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Tech Brief

Roller-Compacted Concrete Pavement

This Tech Brief presents an overview of the best practices for roller-compacted concrete pavement. The Tech Brief discusses RCC pavement uses and provides information on RCC mixtures and construction of RCC pavements.

INTRODUCTION

Roller-compacted concrete (RCC) as a paved surface offers facility owners and pavement designers a concrete pavement alternative that may better meet the requirements of specific pavement projects than conventionally cast-in-place concrete pavements. RCC pavement applications can be tailored to the specific needs of a project, particularly those associated with roadway projects within the residential, commercial, and urban roadway sectors. RCC pavement has been used in the following applications [1]:

- Heavy-duty applications
  - Ports and airports
  - Military installations
  - Intermodal facilities
- Light commercial industrial applications
  - Warehouses and manufacturing facilities
  - Commercial and industrial parking lots
  - Maintenance and storage yards
- Roadway applications
  - Highway frontage roads and shoulders
  - Minor arterials
  - City streets and local roads

An important benefit of RCC is its cost-effectiveness and ease of construction. RCC pavement essentially mirrors a conventional portland cement concrete (PCC) pavement in terms of joint spacing and design thickness. However, RCC is engineered and constructed differently than conventional concrete, involving different placement and design considerations even though the concrete mixture is made of the same constituent materials. Some of the differences include the following [1]:

- RCC is placed with asphalt-type pavers, not with the typical slip-form concrete paving machines or vibrating screeds.

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- RCC mixtures require compaction with the use of vibratory, tamper bar screeds, and typically but not always with either static or vibratory rollers to achieve a target density. RCC does not involve the use of internal vibration that typically is used to consolidate concrete used in conventional paving operations.
- RCC mixtures have “negative” slump. Any slump in an RCC mixture is too much. Conventional concrete paving mixtures often involve a slump between 1 and 4 inches, depending on placement method.
- RCC mixtures require a different type of mixing than conventional concrete mixtures. RCC mixtures are most efficiently produced in horizontal, twin-shaft mixing chambers in a continuous or batch fashion.
- RCC mixtures are relatively dry and depend on the inherent stiffness in the plastic state to support the paver screed and rollers during placement and compaction operations. As a consequence, RCC pavements typically have been finished with rolling to achieve the specified density. Recently, admixtures have been developed and introduced into the market which allow for a broom finish. These technologies are reducing the occurrence of inconsistencies including minor surface tearing, checking, pitting, or even pockmarks. Alternately, diamond grinding can be used to achieve a specified level of smoothness and adequate surface friction.
- RCC mixtures have suffered only minor spalling distress under freeze/thaw action and typically are not susceptible to freeze/thaw damage. Therefore, air entrainment typically is not required in RCC mixtures.
- Historically, transverse joints have not been sawcut in RCC pavement. However, recently this practice has been changing.
- RCC is not reinforced, and dowel bars are not used at joints (except in transition areas) to supplement the transfer of load. The load transfer along the transverse cracks provided through aggregate interlock, in conjunction with good frictional resistance along the subbase interface, is sufficient to assure long-term joint/crack performance.

MATERIALS USED FOR RCC PAVEMENTS

Due to moisture sensitivity and other factors, choosing the appropriate aggregate gradation is a major part of successful RCC construction. Therefore, it is important to characterize the sources of aggregate planned for a project with respect to its gradation. Some have advocated the use of an optimized mixture design by holding the combined gradation curve to the 0.45 power curve and thus avoiding gaps in the gradation curve. However, the number of aggregates to be included depends on the method of mixing, as discussed further below.

Therefore, two items are important for aggregates used in RCC construction: gradation and mixture stability during paving under moisture content fluctuations. Most gradations for RCC mixtures are optimized for density by making the combined gradation as well distributed as possible. The mixture stability under moisture content fluctuations relates to the sharpness of the moisture-density curve and the rate at which the curve’s slope changes from positive to negative, as well as aggregate shape. Mixtures optimized for density typically follow the 0.45 power gradation, as shown in figure 1. These mixtures have well distributed aggregate sizes throughout, which helps facilitate placement and densification.

