
Concrete Pavement Mixture Design and Analysis (MDA)

National Concrete Pavement
Technology Center



Guide Specification for Highway Concrete Pavements: Commentary October 2012

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**CONCRETE PAVEMENT MIXTURE DESIGN AND
ANALYSIS (MDA)
GUIDE SPECIFICATION FOR HIGHWAY CONCRETE
PAVEMENTS: COMMENTARY**

**Guide Specification Commentary
October 2012**

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1.0 DESCRIPTION

1.1 General

The following concrete pavement types are considered:

1. Jointed plain concrete pavement - most commonly used pavement type and may be doweled or non-doweled at transverse joints.
2. Continuously reinforced concrete pavement - typically constructed without any transverse joints. Typically used for locations with high truck traffic loads and/or poor support conditions.

The proposed specification incorporates requirements for the following:

1. End product
2. Submittals
3. Construction materials, including concrete mixture
4. Construction equipment
5. Weather Management
6. Concrete paving
7. Quality Assurance
8. Acceptance testing
9. Treatment of defective product
10. Measurement
11. Payment

Primary assumptions of the proposed specification are:

1. The constructed concrete pavement will be durable.
2. The pavement should exhibit failure due to anticipated traffic loadings over the design period and not due to material deficiencies that are a result of construction quality and soundness of materials used.

1.2 End Product

All work and all materials furnished shall be in reasonably close conformity with the lines, grades, grading sections, cross sections, dimensions, material requirements, and testing requirements that are specified (including specified tolerances) in the contract, plans, or specifications. If the engineer finds the materials furnished, work performed, or the finished product are not in conformity with the plans and specifications and have resulted in an unacceptable finished product, the affected work or materials shall be removed and replaced or otherwise corrected by, and at the expense of, the contractor in accordance with the engineer's written orders.

A concern with concrete pavement construction is that both the process control testing and acceptance testing deal primarily with the as-delivered concrete. There is little testing performed to characterize the properties of the as-placed concrete. There is a need to ensure that the fresh concrete that is accepted for placement can be placed and consolidated without segregation or excess surface paste or without requiring excessive hand finishing at the corners and edges.

The end product requirements related to concrete and concrete pavement are listed next. The significance of each element is discussed later in the appropriate sections.

1. Cracking (as discussed in Para. 9.3.1 – Cracking) – Structural cracking is detrimental to long-term performance of concrete pavements. However, shallow cracking, less than 2 in. in depth, is not considered structural cracking and can be mitigated. Pavement areas with deeper cracking are considered defective.
2. Joint Spalls (as discussed in Para. 9.3.2– Joint Spalls) – Joint spalls are primarily due to equipment damaging the concrete during the early age. Pavement areas with excessive amount of joint spalling are considered defective.
3. Slab thickness (as discussed in Para. 9.4.2 – Thickness) - This requirement ensures compliance with the design considerations for the pavement. Acceptance of thickness is based on the percent-within-limit provision. Pavement areas with PWL less than 55 are considered defective.
4. Strength (as discussed in Para. 9.4.3 – Strength) - This requirement ensures compliance with the design requirements for the pavement. The concrete mixture is required to attain the specified flexural strength at the specified age. Acceptance of strength is based on the percent-within-limit provision. Pavement areas with PWL less than 55 are considered defective.
5. Surface smoothness (as discussed in Para. 9.4.4 – Straightedge) - Surface smoothness testing is required to assess the pavement roughness and considers impact to the traffic in terms of ride quality and the potential for hydroplaning to develop as a result of ponding.
6. Dowel bar alignment (as discussed in Para. 9.3.4 – Dowel Bar Alignment) – Dowel bars provide load transfer across pavement joints to reduce slab stresses and deflections greatly, thereby reducing the potential for slab cracking. Proper alignment of the dowel bar is important to proper functioning of the dowel bars. Pavement areas having joints with misaligned dowel bars are considered defective.

1.3 End Product Responsibility

The contractor is entirely responsible for the materials and processes that produce the end products specified in this section. It is the contractor's responsibility to prove, at the start of construction, that the process for constructing the concrete pavement is valid.

The engineer will determine if the contractor's materials and processes produce an end product that is in reasonably close conformity with the plans and specifications. Tolerances to determine reasonably close conformity for measurable components of the materials, processes, and end product are provided in the proposed specification.

If the engineer finds that the materials furnished, work performed, or finished product are not within reasonably-close conformity with the plans and specifications, but that the portion of the work affected will, in their opinion, result in a finished product having a level of safety, economy, durability, and workmanship acceptable to the owner, they will advise the owner of their determination that the affected work be accepted and remain in place. In this event, the engineer will document their determination and recommend to the owner a basis of acceptance that will provide for an adjustment in the contract price for the affected portion of the work.

If the engineer finds the materials furnished, work performed, or the finished product are not in reasonably-close conformity with the plans and specifications and have resulted in an unacceptable finished product, the affected work or materials will need to be removed and replaced or otherwise corrected by, and at the expense of, the contractor in accordance with the engineer's written directions.

1.4 Pre-Paving Conference

The pre-paving conference is hosted by the engineer to review, with the contractor and agency personnel, specific project requirements related to the concrete paving and related project planning activities. The following items should be reviewed by the engineer and the contractor:

1. Submittals and status of submittals
2. Critical material supply/availability issues
3. Concrete plant and aggregate stockpile management
4. Concrete paving requirements
5. Paving schedule
6. Weather management plan
7. Haul routes and traffic maintenance
8. Test section requirements
9. Contractor process testing
10. Contractor acceptance testing requirements
11. Engineer monitoring of acceptance testing
12. Who on contractor's staff has stop work authority
13. Who on owner's staff has stop work authority
14. Issues and disputes resolution hierarchy

The concrete pre-paving conference is the last opportunity to discuss concrete paving process issues before the equipment starts moving. If these items are discussed before paving begins, the parties are able to review potential problems and create solutions that work for everyone on the project. Meeting minutes need to be distributed to all parties.

For projects involving more than 50,000 square yards of concrete paving, it is recommended that a half-day concrete pavement construction workshop be conducted that would also include discussion of project specific plans and specifications. Attendees at this workshop may include key staff from the contractor's field crew and the testing and inspection crews. A workshop such as this will ensure that all involved parties have the same understanding of project requirements and that all parties are committed to a successful project.

Graduated Requirements

The proposed specification incorporates comprehensive requirements to assure that the end product, the concrete pavement, is durable and will provide the expected service without occurrence of premature distresses. These requirements have been developed for production paving involving more than about 10,000 cubic yards of concrete placement.

For projects involving less than about 10,000 cubic yards of concrete, it is not considered cost-effective to require the contractor to develop the extensive amount of submittals or to require extensive amounts of new testing to qualify their materials. The proposed specification makes allowances for smaller projects, or projects generally requiring less than 10,000 cubic yards of concrete.

However, the end product requirements for small as well as large projects are similar to ensure the concrete pavement will be durable.

2.0 SUBMITTALS

Submittals are required from the contractor to assess the level of conformance with the project specifications. The submittals list is always a challenge for both the contractor and the engineer. The contractor may not fully understand what needs to be provided to the engineer and many engineers may not fully understand what to specify and how to review many of the submittals, including the submittal for the concrete mixture proportions.

