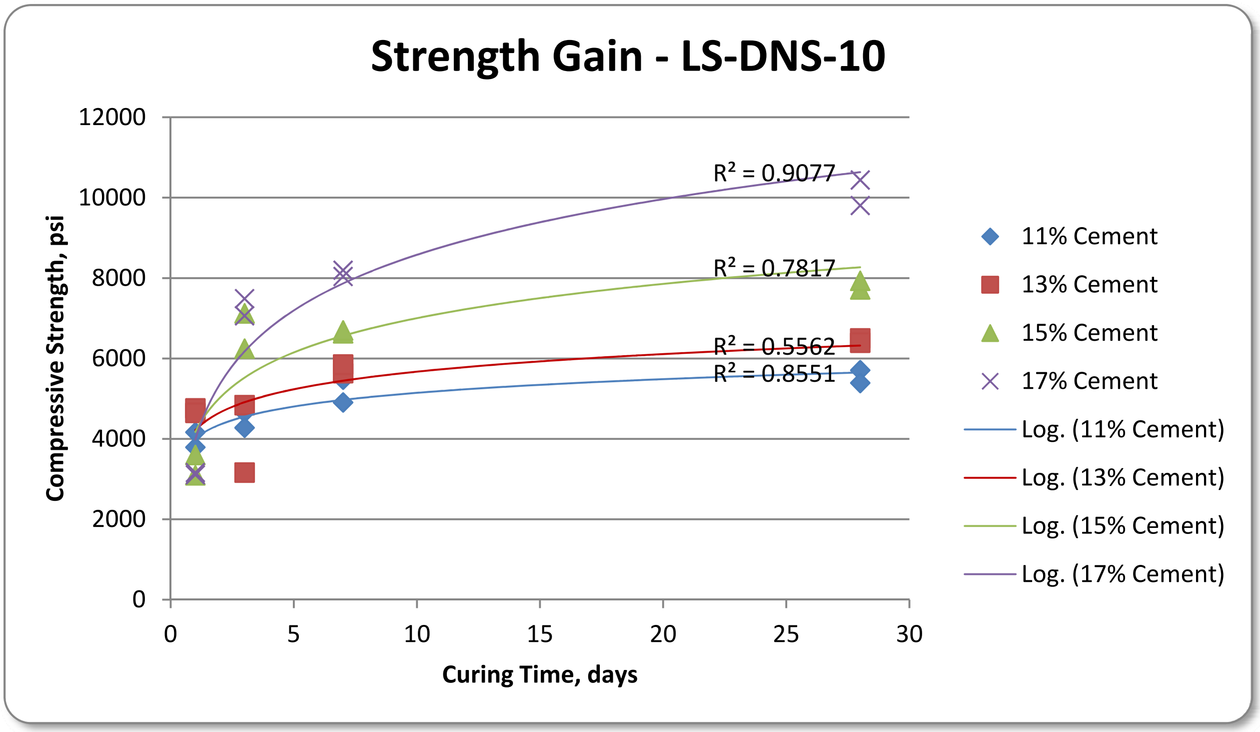

Figure B-5. Strength Gain vs. Time for Limestone Mixture (LS-DNS-10) at Varying Cement Contents