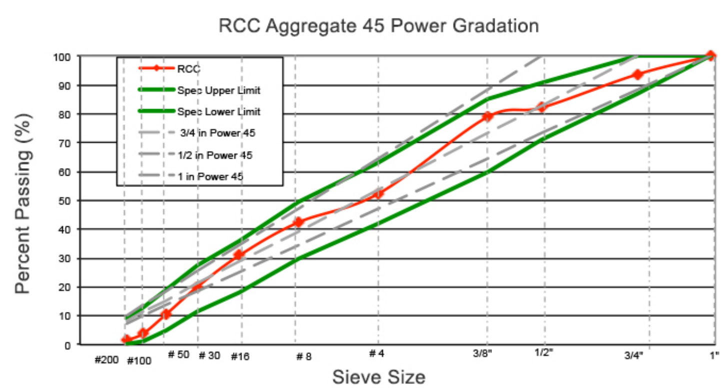

Figure 1. *Example RCC concrete gradation.*

Furthermore, the greater the density, the lower the percentage of voids in the aggregate mixture. Less cementitious material is needed to fill voids, aiding mobility of the mixture and potentially reducing its cost. However, there are other factors that affect the percent voids, such as the maximum aggregate size, compactive effort, and angularity of the aggregate particles. It should also be pointed out that the percent voids is determined as a function of the dry-rodded unit weight (ASTM C29) and the specific gravity (ASTM C33) of the base material. These test procedures are common and can be carried out by most testing laboratories.

With respect to mixture stability and moisture sensitivity, two density moisture curves are compared in figure 2. The upper curve has a steeper slope and a narrower base than the lower curve, indicating greater susceptibility to moisture changes. Most experts agree that a broader range in moisture with little effect on density (as depicted in the lower curve) is desirable for a concrete mixture for RCC construction.

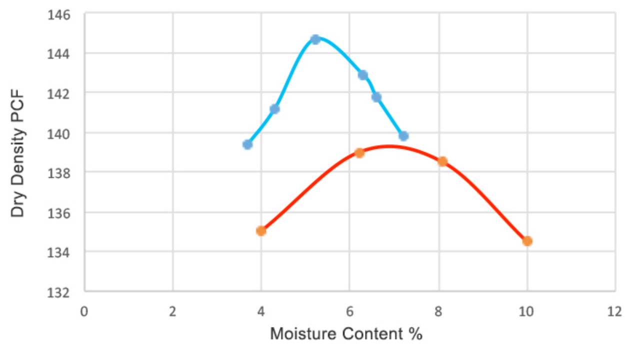

Figure 2. *RCC mixture moisture sensitivity.*

Concrete Mixtures

To develop a mixture with the greatest density and strength at the lowest cement content, the designer has some choice in optimizing a mixture for a given project. The following components typically are considered:

- Nominal maximum aggregate size
- Water content
- Sand content
- Cement and fly ash content based on strength and density (minimum of 450 lb/cy)
- Aggregate gradation, blending, stockpiling, and potential for segregation
- Moisture–density relationship
- Aggregate size
- Aggregate top size
- Minus 200 aggregate content (ranges from 0 to 8 percent)
- Use of admixtures
- Consistency of the concrete mixture; it must be stiff enough to sustain vibratory rolling (see figure 3)
- Water content to achieve the needed consistency for mixing and placement

Figure 3. *RCC consistency.*

The mixture design procedures involve the following steps:

1. Select well-graded aggregates.
2. Select the cement content (as a percentage of total weight).
3. Develop moisture–density relationships; determine the maximum dry density and the optimum moisture content.
4. Cast strength specimens at maximum density and optimum moisture content.

Figure 4 shows typical mixture proportions, where a common amount of cement is 450 lb/cy. The amounts of sand and coarse aggregate are the opposite of what is used in conventional concrete, with the sand being 50 to 55 percent of the aggregate weight and the coarse material being 45 to 50 percent. The range of water to cement ratio in RCC mixtures can be as low as 0.36 and as high as 0.45, but it is effectively a result of the optimum moisture content derived from the moisture density curve (rather than taken simply as an input that conventionally has dictated the water content in a mixture design) [1]. Enough water is used to facilitate mixing and compaction while maintaining stability behind the paver and under the rollers.