The submittals to be provided to the engineer may include information provided by equipment makers, material suppliers, state department of transportation (DOT) certification, and contractor-sponsored material test data.

All personnel and laboratories conducting the aggregate and concrete-related testing for the project need to meet the requirements of Para. 8.1 – Testing Personnel and Para. 8.2 – Testing Laboratory Requirements, respectively. These requirements are important to assure that the testing is reliable, accurate, and precise. Highly variable test results can be costly to the contractor and may result in time delays.

Three categories of submittals are required, as follows.

2.1 Pre-Construction Submittals

These submittals are related to qualification of materials, concrete mixtures, and equipment. These submittals should be submitted to the engineer before concrete placement activities can begin. These submittals include, but are not limited to, the following:

1. Qualifications of the concrete plant inspector, when applicable
2. Certified concrete plant checklist as per the requirements of the department or the National Ready Mix Concrete Association (NRMCA) QC3 (Plant Certification Check List) process
3. Contractor's concrete testing laboratory certification
4. Contractor testing personnel certification
5. Cement mill certificates
6. Supplementary cementing material mill certificates
7. Aggregate certification (source and approved source certification)
8. Admixture certification
9. Water certification
10. Dowel bar steel certification
11. Tie bar steel certification
12. Dowel bar corrosion mitigation coating certification
13. Curing material certification
14. For each concrete mixture to be used:
 - a. Combined aggregate gradation
 - b. Concrete mixture proportions
 - c. Concrete flexural strength

- d. Concrete compressive strength
 - e. Concrete splitting tensile strength, if applicable
 - f. Air content, when applicable
 - g. Unit weight
 - h. Slump
- 15. Concrete uniformity test results for each concrete plant to be used
 - 16. Reactive aggregate mitigation plan, when applicable
 - 17. Weather management plan
 - 18. Contractor quality control/acceptance testing program
 - 19. Paving plan
 - 20. List of paving equipment and manufacturers' operational requirements for the paving equipment

2.2 Contractor Quality Control Testing Submittals

These submittals are related to the contractor's process control to ensure that quality control measures are integrated during each day of production paving. These submittals include, but are not limited to, the following process control tests:

- 1. Accuracy of plant batching
- 2. Aggregate moisture content
- 3. Combined aggregate gradation – Workability and Coarseness Factors
- 4. For site delivered concrete
 - a. Air content, when applicable
 - b. Concrete temperature.
 - c. Unit weight of fresh concrete

2.3 Contractor Acceptance Testing Submittals

These submittals are related to the required acceptance testing to ensure that the owner is provided with a product that has been specified. These submittals include, but are not limited to, the following acceptance testing tests:

- 1. Concrete thickness.
- 2. Concrete flexural strength.
- 3. Pavement smoothness

Some key submittals-related issues are as follows:

1. Cement supplies need to be secured to ensure supply during the peak construction season. If the cement source is changed, additional mix design and compatibility testing is required. It is advisable to pre-qualify mixture designs using different cementitious materials so that if a substitution needs to be made, the mix design data are already available and the new materials can be accommodated without delay.
2. Typically, about 60 to 90 days lead-time is available from contract award to start of work, so aggregate acceptance needs to be done within that time or before the award.
3. The materials related submittals need to be submitted for the engineer's review before new materials are used for the work.
4. For aggregate and concrete mixtures to be used on the project, the pre-construction certifications, except for the reactive aggregate mitigation plan, developed using materials sampled not more than 180 days before the start of concrete placement are acceptable. The certification shall include flexural versus compressive or splitting tensile strength correlation data, if applicable, for the concrete mixture to be used for the project.
5. Cement and supplementary cementing material mill certification need to be submitted for each truckload of the material for the engineer's review within 24 hours of material delivery.

3.0 MATERIALS

The engineer and the contractor need to understand the many and sometimes complex requirements related to concrete materials. The contractor needs to be aware that if alternate materials are going to be proposed, he needs to ensure that the testing requirements of the specification are met. Testing requirements for concrete aggregates may have long lead times and scheduling conflicts could arise if materials are not pre-qualified in a timely manner.

3.1 Cementitious Materials

Cementitious materials include hydraulic cements, such as portland cement and ground granulated blast furnace slag (GGBFS), and pozzolanic materials, such as fly ash. Fly ash and GGBFS are also referred to as supplementary cementitious materials (SCMs). Current practice for paving concrete is to incorporate portland cement and one or more SCM. Some agencies allow use of ternary concrete mixtures that incorporate portland cement and two SCMs.

Cement specifications for blended cements are also permitting the inclusion of up to 15% ground limestone in the cement.

The use of supplementary cementitious materials may offer the potential of improved performance of concrete and/or reduced cost. These materials, as partial replacement of portland cement, may provide some benefits more economically and sometimes more effectively than use of 100% portland cement. The benefits include the following:

1. Control of expansions due to alkali-silica reaction
2. Sulfate resistance
3. Reduced heat of hydration
4. Long-term strength gain
5. Improved workability
6. Reduced permeability

Engineer Notes

1. Check local availability of cements before specifying cement types.
2. Do not specify cements with special properties unless these properties are necessary.
3. Limiting a project to a single cement type or a single brand may result in increased costs and project delays.
4. Specifications should focus on the specific needs of the project and allow use of a variety of materials to meet these needs.

Contractor Notes

1. Cement supplies need to be secured to ensure supply during the peak construction season. If the cement source is changed, additional mix design and compatibility testing is required.
2. It is advisable to pre-qualify mixture designs using different cementitious materials so that if a substitution needs to be made, the mixture design data are already available and the new materials can be used without delay.

3.1.1 Hydraulic Cement

Hydraulic cements need to conform to one of the following standards:

1. ASTM C 150 or AASHTO M 85 (portland cement)
2. ASTM C 595 or AASHTO M 240 (blended cement)
3. ASTM C 1157 (hydraulic cement)

ASTM C 150 and AASHTO M 85 specify five types of cement, not all of which are available in all areas of the US and Canada. The cement types are as follows:

1. Type I, the most widely available, is used when the special properties of the other types are not required.
2. Type II is for general use, but particularly when either moderate sulfate resistance or moderate heat of hydration is required. Some cements meet the requirements for both Types I and II and are designated Type I/II.
3. Type III cement is used for high early strength.
4. Type IV is used when low heat of hydration is required. However, Type IV cement is not readily available in the US.
5. Type V is used for high sulfate resistance.

Additional notes related to portland cements include the following:

1. The specifications define optional chemical requirements, such as limits on the maximum alkali content, and optional physical requirements, such as heat of hydration. These need to be specified carefully, if at all, given they will often add to the cost and/or limit the available options. Frequently there are equally acceptable or even preferable alternatives.

For example, deleterious expansions due to alkali-silica reaction may be controlled as well or better by a combination of cement with Class F fly ash and/or slag than with low-alkali cement.

2. It is generally not advisable to specify a maximum limit on the alkali content of the cement. This may not be sufficient to control deleterious expansions. In some cases, higher alkali content may be desirable to increase the rate of hydration during cool weather or when supplementary cementitious materials are being used.
3. Sulfate resistance may be obtained by the use of sufficient quantities of slag or an appropriate fly ash as well as (or better than) a Type II or Type V cement.
4. Heat of hydration may be reduced by the use of some combination of slag, Class F fly ash, and/or natural pozzolan with portland cement.
5. If the cement is to be used on its own (that is, without supplementary cementitious materials), it may be advisable to specify the optional requirement for false set. However, setting characteristics need to be evaluated on concrete.