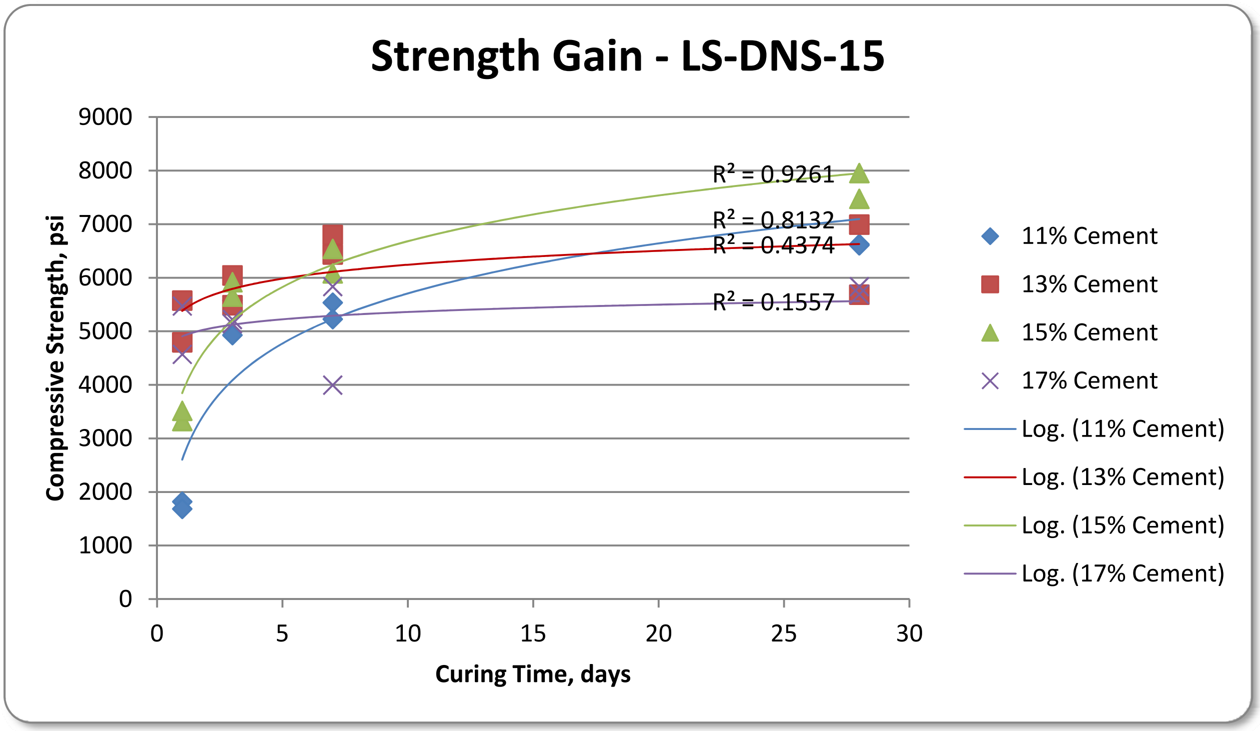

Figure B-6. Strength Gain vs. Time for Limestone Mixture (LS-DNS-15) at Varying Cement Contents

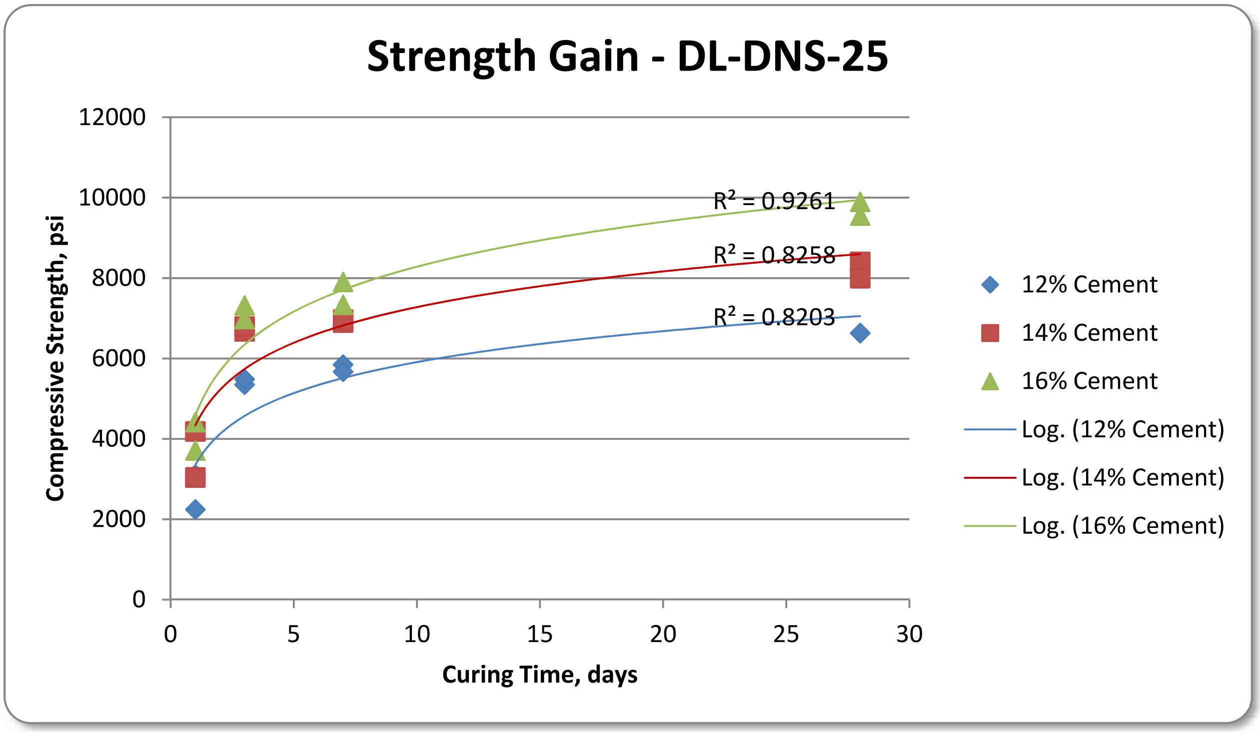

Figure B-7. Strength Gain vs. Time for Dolomite Mixture (DL-DNS-25) at Varying Cement Contents