Ingredient		Batch Weight (Dry) (lbs/CY)	Batch Weight (SSD) (lbs/CY)	Specific Gravity (SSD)	Absolute Volume (CF)
Cement		450	450	3.150	2.289
Fly Ash		0	0	2.350	0.000
CA #1	1/2" x #8	693	701	2.680	4.190
FA #1	Concrete Sand	1906	1938	2.630	11.810
CA #2	3/8" x 1/4" Crushed	866	876	2.680	5.237
FA#2	0	0	0	2.570	0.000
Total Water content (lbs)		211	211		
Water in Aggregates (lbs)		0.0	49.5		
Water added by Plant (Free Water) (lbs)		211.4	161.9	1.000	2.594

The "Typical" Mix Design parameters can then be calculated

Total Final Volume (CF)			26.120
Calculated Air Volume (CF)			0.880
Calculated % Air Volume			3.26%
Water absorbed in Aggregates	49.55		
Free Water	162		
W/CM Ratio	0.36		
Aggregate / Cement Ratio	7.70		

Figure 4. *Typical RCC mixture proportions.*

Design Approaches for RCC Pavements

Most pavement design procedures typically focus on calculations related to the types of distresses that occur due to the effects of traffic load and climate variations. However, in the case of RCC (and jointed concrete in general), very few failures are purely fatigue related, especially since RCC is often placed on stiff or well-compacted subbase layers. Given the typical curing practices for RCC configured in this manner, cracking that develops in the pavement is likely caused by the induction of curling and warping stresses shortly after construction. Therefore, it is important to include climatic effects of this nature in the estimation of cracking distress, since it ties the effect of joint spacing, the concrete coefficient of thermal expansion (CTE), and the stiffness of the base layer to the design of the pavement thickness. Curing effectiveness could also be included in this list, as it affects the zero-stress state of a paved slab prior to the onset of curling and warping stress. The timing, season, and prevailing weather conditions during paving operations all can affect the performance of an RCC pavement.

Design Approaches

Applicable design procedures for RCC pavement include the American Association of State Highway and Transportation Officials (AASHTO) Pavement ME Design [2], American Concrete Institute 330 [3] and 325 [4, 5], RCC-Pave [6], American Concrete Pavement Association StreetPave^{TM} [7], U.S. Army Corps of Engineers thickness design procedure [8], and AASHTO 1998 [9]. However, these procedures are limited to the consideration of fatigue cracking and are less focused on jointing scheme, subbase thickness, and subbase stiffness design for a given traffic level and flow. Slab bending stresses in these procedures are typically greatest along the longitudinal pavement edge. For those procedures that delineate edge stress with respect to load transfer efficiency across the longitudinal joint, some design benefit can perhaps be gained by accounting for load position relative to that joint since its stiffness is rather low. One of the only options for reduced design stresses is by minimizing loading of the longitudinal joints, which can be facilitated by knowing the expected loading patterns. Additionally, strategic placement of flow patterns and break lines will facilitate reduced saturation and infiltration of joint interfaces and potential weakening of subgrade support.

Another aspect of RCC pavement design pertains to the tightness or stiffness of the transverse cracks. Conventionally constructed RCC has not always included sawed joints, which has often resulted in some transverse cracks opening wider and moving more than others, manifesting poor load transfer characteristics that ultimately lead to localized joint failure. Sawcutting joints facilitates continuity between the design assumptions and the configuration of the constructed pavement section.

Construction of RCC Pavements

The differences between RCC and jointed concrete pavement are most evident in the construction methods used. RCC is:

- Placed with a high-density asphalt paver
- Compacted with a combination of passes with the vibratory roller
- Placed without forms, reinforcing steel, or surface finishing

As noted earlier, sawcutting has not always been used in RCC construction, but it is gaining popularity as a measure to maintain small crack widths and good load transfer. It is well accepted that tight cracks are more conducive to high load transfer, which is an important feature of roadway design.

Other differences can be found in the texture of the final surface (see figure 5). The texture of the RCC surface is more open, similar to an asphalt concrete (AC) surface, since the mixture designs consist of similar aggregate gradations and shares similar placement methods. Some have noted that an RCC surface can lose some fine aggregate in the initial years of service. This loss can be minimized if the surface is diamond ground after construction. Diamond grinding is often performed to facilitate roadway smoothness and provide for better surface texture with desirable frictional characteristics.