The specifications for blended cements include the following:

1. Type IS (X) cement (portland blast-furnace slag cement) contains blast furnace slag
2. Types IP (X) cement (portland-pozzolan cements) contains pozzolan (fly ash or natural pozzolan)
3. Type IL(X) – Portland limestone cement
4. Type IT(A)(X)(BY) – Ternary blended cement

The X and Y in parenthesis denote the targeted percent of pozzolan, slag, or limestone in the blended cement. A and B denote the materials used in a ternary cement.

Blended cements have comparable strength requirements to those specified for Type I cement. However, the actual strengths at early ages will generally be somewhat lower because slag and pozzolans included in blended cements react more slowly than cement alone. The naming practice for blended cements requires addition of a suffix (X) to the type designation, where (X) equals the targeted maximum percentage of slag or pozzolan in the product expressed as a whole number by mass of the final blended product.

ASTM C 1157 is a specification for hydraulic cements that sets limits on their performance attributes. These cements must meet physical performance test requirements, as opposed to prescriptive restrictions on ingredients or cement chemistry as found in other cement specifications. This specification is designed generically for hydraulic cements and includes six types as follows:

1. Type GU is for general use
2. Type HE is for high early strength
3. Type MS is for moderate sulfate resistance
4. Type HS is for high sulfate resistance
5. Type MH is for moderate heat of hydration
6. Type LH is for low heat of hydration

As of 2012, ASTM C 1157 has not been widely used for pavement applications.

Cement Certification and Uniformity

Mill certificates are provided monthly by cement manufacturers. These certificates report an average of multiple tests conducted on composite samples taken at intervals (typically daily) from the plant. While these may confirm that, on average, the cement was compliant with the specification, there is little assurance that every load delivered to the project site has done so, nor do they address variability between truckloads. The primary warrant for better characterization of the as-delivered cement is that the contractor is able to respond in a timely manner if the cement is varying sufficiently in composition and properties. This is a contractor quality control issue. A difficulty inherent in asking for frequent reporting is that the testing, by definition, will take several days to conduct; therefore, a full report is likely only available some time after the cement has been used. In addition, the contractor typically does not have excess storage capacity available at the site to hold the cement while testing is performed on the delivered cement.

The contractor should review the cement chemical analyses and the mortar cube strength data for each cement load delivered to monitor the overall uniformity of the cement being delivered.

The following recommendations on interpreting cement data are intended as broad guidelines.

- High C_3A cements (>8%) are more likely to be prone to aluminate/sulfate imbalances. Changes of more than 2% may indicate potential changes in the performance of the mixture, especially with respect to the risk of early stiffening of the concrete.
- Likewise, it is not the total sulfate content that is of concern, but materials with low sulfate contents (<3%) are more likely to be problematic. Changes of more than 0.5% may indicate potential changes in the performance of the mixture, especially with respect to the risk of early stiffening of the concrete.
- Cements with high alkali contents (>0.8) are generally more reactive and may therefore be more prone to unexpected or imbalanced reactions including greater risk of cracking and air-void system problems. Changes of more than 0.2% may indicate potential changes in the performance of the mixture.
- The finer the cement, the greater the risk of uncontrolled C_3A reactions with other ingredients in the concrete. Changes of more than 50 m^2/kg may indicate potential changes in the performance of the mixture.

In addition, cement sources should be identified for each cement load. A change in cement source will require submittal of new concrete mixture proportions.

3.1.2 Supplementary Cementitious Materials

For paving applications, the choice of SCM should be limited to fly ash and GGBFS. The delayed set time and lower shrinkage with mixtures containing SCMs may be a benefit on high-friction bases such as open-graded stabilized drainage layers.

The replacement dosage for SCMs (flyash and GGBFS) should be compatible with the needs for strength and durability. The desired SCM content should be established considering the importance of early strength, durability concerns, the curing temperatures, and the properties of the SCMs, the cement, and other concrete materials. The replacement dosage rates are discussed in Para. 4.1.

It should be noted that fly ash and slag are covered under the Environmental Protection Agency's Comprehensive Procurement Guidelines (CPG). The CPGs are Federal Law that requires federally funded construction projects to include certain recycled materials in construction specifications. Concrete specifications, therefore, must include provisions that allow use of fly ash and slag. The CPGs state that no preference should be given to one of these materials over another; rather, they should all be included in the specification.

Fly Ash

Fly ash must meet the requirements of ASTM C 618. However, care should be taken in applying ASTM C 618, as it is rather broad. Class F fly ash is the preferred choice for controlling ASR and it also improves sulfate resistance. Selection of fly ash type and dosage for ASR mitigation should be based on the guidelines provided in the proposed specification.

Contractor On-Site Cement Testing

It is recommended that the contractor retain 10 lb of cement and 10 lb of each SCM as weekly composite samples to be available for forensic analyses should concrete placement or concrete testing problems or early-age distress develop.

In addition, it is recommended that the contractor perform a simple semi-adiabatic calorimetry test on each cement and SCM delivery for internal quality control. Such a method is being developed at ASTM.

The contractor may also wish to perform a 3 day or 7 day cement strength test as per ASTM C 109 for each day of concrete paving.

During warm summer months, the contractor should monitor the temperature of cement as delivered. Hot (fresh-from-the-mill) cement use during peak construction season may result in the following:

- Tendency to false set
- Admixture demand increase – May need more in the field than required in the laboratory

Key items related to fly ash use are as follows:

1. Typical dosages for Class F fly ash are generally between 15% and 25% by mass of cementitious materials. Sources must be evaluated for typical usage rates.
2. In cool weather, concrete with Class F fly ash may not gain strength rapidly enough to allow joint sawing before shrinkage cracks begin to form. Generally, this does not occur at lower (about 20%) dosage, but appears frequently at 25% and higher dosage rates.
3. As the amount of fly ash increases, some air entraining and water reducing admixtures are not as effective and require higher dosage rates due to interactions with the carbon in the fly ash. The dosage of admixtures will further increase as the daytime temperature increases. This generally occurs when the fly ash content is 25% or more.
4. While ASTM C 618 permits up to 6% LOI, experience has shown that materials containing 4% or more LOI will likely result in difficulties in achieving the required air void system consistently. Changes in LOI will indicate changes for the amount of air-entraining admixture required in the mixture. If the source of the fly ash is likely to be variable, it is advisable to conduct a “Foam Index Test” on each delivery so that such changes can be accommodated.
5. Some Class C fly ashes perform very well, while others have been problematic. Sources must be evaluated independently. Class C fly ashes with high C3A contents may cause problems with premature stiffening, particularly in hot weather. The potential for early stiffening in the presence of certain water reducers and in hot weather should be verified.
6. If fly ash will be used to control expansions due to ASR, the lower the CaO content the more effective it will be. Ideally, the CaO content should not exceed 8%. The fly ash effectiveness and dosage requirements should be verified by test.
7. Natural pozzolans are available either as components of Type IP cement or as additives. They can be effective in controlling expansions due to alkali-silica reaction and in reducing heat of hydration.
8. Some regions of the country only have a fly ash that may vary from a Class F to a Class C from day to day due to small changes in their chemistry. These fly ashes should meet the uniformity requirements of ASTM C 618, Table 3.