APPENDIX C

ROLLER COMPACTED CONCRETE PAVEMENT
DRAFT SPECIFICATION

DESCRIPTION: This item shall consist of constructing a Roller Compacted Concrete (RCC) Pavement according to these specifications and conforming to the lines, grades, thicknesses, and typical cross sections shown on the plans or established by the Engineer.

MATERIALS:
General: All materials to be used for RCC construction shall be approved by the Engineer based on laboratory tests or certifications of representative materials, which will be used in the actual construction. All materials shall conform to Section 501.02 of the latest edition of the *AHTD Standard Specifications for Highway Construction*, unless otherwise modified herein.

Aggregates: The design of the RCC pavement mixture approved for use in this project shall contain a nominal maximum aggregate size of ¾ inch, and shall conform to the following gradation requirements. The aggregate blend shall consist of both fine and coarse aggregate and will be a blend of 2 to 4 aggregates.

Table 1. Gradation Requirement for Roller Compacted Concrete Paving Mixture

Sieve Size, inch (mm)	Minimum % Passing	Maximum % Passing
1” (25.0mm)	100	100
¾” (19.0mm)	90	100
½” (12.5mm)	70	90
3/8” (9.5mm)	60	85
#4 (4.75mm)	40	60
#16 (1.18mm)	20	40
#100 (150mm)	6	18
#200 (0.075mm)	2	8

Mix Design: The mix design will be done by the contractor in accordance with section 501.03 except as modified herein. The proportion used in the mix shall be determined by the proctor method according to AASHTO T180, Method D. The RCC pavement mixture shall have a minimum 28-day compressive strength of 5,000 psi. All specimen fabrication shall be performed in accordance with AASHTO R39 and ASTM C 1435. Designs shall include the blend gradation for the job mix formula, including cement content, water content, w/c ratio, and 28-day strength.

QUALITY CONTROL, ACCEPTANCE AND ADJUSTMENT:
Quality control and acceptance testing shall be performed by the contractor in accordance with section 501.04 except as modified herein. The Standard Lot size for acceptance testing shall be in accordance with section 501.04 except as modified herein. The Standard Lot size for acceptance will be 4000 square yards (square meters), with each standard lot divided into four sublots of 1000 square yards (square meters) each. No testing for slump or air content will be required.

Lot and sublot compliance, rejection, and price reductions shall be determined based on the values in Table 2 in lieu of Table 501-1. Compressive strengths may be based on cylinders or cores. Cylinders shall be prepared according to ASTM C 1435 and cured according to ASTM C 31, and cores shall be treated in accordance with AASHTO T24.

Table 2. Compliance, Price Reductions, and Rejection Limits for Roller Compacted Concrete Pavement

Property	Compliance Limits	Price Reduction Limits	Price Reduction	Rejection Limits
Compressive Strength	5000 psi	4999-4000 psi	10%	Less than 3500 psi
		3999-3500 psi	20%	

Tolerance in Pavement Thickness: Tolerance in the thickness shall be in accordance with section 501.10. Subsection 501.10 shall be modified to further include the following:

The equipment and methods employed in placing the roller compacted concrete material shall ensure accuracy and uniformity of depth and width. If conditions arise where such uniformity in the placing cannot be obtained, the Engineer may require additional equipment or modification in the placing procedure to obtain satisfactory results.

EQUIPMENT:

General: Roller compacted concrete shall be constructed with any combination of equipment that will produce a completed pavement meeting the requirements for mixing, transporting, placing, compacting, finishing, and curing as provided in this specification.

Mixing Plant: The RCC pavement mixture shall be produced in a twin-shaft pug mill plant or central batch plant, at a rate that is consistent with placement, and will allow for continuous movement of the paver. Concrete shall be delivered and discharged from the truck into the paver within one hour after the introduction of the mixing water to the cement. Close control of water content is required and thorough mixing is necessary to achieve a homogenous mixture.