Figure 5. *RCC surface texture.*

Method of Batching

The number of aggregates to be included depends on the number of available aggregate bins at the mixing plant and the method of mixing. Various mixer types have been used, but the types shown in figures 6 and 7 are the standard recommendation for consistent production and mixing efficiency.

Figure 6. *Twin shaft horizontal mixer—batch type.*

Figure 7. *Twin shaft horizontal mixer—continuous type.*

The batch-type horizontal shaft mixer can yield production rates up to approximately 100 to 140 cy/hour while providing excellent mixing efficiency for dry materials. This mixer is reasonably mobile and can be easily set up in one day. This mixer needs to be augmented with a batching operation as it is inserted underneath a dry batch ready mix plant.

The continuous-type horizontal shaft mixer provides a higher range in production rates up to 500 cy/hr, with most around 200 cy/hr. The mixture consistency is good, maintaining minimal moisture fluctuation and easy moisture adjustment. This type of mixer can also be easily moved and erected on site, as it is a self-contained operation that requires only two or three people to operate it. It can typically handle up to two aggregate sources, but it can be augmented with additional aggregate bins allowing up to four aggregate sources.

RCC Pavers

High-density asphalt laydown machines, like the one shown in figure 8, are used for RCC construction. These pavers provide a high initial density in the range of 90 to 96 percent. These types of pavers can achieve a smoother surface with less rolling (or none at all) in obtaining the final density. Productivity is very good, paving 6 to 8 ft/min. The high-density pavers can place lifts from 4 to 9 inches thick and place lanes widths from 10 to 30 ft.

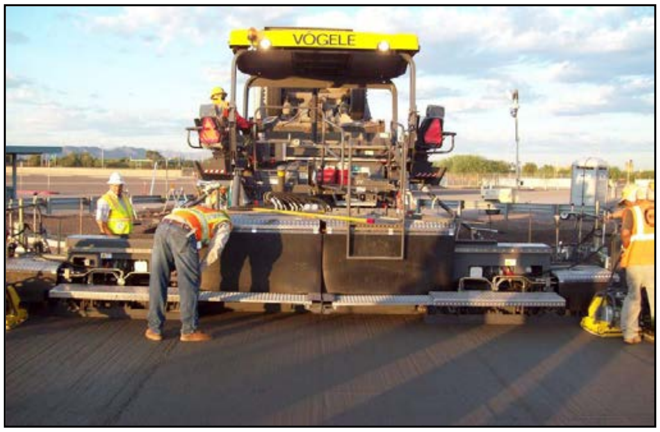

Figure 8. *High-density RCC paver.*

Rolling Operations

When needed, a major part of the construction of a RCC pavement is the rolling operation (see roller pattern in figure 9), which typically consists of initial compaction and then finished rolling. Initial compaction usually is done with a 10- to 12-ton vibratory roller. While the roll pattern is being established, the density is checked on a regular basis. The roll pattern is adjusted according to the moisture content of the mixture, but the goal is to achieve at least 98 percent density.

Figure 9. *RCC construction.*

Density typically is tested using a nuclear gauge and taken behind the paver after rolling has been completed to validate the performance of the paver and to confirm that the rolling complies with the minimum 98 percent density specification. Large changes in the mixture moisture content lead to changes in compactability and final smoothness of the pavement surface. Strength specimens are also prepared following ASTM C 1435 using a vibratory hammer and standard sized compression cylinders. Finer gradations tend to achieve the target density at a lower compactive effort.

Finish rolling is normally done with a 3- to 6-ton roller and can be a combination of dual steel or rubber tired rolling. The goal of the finish rolling is to remove roller marks from the surface.

Jointing RCC Pavement

Longitudinal joints may be constructed in one of three ways, as illustrated in figure 10. Vertical cold joints are placed by paving the width of the lane and then sawcutting full depth the following day to facilitate trimming the edge with a blading and loader operation. However, this results in waste and can also be time-consuming.

a *Vertical Cold Joint.*

b *Angular Cold Joint.*

c *Fresh Joint.*

Figure 10. *Longitudinal joint construction in RCC pavement.*

Waste can be reduced if a paver shoe is used and adequate compaction is provided, allowing the edge to remain in place. The adjacent lane is then paved to match the thickness of the existing lane, and a cold joint is formed. This type of joint has shown good performance but has no load transfer capability. The angular cold joint requires the use of a high-density paver with a shoe attached to the screed. The maximum angle for the joint is 15 degrees. A plate tamper can be used to improve edge durability; in this case, no sawcutting is used, which provides a low-cost solution to placing the longitudinal joint. The adjacent lane can be paved as soon as one lane is completed.