Ground Granulated Blast Furnace Slag (GGBFS)

Finely ground granulated blast furnace slag must meet the requirements of ASTM C 989. The following three grades are based on their activity index:

1. Grade 80. This is the least reactive, is not typically used, and may not be allowed.
2. Grade 100. This is moderately reactive.

3. Grade 120. This is the most reactive, with the difference obtained primarily through finer grinding. Grade 120 is often difficult to obtain in some regions of the US.

Typical dosages of slag should be between 25% and 50% of cementitious materials. It should be noted that concrete strength at early ages (up to 28 days) may be lower using slag-cement combinations, particularly at low temperatures or at high slag percentages. The desired concrete properties must be established considering the importance of early strengths; the curing temperatures; and the properties of the slag, the cement, and other concrete materials.

If the concrete is to be used when the air temperature is expected to be lower than 55 F, the percentage of slag should not exceed 30% by weight of the cementitious materials.

Other SCMs

Fly ash and slag are the two most common SCMs used for paving applications. Another SCM that is used for certain applications, e.g., bridge deck concrete, is silica fume. Use of silica fume results in very low permeability concrete and can also increase concrete strength. However, because of cost considerations, use of silica fume is not a standard practice for concrete paving.

3.2 Aggregates

Aggregates are a key component of concrete and can affect the properties of fresh and hardened concrete. Aggregate selection should allow for maximizing the volume of aggregate in the concrete mixture in order to minimize the volume of cementitious paste without compromising the workability, durability, and strength of the concrete mixture. The specification does make references to aggregates as coarse and fine aggregates. Rather, the aggregate size distinction is based on aggregates passing the No. 4 sieve or that retained on the No. 4 sieve.

Maximum Aggregate Size

The concern with size involves selecting an aggregate that will maximize aggregate volume and minimize cementitious materials volume. The method of placement and finishing also influences aggregate size selection. In general, the larger the maximum size of the coarse aggregate, the less cementitious materials are required, potentially leading to lower costs, less heat of hydration during hot weather, and reduced shrinkage. Ideally, the contractor should determine the maximum aggregate size to be used. The contractor should base their selection on project-specific needs and locally-available aggregates. Exceptions to this include the following cases:

1. Use of smaller maximum size aggregate (e.g., 3/4 in. maximum size) for D-cracking regions. However, the use of 3/4 in. maximum aggregate size alone does not prevent D-cracking, and many state agencies have criteria for D-cracking other than maximum aggregate size. The 3/4 in. is only to be specified by the engineer after careful consideration of D-cracking mitigation methods, discussed in Para. 3.2.2 Aggregate Quality.
2. Owner-specific criteria.

Aggregate Sizes

The contractor is permitted to use any number of aggregate sizes to optimize the combined aggregate gradation (discussed next). Typically, three aggregate sizes can result in an optimized combined gradation that will produce a workable concrete mixture for slipform paving.

3.2.1 Gradation Evaluation of the Proposed Aggregates

This specification is targeted for a combined aggregate gradation. This approach evaluates the mixture properties based upon the combination of all of the aggregates, and does not require specification of individual coarse, intermediate, and fine aggregates. The aggregate grading should be based upon a combined gradation of all the aggregates to be used for the mixture proportioning studies. Grading reports should include the following sieve sizes: 2 ½ inch, 2 inch, 1.5 inch, 1 inch, ¾ inch, ½ inch, ⅜ inch, No. 4, No. 8, No. 16, No. 30, No. 50, and No. 100.

Method of Evaluation

Shilstone first published information on the use of combined gradations for concrete applications. It is recognized that the use of combined gradations is a positive direction for pavements, especially in the reduction of joint spalls. However, there is no single industry standard for establishing the optimum combined aggregate gradation that is directly applicable for all applications. The proposed specification incorporates a Standard Method to evaluate the combined aggregate gradation. The Standard Method is based on the Shilstone method and allows for material variation in various regions.

It is mandatory that the method given in the specification be used to evaluate if the aggregates meet the criteria for an optimized combined gradation. If the criteria for an optimized combined aggregate gradation are not met, the aggregates proportions may need to be adjusted or new aggregates may be required.

Concrete mixtures produced with a combined aggregate gradation that produces a dense aggregate matrix tend to:

1. Reduce the water demand,
2. Reduce the cementitious material demand,
3. Reduce the shrinkage potential,
4. Improve workability,
5. Require minimal finishing,
6. Consolidate without segregation,
7. Enhance strength and long-term performance.

Concrete mixtures produced with a gap-graded aggregate combination may:

1. Segregate easily,
2. Contain higher amounts of fines,
3. Require more water,
4. Require more cementitious material to meet strength requirements,
5. Increase susceptibility to shrinkage,
6. Limit long-term performance.

Key items to note are as follows:

1. The contractor may choose to purchase the individual aggregates based upon ASTM C33 or state DOT gradations. However, it is advisable for the contractor to specify the standard stone size or name, the gradation, and the tolerances on each sieve of the

gradation. Use of ASTM C33 or state DOT materials does not negate meeting the aggregate quality requirements of the proposed specification.

2. There is no limit on the number of aggregates that may be used. In many instances, the mixture proportioning studies will indicate a need for aggregates in the 3/8 to No. 4 range to improve the workability of the mixture. Typically, contractors use three aggregates to produce a dense graded aggregate.
3. The combined gradation approach does allow the use of materials that would not normally meet individual gradations for ASTM C33 or state DOT products.
4. There are significant differences between the optimum particle distribution of natural rounded gravel and sand and elongated stone, flat crushed stone, and manufactured sand. Generally, as the particles become flatter, elongated, or sharper on the edges, the greater is the need for fine aggregate, admixtures, and water to lubricate the concrete and facilitate placement and finishing.
5. In the past, gap graded aggregates meeting the gradation limits of ASTM C 33 were routinely used for paving concrete. The proposed specification emphasizes that the aggregate gradation be optimized by using a combined aggregate gradation that produces a dense aggregate matrix that can be easily placed, consolidated, and finished.

The prescribed method of evaluation is based on the Workability and Coarseness Factors Method. The Workability and Coarseness Factors are determined for the combined aggregate gradation as follows:

1. The Workability Factor is the percent of the combined aggregate that passes the No. 8 sieve
2. The Coarseness Factor is the percent of material retained on the 3/8 in. sieve divided by the percent of all the aggregate retained on the No. 8 sieve and multiplying the ratio by 100.