Haul Trucks: The mixture shall be delivered to the site in dump trucks, which are suited for depositing the mixture into the hopper of the paver. Each load transported to the site shall be covered to prevent contamination and evaporation. A suitable number of trucks must be available to ensure a constant supply of RCC pavement material in the hopper, allowing the paver to proceed at a consistent rate. Stopping and starting the paver should be kept to a minimum.

Paver: The paver should be capable of producing 85 percent of the laboratory-derived maximum density. A high density paver is preferred, especially for lift thicknesses of 8 inches or greater.

Compactors: Self-propelled steel drum vibratory rollers having a minimum static weight of 10 tons shall be used for primary compaction. For final compaction, either a steel drum roller, operated in a static mode, or a rubber-tired roller of equal or greater weight shall be utilized. Walk-behind vibratory rollers or plate tampers shall only be used for compacting areas inaccessible to large rollers.

Water Trucks: At least one water truck, or other similar equipment, shall be on-site and available for use throughout the paving and curing process. Such equipment shall be equipped with a spreader pipe containing fog spray nozzles capable of evenly applying a fine spray of water to the surface of the RCC without damaging the final surface.

Inspection of Equipment: Before start-up, the Contractor's equipment will be carefully inspected. Should any of the equipment fail to operate properly, no work will proceed until the deficiencies are corrected.

Access for Inspection and Calibration: The Engineer and his representatives shall have access at all times for any plant, equipment, or machinery to be used in order to check calibration, scales, controls, or operating adjustments.

PROFICIENCY REQUIREMENTS:

The Contractor placing the roller compacted concrete pavement shall demonstrate proficiency with that material by providing documentation and/or reference letters from two (2) successful previously placed projects. If the contractor cannot demonstrate proficiency with RCC, then the contractor is required to have an individual with RCC expertise on site throughout the construction of the RCC pavement. The individual shall demonstrate proficiency with RCC by providing documentation and/or reference letters from two (2) successful previously placed projects.

CONSTRUCTION REQUIREMENTS:

Rolling and Density Requirements: At the beginning of placement of each mix design, the Contractor shall establish an optimum rolling pattern for the mix being placed. A sufficient number of coverages of the entire mat by the rollers proposed to be used by the Contractor during production paving operations shall be made to achieve the maximum density possible. The Engineer will observe the Contractor's use of a nuclear density gauge to verify that the maximum densities possible are obtained.

The established rolling pattern shall be used for compacting all mix placed. If a change in the accepted mix design occurs, or if the compaction method or equipment is changed, or if unacceptable results are obtained, a new optimum rolling pattern shall be established.

If for any reason a rolling pattern cannot be established to produce the specified density, a new mix design will be required. The Contractor shall establish an optimum rolling pattern that will produce the maximum density using the new mix design. Continuous production of the mix shall not begin until an optimum rolling pattern that produces the specified density within the allowable range has been established.

Rolling shall start longitudinally at the low edge and proceed toward the higher portion of the mat. When paving in echelon or abutting a previously placed lane, the longitudinal joint shall be rolled first followed by the regular rolling procedure. Alternate passes of the roller shall be terminated at least 3' (1 m) from any preceding stop. Rolling on super elevated curves shall progress from the low side. Rollers shall not be stopped perpendicular to the centerline of the traveled way.

Compaction: Initial compaction shall begin immediately after paving, and shall be performed using a smooth steel drum vibratory roller. Finish rolling may be performed using a steel drum roller in static mode or a rubber-tired roller. Walk-behind tampers or rollers may be used for areas not accessible to large rollers. At no time shall the rolling operation cause movement of the mat or tearing of the surface. On the first pass, the roller shall maintain a distance of at least 6 inches from the unconfined edge, then compacting the unconfined edge on subsequent passes.

The RCC pavement mat shall be compacted to a minimum of 98 percent of the maximum laboratory density obtained by AASHTO T180 Method D, based on wet density. The moisture content shall be maintained at the optimum value ± 1 percent. The in-place density and moisture content shall be determined by using AASHTO T-310, Direct Transmission. A minimum of one density test shall be taken by the Contractor for every 1000 square yards of RCC pavement for the purpose of quality control.

Base/Subbase Preparation: Base/subbase should be uniformly compacted to at least 95 percent of maximum density, and shall not exhibit any instability, as determined by proof rolling. Immediately prior to the placement of RCC pavement, the subgrade or subbase shall be clean and free of debris, and then uniformly moistened using a water truck with a spray bar. No standing water should be present.