Fresh joints are placed as they are in asphalt concrete pavements. Coordination between paving operations and plant operations is key and breakdowns must be avoided. The process involves paving for about 30 minutes accompanied by rolling operations without compaction within 2 feet of the joint edge. The second lane is placed by moving back to where the laydown began and matching the original lane by rolling up against it. This joint can also be sawcut for sealing purposes, but the performance of this type of joint has been mixed. Poor performance has been noted on these joints when they are allowed to dry out before paving the adjacent lane.

RCC pavements are cured just as conventional concrete pavement, typically using curing compounds but perhaps at a higher rate to compensate for the openness of the surface. Although not typically done, the transverse cracks can be initiated via sawcutting to provide a more aesthetically pleasing surface. Early entry saws have worked well in this application as long as the cuts are made 2 to 6 hours after placement.

OTHER IMPORTANT DESIGN AND CONSTRUCTION CONSIDERATIONS

This section describes other design and construction factors related to transitions and jointing patterns that may have either a direct or indirect effect on the performance of RCC pavements.

Transitions and Jointing Detail

Typically, pavement transitions are used where immovable objects are incorporated in a pavement structure which results in joints or cracks becoming wide enough to affect load transfer or the potential for infiltration to take place during a rainfall event.

Transitions in RCC are necessary at some locations, such as where the RCC pavement is constructed next to an asphalt concrete pavement.

Figure 11 shows a diagram of such a transition. This example involves the use of a precast element but also shows the transition and the load transfer details at the joint while protecting the RCC/asphalt concrete interface and accommodating the relative movements between the two pavement types. It is important to note the extension of the subbase support beyond the joint and that both joints need to be properly sealed. Other areas requiring transition details would be the longitudinal joint subjected to frequent loading, changes in base type, or slab thickness.

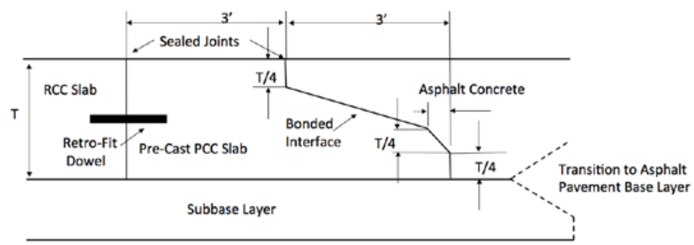

Figure 11. *Transition of RCC/AC pavement interface [10].*

Coefficient of Thermal Expansion

The thermal expansion characteristics of RCC pavement are governed by the thermal characteristics of the coarse aggregate contained within the mixture. For an RCC pavement structure, the interest in CTE from a design standpoint is blowup potential, since RCC is likely to be under compressive restraint during higher temperature seasons. The low shrinkage typical of RCC mixtures tends to enhance the possibility of high compressive strain conditions. This restraint is reduced at pavement temperatures below the set temperature of the concrete.

In addition to CTE and set temperature, the factors that affect the development of blowup distress include [11]:

- Slab thickness
- Drainage profile
- Slab/subbase interface friction
- Joint load transfer or stiffness

The greater the set temperature (which is likely to be a function of the season of placement), slab thickness, and subbase friction and the lower the CTE, the lower the potential for blowup distress. Essentially, the effects of slab thickness, joint stiffness, and subbase friction can be combined into a single parameter represented by the effective slab thickness.

The drainage profile of a pavement surface becomes important at break lines that facilitate drainage movement. The change in grading potentially creates a weakened location that increases the chances of a blowup. Depending on the season of placement, if a drainage break line follows a longitudinal joint, slab thickening or retrofitting with reinforcing tie bars may add sufficient stiffness to reduce the blowup potential.

Base Requirements

A variety of subbase types can be used under an RCC pavement structure, but due to the tightness of the transverse cracks in RCC, it is not always necessary to use a stabilized base layer.