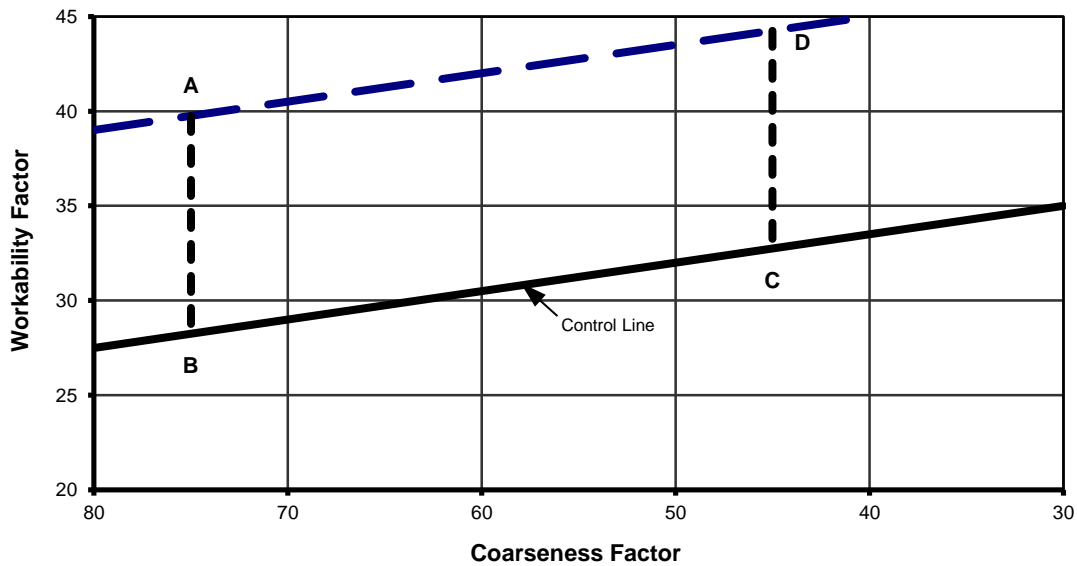
The Workability Factor indicates how much of the total aggregate is fine aggregate and provides an estimate of the degree of the mobility of the mixture or the ease of placement of paving mixtures. It has no relationship to consistency or slump of concrete. The Workability Factor can vary from inadequate to excessive. Maintaining the Workability Factor within the range of recommended limits provides a greater assurance that the concrete mixture has been optimized for workability, durability, and strength.

A Coarseness Factor of 100 describes a gradation that has no intermediate aggregate, i.e., no particles retained on the No. 4 and No. 8 sieves. A value of zero describes a mixture with no coarse aggregate, i.e., no particles retained on the 3/8 in. sieve. Maintaining the Coarseness Factor within the range of recommended limits provides a greater assurance that the concrete mixture has been optimized for workability, durability, and strength.

Combined Aggregate Gradation Criteria

The aggregates, as proportioned, shall be deemed to have met the requirements of a combined aggregate gradation when the following criterion is achieved:

- The WF and CF shall be within the parallelogram ABCD of the Aggregate Constructability Chart (Figure 1).



Point A – CF = 75; WF = 40; Point B – CF = 75; WF = 28

Point C – CF = 45; WF = 32; Point D – CF = 45; WF = 44

Figure 1. Aggregate constructability chart

In accordance with the Shilstone method, materials with WF and CF within parallelogram ABCD of Figure 1 are considered as meeting the criteria for optimized combined aggregate gradation. The diagonal control line defines a region where combined rounded or cubical crushed stone and well-graded natural sand are in balance. However, such mixtures have limited application, as the aggregate gradation must be well controlled. These mixtures are often excellent for bucket placed concrete in large footings. Mixtures represented by plots above the control line identify mixtures with increasing amounts of fine aggregate. Those below the control line generally contain an over-abundance of coarse particles and are not desirable for concrete paving.

It is recognized that some contractors may not have used a combined aggregate gradation due to availability of local materials. However, the use of gap graded concrete is not acceptable in the proposed specification. Gap-graded aggregates are prone to workability issues, segregation, and joint spalling, which are elements that affect long-term durability of the concrete pavement.

Based on field experience, not all mixes contained within parallelogram ABCD of the Aggregate Constructability Chart may be workable and durable. The contractor may still need to refine the mixes to be workable for the paving equipment and conditions.

Aggregates Not Meeting Optimized Combined Aggregate Gradation Criterion

In regions where achieving an optimal combined gradation is difficult because of availability of aggregate types, other innovative methods should be explored. The economics of the project will dictate the methods to be used. If possible, a four bin plant will provide a significant amount of flexibility to the contractor to adapt to local aggregate markets. The aggregate supplier may also have the ability to pre-blend aggregates. Some contractors use double-washed asphalt sand to provide the proper sizing to improve the combined gradation.

3.2.2 Aggregate Quality

Deleterious Substances

Deleterious substances are contaminants that are detrimental to the aggregate's use in concrete and need to be considered for the aggregate portion retained on the No. 4 sieve as well as for the aggregate portion passing the No. 4 sieve. ASTM C 33 lists the following as deleterious substances:

1. Clay lumps and friable particles
2. Chert (with saturated surface dry specific gravity < 2.40)
3. Material finer than No. 200 sieve
4. Coal and lignite

For the coarser portion of the aggregate, the maximum allowable portions of the deleterious substances are dependent on the weathering region. Inclusion of larger than allowable amounts of the deleterious substances can have a serious impact on both the strength and durability of concrete.

Soundness

The soundness test measures the aggregate's resistance to weathering, particularly frost resistance. ASTM C 88 test for soundness has a poor precision record. Aggregates that fail this test may be re-evaluated using ASTM C 666 or its suitability determined based on local service history.

Flat and Elongated Pieces

Flat and elongated particles impact workability of fresh concrete and may negatively affect the strength of hardened concrete. Thus, the amount of these particles needs to be limited.

Los Angeles Abrasion Test

The Los Angeles Abrasion Test provides a relative assessment of the hardness of the aggregate. Harder aggregates maintain skid resistance longer and hardness is an indicator of aggregate quality.

Durability (D-Cracking)

Durability cracking (D-Cracking) is a concern for aggregate particles that have a coarse pore structure and which are saturated and subjected to freezing. It is a good practice to review the successful state DOT practices to determine if locally available materials are susceptible to D-cracking and to identify successful mitigation measures implemented by the DOT. The engineer must carefully incorporate successful DOT methods for D-cracking to avoid conflicting with other necessary criteria in this specification.

The following is recommended:

1. The engineer shall determine if D-cracking related requirements are necessary based on local experience. Typically, the state DOT will have already identified D-Cracking issues, and the engineer shall insert the state DOT provisions for appropriate approved aggregate sources. Note that the state DOT requirements for D-cracking may be different than for maximum aggregate size. Therefore, this item should be coordinated with Para. 3.2 - Aggregates. The engineer is cautioned to refer to the applicable state DOT specifications related to D-cracking carefully to ensure that these requirements will not conflict with other coarse aggregate requirements in the proposed specification. Do not make a blanket reference to DOT standards; carefully select and cite the appropriate paragraphs and sections, and ensure non-applicable references in the DOT manual to other DOT requirements are stricken.
2. If the contractor uses an out-of-state aggregate source and the state from which the aggregates are originating does not have D-cracking-related requirements that equal or exceed the requirements of the local state DOT, the engineer will require the conduct of ASTM C-666 testing, knowing that a lead time of about four months will be necessary to conduct the ASTM C-666 testing. The Durability Factor shall be > 95 (Method A).
3. Some projects may be close to state borders where importing better quality aggregates is desirable by the contractor. In these situations, the engineer shall consider the surrounding state materials and include applicable provisions discussed above.
4. There is no specific requirement of service record as this requirement is incorporated in a state DOT's approval of an aggregate source. Also, there is no specific discussion of mitigation methods such as use of smaller-sized aggregates as such guidance and requirement will be incorporated in the state DOT's approval of an aggregate source.
5. Some state-specific requirements in severe D-cracking states that have been used for FAA projects in the past may be used after a determination is made that these requirements are still applicable.

Slag Aggregates

Properly aged air-cooled iron ore blast-furnace slag aggregates should only be used as a coarse aggregate if there is substantial history of successful pavement performance.