Curing: After final compaction and density testing is complete, the RCC pavement surface shall be kept moist using a fine mist of water, until a curing compound has been applied in accordance with Section 501.05 (I)(3) AHTD specifications. When the RCC pavement is to be covered with a bituminous wearing course, an approved emulsion product may be used for curing purposes.

Placement: The RCC pavement shall not be placed on a frozen or frost-covered surface, and should be placed when the air temperature is at least 40°F. The temperature of the RCC pavement surface should be protected such that its surface temperature does not drop below 40°F for at least 5 days. During hot weather paving, precautions should be taken to maintain appropriate moisture levels. Paving must be suspended during periods of rain, and may be suspended during periods of heavy mist if water ponds on the pavement surface. In such cases, the Engineer will determine whether paving is suspended.

If possible, RCC pavements should be constructed in one lift. Pavements greater than 10 inches in thickness should be constructed in two equal lifts. For multiple lift pavements, the second lift should be placed within 60 minutes of the first lift.

RCC pavement shall be placed continuously, and without segregation, such that a smooth surface results. Segregated coarse aggregate should be removed from the surface, though hand work shall be kept to an absolute minimum. If the paving process results in significant segregation or tearing of the mat, paving shall cease until the problem has been resolved.

If possible, the adjacent lane should be placed within 60 minutes of the first lane, creating a fresh longitudinal joint. If this is not possible, then a vertical cut should be made along the exposed edge that will later form the longitudinal joint, removing approximately 4 inches and creating a vertical face. This cut should be made within 2 hours of placing the RCC pavement, and in a manner that maintains a smooth edge (i.e., no raveling). Clean and moisten the face of the joint prior to placing the adjacent lane. Ensure that a sufficient quantity of material is present at the joint to create a densely compacted joint at the appropriate mat height.

Traffic: The RCC pavement mat may be opened to light traffic after 24 hours, provided a compressive strength of at least 1800 psi has been obtained. Unrestricted traffic may be allowed on the pavement after the compressive strength has reached 2500 psi. The Contractor shall obtain 1 day, 3 day, 7 day and 28 day compressive strengths. These strengths will be determined based on the Contractor's compressive strength testing of cores obtained by the Contractor. The Contractor will be responsible for appropriate traffic control during lane closures.

Smoothness: When the RCC pavement will be used as the final roadway surface as indicated by the typical section, the surface shall be ground in accordance with Section 510, Grinding Portland Cement Concrete Pavement except that the entire surface shall be ground to a minimum depth of 1/16”. This grinding will be paid for at the unit price for “Grinding Portland Cement Concrete Pavement”. When the RCC pavement will have an ACHM layer placed over it as indicated by the typical section, grinding of the RCC pavement may be necessary in order to achieve the smoothness requirements of the ACHM Surface Layer. Grinding for this purpose shall be at no cost to the Department.

METHOD OF MEASUREMENT:

Roller Compacted Concrete will be measured by the square yard (square meter). The width for measurement will be the width as constructed according to the plans and typical cross sections or as directed by the Engineer.

BASIS OF PAYMENT:

Work completed and accepted and measured as provided above will be paid for at the contract unit price bid per square yard (square meter) for Roller Compacted Concrete Pavement, of the thickness and type specified, which price shall be full compensation for preparing the subgrade or base and shaping the shoulders unless otherwise specified; for furnishing, transporting, and placing materials, and all other joint materials; for the preparation and processing of materials; for mixing, spreading, vibrating, compacting, finishing, and curing, for performing mix designs and quality control and acceptance sampling and testing; for sawing and cleaning joints; for half width construction; for furnishing the profilograph; taking all required profiles, performing all necessary computations; and for all labor, equipment, tools, and incidentals necessary to complete the work; provided, that for such area as is deficient in thickness, only the adjusted priced will be paid as specified in Subsection 501.10. No payment will be made for pavement deficient in thickness in excess of ½” (12 mm), even though the deficient pavement may be allowed to remain in place, nor for repair as specified in Subsection 501.09.

Payment will be made under:

Pay Item	**Pay Unit**
Roller Compacted Concrete (5”)	Square Yards
Roller Compacted Concrete (6”)	Square Yards
Roller Compacted Concrete (7”)	Square Yards
Roller Compacted Concrete (8”)	Square Yards