A key factor in the performance of a concrete pavement is the potential for erosion to occur, causing a loss of support and a shortened pavement life. Erosion is a function of traffic load, subbase shear strength, and the presence of moisture. Because of the narrow cracks associated with RCC pavement, the subbase/subgrade layer is well protected from moisture infiltration, significantly reducing the potential for moisture to accumulate at the slab/subbase interface. As long as this interface is dry, pumping of eroded material will not take place. The only areas that may be of concern are where longitudinal or transition joints may allow moisture to infiltrate the pavement structure.

As noted above, the joints in the transition areas should be sealed to maintain a closed path to water movement into the joint. For base layers consisting of lower shear strength (i.e., unbound materials), precautions should be taken to seal cold and transition joints. Appropriate measures also should be taken at changes in drainage profile to guard against blowup failure.

PAVING OPERATIONS

Certain aspects of the laydown process are important, particularly when two-lift construction is involved.

Curing Management and Quality

In two-lift paving, bond strength at the interface of the RCC lifts is a critical engineering property. Bond strength determines whether RCC pavements constructed in multiple lifts will behave as a single layer or as partially bonded or unbonded lifts. The load-carrying capacity of partially bonded or unbonded lifts is much lower than that of bonded lifts of equal thickness.

The practice of two-lift paving has been based on the assumption that adequate bond strength can be achieved when pavement lifts are placed within an hour of each other, but the key to bonding the lifts together is minimizing the separation movement of the upper lift during the hardening period. The critical areas for separation are along slab edges and corners and, in extreme cases, in the slab interior areas. RCC surfaces should be cured to a greater degree since they typically have an open, textured surface (besides having a lower water to cement ratio) that otherwise tends to make RCC pavements more susceptible to early warping movements that may separate them from the lower layers [12]. The curing quality for RCC construction is a key aspect of limiting slab movements for a sufficient period of time to allow the bond to develop between lifts.

Surface Texturing and Smoothness

The finished surface of RCC pavement typically is far from smooth, due to the effect of using steel-wheeled rollers to densify the concrete. Removing the roller marks can contribute to a finished surface requiring grinding after hardening in order to create a smooth surface.

Efforts have been underway to eliminate the need for rolling and to use only the densification provided by the paver screed to meet the compaction specifications. This approach results in a much smoother surface at a lower cost while still meeting the required strength and specified density. It may be useful to experiment with different methods to enhance the finished surface of an RCC pavement (as shown in figure 12) without significant loss of skid resistance to partially close up a surface and reduce moisture loss. As previously stated, admixtures also are available to enhance the finishability of the surface concrete.

Figure 12. *Method to improve upon RCC finished surface.*

Paving and Jointing Plan

Planning the paving lanes for RCC is critical to the success of the pavement design, especially with respect to the placement of the longitudinal construction joints and the layout of the surface drainage. Each project site should be studied to understand the expected flow of traffic, especially with respect to trucks entering, using, and exiting the paved area.

Transverse cracking in a RCC pavement is much more suited to carry traffic loads, as these cracks typically possess the requisite stiffness and load transfer capacity to do so. On the other hand, the longitudinal joints are typically construction type joints, and their ability to transfer load is limited. As a consequence, these joints should not be placed where significant truck traffic will traverse them on a regular basis. If this cannot be avoided for a particular portion of a longitudinal joint, then special precautions should be taken, such as retrofitting the joint with reinforcing bars or using a sleeper slab to support the joint and facilitate load transfer.

The surface drainage for an RCC pavement should also be well planned to avoid long drainage paths or poorly drained configurations that cause the runoff to stagnate or pond unnecessarily. These situations can lead to weakened subgrades and localized failures requiring major repairs early in the life of the pavement. Again, break lines could be aligned with the longitudinal joints but should be sealed, especially where flow paths may coincide with them. Transverse cracks are tight enough to limit moisture infiltration and typically would not require sealing even if they were induced with a single blade sawcut.

CONCLUSION

RCC clearly has many benefits from a cost and constructability standpoint that, in combination with appropriate design details and features, will make it a long-lasting and cost-effective pavement choice.

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Contracting Officer's Representative:

Sam Tyson, P.E., Concrete Pavement Engineer
Federal Highway Administration
1200 New Jersey Avenue, S.E. – E73-440
Washington, DC 20590
202-366-1326, sam.tyson@dot.gov

Authors:

Dan Zollinger, Ph.D., P.E.
CMS Engineering Group
979-587-0421, dzollinger@cmseg.net

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