1. Control of moisture content is very important when slag aggregates are used. Potential problems include variations in workability and consolidation. The porosity of the individual slag aggregates may vary; therefore, the moisture demand may vary.
2. If slag aggregate moisture is not managed well, the in-place concrete may exhibit honeycombing and poorly formed edges.

Steel-making slag (from open-hearth basic oxygen or electric arc processes) should not be used as concrete aggregate because of the expansive nature of the steel slag aggregates. In addition, fine aggregate manufactured from steel slag should not be used in paving concrete.

Recycled Concrete Aggregates

If specified, recycled concrete aggregate needs to be from a single known source, such as a pavement that is being demolished as part of the project. Use of recycled concrete from a commercial recycle yard should not be permitted as it may include reactive, deleterious, or variable materials and it is not possible to quantify the sources. The engineer needs to have petrographic testing conducted, especially for Alkali Silica Reactivity (ASR) and Durability Cracking (D-Cracking) prior to specifying recycled aggregates and not allow the recycled concrete if these or other detrimental properties are present.

3.2.3 Reactive Aggregate Screening

Alkali-silica reaction (ASR) is a deleterious chemical reaction between the reactive silica constituents in the aggregates and alkali hydroxides in the concrete. The product of this reaction often results in significant expansion and cracking of the concrete.

The engineer will consider the time requirement for ASR-related testing when the project is advertised and when it is let to allow the contractors adequate time to perform the necessary ASR-related testing.

AASHTO Recommended Practice PP 65-10, Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete, is an approach that can be used to assess the reactivity of an aggregate and the effectiveness of mitigation methods.

3.3 Water

Suitable mixing water for making concrete includes potable water (fit for human consumption), non-potable water, and recycled water from concrete production operations. Testing is required for the last two sources or any questionable water to ensure that they do not contain impurities

that affect strength, set time, or other concrete properties. Acceptance criteria for water to be used in concrete are given in ASTM C 1602.

3.4 Chemical Admixtures

Chemical admixtures are ingredients commonly used in paving concrete and their use is well established. They are used to obtain or enhance specific properties of concrete, such as, workability, setting time, or air content. The following practices related to chemical admixtures should be observed:

1. Chemical admixtures must meet the requirements of ASTM C 260 or ASTM C 494. ASTM C 260 specifies the requirements for air-entraining admixtures.
2. For concretes with multiple admixtures, the admixtures need to be purchased from the same manufacturer. The large manufacturers test their own admixtures for incompatibility and other interactions and can provide helpful advice for avoiding undesirable reactions.
3. Not all admixtures work well in all applications. For example, the low slumps typical of paving concrete make certain air-entraining admixtures less effective.
4. The contractor is encouraged to seek the advice of the manufacturer on applying and using admixtures. Batching requirements, mixing procedures, and recommended dosages need to be obtained from the manufacturer. Exact dosages for the particular concrete mixture design need to be determined through the use of trial batches.
5. Placement temperatures affect the required dosages of chemical admixtures. Trial batches should be developed accordingly.
6. Admixtures are never used to compensate for marginal concrete mixtures.
7. The admixtures must be added separately to the concrete. Admixtures should not be put directly on dry aggregate or on dry cement, as they may be absorbed and not available to readily mix with the concrete.
8. Consult the manufacturer for information about potential interactions between admixtures.
9. Some water reducers may retard setting and/or strength gain when used in higher dosages.

Proper Use of Admixtures

As stressed by Neville, while properly used admixtures are beneficial to concrete, they are no remedy for poor quality materials, for use of incorrect mixture proportions, or for poor workmanship in transporting, placing, and consolidating the concrete.

3.4.1 Air-Entraining

Air-entraining admixtures entrain a system of finely divided air bubbles in the cement paste. They are essential protection for any concrete that will be exposed to freezing, as they provide outlets for freezable water to expand so that it does not disrupt the internal structure of the concrete. Air-entraining admixtures may also be used to improve the workability of fresh concrete. They may also reduce water demand, bleeding, and segregation.

The selection of an admixture, meeting the requirements of ASTM C 260, needs to be appropriate for pavement use; some admixtures are meant to be used only in concretes with higher slump allowances than that typical of pavements. In addition, the dosage rate needed to obtain the desired air content will be affected by ambient temperature, w/cm ratio, types of cementitious materials, aggregate gradation, mixing time, and other admixtures in the concrete mixture.

Air Void Clustering

Since late 1990s, it has been recognized that use of some non-vinsol AEAs may lead to low concrete strengths due to clustering of air voids around coarse aggregate particles, for concrete delivered by transit truck mixers. Studies conducted by the Portland Cement Association, South Dakota DOT, and others have confirmed this behavior. In summary, use of synthetic AEAs may lead to the following:

1. Air voids may randomly flocculate around aggregate particles and become similar to entrapped air.
2. Air void clustering around aggregates particles reduce the paste-aggregate bond interface area, leading to low compressive and flexural strengths.
3. Air void clustering typically develops after late addition of water to the concrete mixture, even though the added water may be within the allowable w/cm ratio.
4. The severity of air void clustering may increase when the retempered concrete is mixed for a longer period of time.

With reference to the air void clustering and subsequent strength loss in concrete, the Product Note for a synthetic air entraining admixture has the following precaution note:

“In a 2005 publication from the Portland Cement Association (PCA R&D Serial No. 2789), it was reported that problematic air-void clustering that can potentially lead to above normal decreases in strength was found to coincide with late addition of water to air-entrained concretes. Late additions of water include the conventional practice of holding back water during batching for addition at the jobsite. Therefore, caution should be exercised with delayed additions to air-entrained concrete. Furthermore, an air content check should be performed after any post-batching addition to an air-entrained concrete mixture.”

Weak paste-aggregate bond can result in aggregate popout (dislodgement) during sawing, grinding, and grooving operations.

3.4.2 Water Reducing, Set Retarding, and Accelerating Admixture

Water reducing, set retarding, and accelerating admixtures are specified in accordance with ASTM C 494. The types of admixtures specified by ASTM C 494 include the following:

1. Type A, water-reducing admixtures
2. Type B, retarding admixtures
3. Type C, accelerating admixtures
4. Type D, water-reducing and retarding admixtures
5. Type E, water-reducing and accelerating admixtures
6. Type F, water-reducing, high range admixtures
7. Type G, water-reducing, high range, and retarding admixtures
8. Type S, Specific performance admixtures

Types A, B, C, D, and E are typically used for paving applications to obtain one of the following benefits:

1. Reduce the water/cement ratio at a given workability
2. Increase the workability for a given water content
3. Reduce the water and cement contents for a given workability

Items to note include the following:

1. Some Type A water-reducing admixtures act as Type D (water-reducing and retarding) admixtures at higher dosages.
2. Some mixtures containing Type A water-reducing admixtures and supplementary cementitious materials may stiffen and set unexpectedly, particularly at elevated temperatures. This should be assessed using trial batches. Changing the source or dosage of either the water reducer or the SCM often solves this problem.
3. High dosages of water-reducing admixtures may lead to excessive set retardation.
4. The concrete workability may be affected when high dosage of water-reducing admixtures is used.
5. Some water-reducing admixtures enhance the effectiveness of air-entraining admixtures so that a lower dosage of the air entraining admixture achieves the required air content.
6. Typically, the water-reducing admixtures reduce the water content by approximately 5% to 10%.

7. Mid-range and high-range water reducers are not widely used in pavement concrete and their use should be approached with caution.
8. Admixtures based on polycarboxylates may affect the air void system

Set Retarding Admixtures

Retarding admixtures, classified as Type B (Retarding Admixture) and Type D by ASTM C 494, delay the initial and final setting times.

Items to note include the following:

1. Retarding admixtures slow down the rate of hydration of the freshly placed concrete and extend the period during which concrete remains workable
2. Retarding admixtures will not prevent loss in workability due to moisture loss through surface evaporation
3. Retarding admixtures affect the rate of strength gain for as little as 1 or 2 days, or as long as 7 days, depending on the dosage
4. They may be used in hot weather for longer haul times (if permitted) or to prevent the formation of cold joints
5. Increasing the setting time of a mixture may increase the risk of cracking because sawing cannot start before excessive shrinkage occurs
6. Changes in temperature may require adjustments in admixture dosage to maintain the desired setting time

Accelerating Admixtures

Accelerating admixtures are classified as Type C (Accelerating Admixture) and Type E by ASTM C 494. They accelerate the setting and/or early strength gain of concrete. Normally they would be used only in cold weather or for repairs when the reduction of an hour or two in the setting time is important. They are also used when some increase in the early-age strength is needed. If any of these properties are needed over the course of the job, it is preferable to design the concrete accordingly rather than rely on accelerating admixtures.

Accelerating admixtures affect primarily the setting time, heat evolution, and strength development. The strength at later ages may be lower and, in aggressive environments, the durability may also be affected adversely. Alternate means of obtaining early strength development include the following:

1. Use of Type III cement
2. Higher cement contents
3. Heating the water and/or aggregates

4. Improving curing and protection of the concrete
5. Some combination of the above

Chemical admixtures, other than those discussed in the preceding sections, may be used to obtain or enhance certain properties of the concrete mixtures. For example, shrinkage reducing admixtures are reported to reduce the total shrinkage of a concrete mixture by modifying the capillary forces of the pore solution. Their use may assist in reducing the risk of shrinkage related cracking.

However, it is important that admixtures that are used be compatible with other admixtures to be used in the concrete. Material incompatibility may be induced by temperature changes. Therefore, trial batches need to be tested at the extremes of temperature anticipated at the project site. The incompatibility can be minimized when admixtures from the same manufacturer are used in a given concrete mixture.

The engineer may exclude certain admixture types or specific admixtures based on local experience and project requirements.

Additional Guidance on Chemical Admixtures for Concrete

Excellent guidance on use of chemical admixtures is provided in the American Concrete Institute's publication, ACI 212.3R – Chemical Admixtures for Concrete.

3.5 Forms

The form length should be not less than half the joint spacing when grades are provided at each transverse joint in the case of a vertical curve. Longer forms may be used for straight sections without any vertical curves.

Forms should be cleaned each time before concrete is placed.

3.6 Expansion Board

Standard specification item.

3.7 Embedded Steel

Standard specification item.

3.8 Tie Bars

Tie bars need to be corrosion resistant in coastal regions to minimize the risk of tie bar corrosion. Therefore, as dictated by local experience or practice, the engineer should consider requiring tie bars to be epoxy coated.

3.9 Dowel Bars

Standard specification item.

3.9.1 Dowel Bar Corrosion Protection Coating

The US practice is to use epoxy-coated bars in harsh environments for highway application to resist the effect of deicing chemicals and salt in the environment. Dowel bars may also be coated with black paint or zinc-based paint. However, epoxy coating is considered to provide more effective protection against salt-based corrosion.

3.9.2 Dowel Bar Bond Breaker

Dowel bars should be coated with a bond breaking material to ensure that the dowel bars do not bond to the concrete. The bond-breaking material may be applied at the factory or applied at the site. If dowel bars with factory applied bond-breaking coating are exposed to the weather at the project site over several months, the effectiveness of the dowel bar coating should be verified in accordance with AASHTO M-254.

3.9.3 Expansion Sleeves

Standard specification item.

3.9.4 Dowel Basket Assemblies

Stability of dowel basket assemblies is very important. The dowel assembly details should be included in the plan drawings. Many engineers specify that the connecting wires of the dowel basket assembly be cut prior to concrete placement. This practice is not necessary. The connecting wires do not need to be cut. Not cutting the connecting wires provides a more stable basket assembly during concrete placement.

3.10 Evaporation Retardants

Approved evaporation retardants, also referred to as monomolecular evaporation reducers, may be considered by the contractor to supplement the curing application. These materials form a thin continuous film and prevent rapid moisture loss of bleed water from the concrete surface. These materials are useful for reducing the risk of plastic shrinkage cracking occurring between initial placing and final finishing/curing of a surface, particularly in hot, dry weather.

There are no standard specifications for use of these materials. However, state DOTs typically maintain an approved list of vendors for the evaporation retardants. The manufacturer's instructions should be followed.

The use of evaporation retardants is recommended for hot weather conditions, typically when the ambient temperature is over 85 F and the risk for plastic shrinkage cracking is high.

3.11 Curing Materials

Curing is the maintenance of adequate moisture and temperature conditions to allow development of required physical properties of the concrete and is one of the most important construction activities. Poor curing practices can result in excessive slab warping, early-age cracking, poor surface abrasion resistance, surface deterioration, and reduced strength and durability.

Curing compounds, properly applied, need to have the following properties:

1. Maintain the relative humidity of the capillaries in the concrete surface above 80% for seven days
2. Be uniform and easily maintained in a thoroughly mixed solution
3. Not sag, run off peaks, or collect in grooves
4. Form a tough film that is able to withstand early construction traffic

In the US, curing is typically viewed in terms of concrete moisture retention. In practice, curing should involve retaining the concrete mixing water as well as protecting the concrete from extreme temperature events of hot and cold weather. Specific curing practices, as applicable, should be addressed in the Weather Management Plan.

It should be noted that concrete hydration is reduced when the relative humidity within the capillary pores is less than 80% and this effect is pronounced at the concrete surface if curing is not applied correctly or is not timely. Poorly-cured concrete can result in an increase in the amount of large pores at the surface and this can seriously affect concrete durability.

Key items to note include the following:

1. Curing compound use is the most common method for retaining mixing water for normal weather conditions. Curing compounds (liquid membrane-forming compounds) need to conform to the requirements of ASTM C 309, Type 2, Class B.
2. ASTM C 309 restricts water loss to a given volume over a fixed period of time and several state DOTs restrict the water loss to a quantity less than specified by ASTM C 309. Depending on local experience, the engineer may specify the local state DOT or other requirement for curing.
3. Pigmented curing compounds are recommended because they make it easy to verify proper application. For concrete placement on sunny days and in hot weather, the curing compound selected should contain a white pigment to reflect the sun's heat.

Other curing materials include white polyethylene film, burlap sheeting, and waterproof paper, all meeting the requirements of ASTM C 171. However, these materials are not commonly used for production paving, except for emergency needs.

ASTM C 156 specifies a method for determining the efficiency of curing compounds, waterproof paper, and plastic sheeting.

4.0 CONCRETE MIXTURE

The engineer shall specify the design properties of the concrete. In this specification, slump testing is not a design or acceptance requirement.

4.1 Concrete Mixture Requirements

The concrete mixture requirements are as follows.

Concrete Strength

The engineer determines the concrete strength. A key consideration is that the concrete strength specified for construction acceptance at 28 days is 5% less than the strength used for the thickness design. The design flexural strength used to determine the concrete slab thickness should be the strength (typically, at least 5% higher than the 28 day strength) when traffic begins to use the pavement.

Use of Splitting Tensile Strength Testing

It should be noted that although the concrete strength is specified in terms of flexural strength, the specification allows acceptance testing for concrete strength to be performed using flexural or splitting tensile strength. If splitting tensile strength testing is selected by the contractor, a project-specific correlation between flexural strength and splitting tensile strength will need to be developed for each concrete mixture during the laboratory stage of the mixture proportioning study. The correlation is then used to establish flexural strength data for the as-delivered concrete from the cylinder splitting tensile strength.

To optimize a pavement design, it is good practice to increase the slab thickness rather than increasing concrete strength above the recommended design levels of 600 to 650 psi. Design concrete strengths higher than 650 psi are not necessary. High concrete strength is not considered necessary for long-term performance of the concrete pavement. Use of the higher design strength levels need to be coordinated with the FAA prior to incorporation on a project. The engineer should consider other design features (e.g., slab thickness) as an alternate to specifying higher concrete strengths.

Minimum Cementitious-Material Content

The minimum cementitious materials content required for durability is greater than the amount required for strength and workability. Although it is possible to optimize a mix to achieve the lowest possible cementitious materials content and still achieve strength requirements, a minimum cementitious materials content is required to ensure that long-term durability of concrete is not compromised.

In fresh concrete, a minimum cement content is required for sufficient paste to coat the aggregates and thus make the mix workable. The minimum amount of paste required to fill all

voids will be dependent on aggregate grading (i.e., the amount of space between aggregate particles).

In hardened concrete, a minimum cement content is required to ensure that there is sufficient paste to coat all of the aggregate particles, and to fill all the spaces between them. Too little cement will mean that there is percolation of voids, i.e., aggressive fluids will be able to penetrate through the matrix. Both strength and potential durability decrease with increasing void content. A well-graded system will require less cement than a poorly graded system to achieve the same performance. Again, this amount will be largely dependent on aggregate properties.

In mild and moderate exposure regions, 470 pounds per cubic yard is acceptable, and 517 pounds per cubic yard is acceptable in severe exposure regions, based on industry-accepted requirements. For most projects, use of the combined aggregate gradation will allow the strength requirements to be readily achieved with these minimum cementitious materials contents. In optimized combined gradations, it is possible to exceed the specified strength and even the design strength following the minimum cementitious content, but with the limitations on water to cementitious ratio and excessive water reducers, it is not likely to achieve a brittle condition.

Water-to-Cementitious Materials Ratio

The optimum water to cementitious materials (w/cm) ratio is the minimum ratio that satisfies the need for concrete strength and durability. Very low w/cm ratios are not recommended. There is a field practice to achieve a higher concrete strength with less cement by using very low w/cm ratio (<0.38) and mid-range or high range water reducing admixtures. A combination of low w/cm ratio (0.35 to 0.40) and a mid- or high-range water reducer used as a plasticizer may produce high concrete flexural strength that can easily reach or exceed 1,000 psi at 28 days. Very high strength concrete can be brittle and result in lower fatigue life. Use of very low w/cm ratio is not recommended as it may also lead to concrete durability issues.

A maximum ratio is specified to ensure that the cementitious materials use is optimized to achieve the desired strength levels, to limit drying shrinkage, and to minimize the amount of capillary porosity in the hardened concrete.

Supplementary Cementing Materials

The US practice, based on field experience, is to limit the use of the supplementary cementing materials as follows:

- Fly ash – not to exceed 25% of total cementitious content
- Slag – not to exceed 50% of total cementitious content
- If both fly ash and slag are used, the total supplementary cementing material shall not exceed 50% of total cementitious content
- Total supplementary cementitious content shall not exceed 50% for mixtures using C 595 or C 1157 cements.
- In case of reactive aggregates, the use of the supplementary cementing material will be governed by the contractor's reactive aggregate mitigation plan

Air Content

A certain level of entrained air is necessary to ensure protection in freezing environments. The target percentage of air in the mix should be based upon the exposure condition and maximum aggregate size in accordance with ASTM C94/C 94M, unless local experience suggests otherwise. The ASTM C 94/C 94M (as of 2004) recommendations for air content (in percentage) for the 1, 1 ½, and 2 in. maximum aggregate sizes are as follows:

Exposure Condition	1 inch	1 ½ inch	2 inch
Mild	3.0	2.5	2.0
Moderate	4.5	4.5	4.0
Severe	6.0	5.5	5.0

Air content should be determined by testing in accordance with ASTM C 231 or ASTM C 173/C 173M, as appropriate. ASTM C 231 procedure is intended for use with concretes made with relatively dense aggregates. The ASTM C173/C 173M procedure is for concrete made with any type of aggregate, whether it is dense, cellular, or lightweight.

Although not a specification requirement, the contractor should consider using a small amount of air-entraining admixture even in non-freezing environments to enhance concrete workability. However, the entrained air for such applications should not exceed about 4% to minimize the impact on concrete strength.

Testing for Concrete Slump

Historically, slump testing has been used as a surrogate measure of concrete workability. For slipform paving, slump has no relationship to workability of the concrete mixture under vibration. Slump testing is an indicator of concrete consistency and is better suited as a contractor quality control test to identify changes that may occur as a result of changes in the characteristics of the concrete materials, mixture proportions, mixing, and haul times.

For slipform paving, acceptable concrete workability is best determined by observing the amount of hand finishing that is required behind the paver to correct the edges and corners and by performing consolidation testing of the in-place concrete. A workable concrete with sound concrete materials is easy to place, consolidate, and finish and produces durable concrete.

4.2 Concrete Mixture Proportions

Mixture proportioning addresses the combination of the individual concrete making materials to produce a concrete mixture that will meet the project requirements discussed in the previous section. The contractor may use any method to develop the concrete mixture. However, the proposed specification is targeted for a combined aggregate gradation that results in a dense concrete matrix. .

There is also no limit to the number of mixtures a contractor may develop and submit for the engineer's review. Concrete mixtures need to be developed for the following:

1. Each expected method of concrete placement
2. The anticipated ambient temperatures - concrete that can be placed at one temperature may not be workable at another
3. Specific construction requirements – normal paving versus fast-track paving, anticipated changes in material supply, etc.

Once the laboratory mixture proportions that meet project mix requirements have been developed and reviewed, the test section is built. The laboratory mixture proportioning is only a starting point and the contractor should verify their mixture at the test section and adjust the individual proportions within the allowed limits to ensure that the concrete mixture is workable for their paving equipment. There is no concern with strength- or durability-related issues if the mixture proportions are adjusted within the allowed limits. The allowed limits for adjusting the concrete mixture proportions are detailed in Para. 7.4 – Production Paving Adjustments to the Concrete Mixture Proportions.

Incompatible Concrete Materials

Incompatible reactions between some cements, supplementary cementitious materials and chemical admixtures have been known to occur, often in hot weather. It is recommended that trial mixtures be run at the maximum temperature expected in the field to determine whether there is a significant change in admixture dosages, the rate of slump loss, setting time, or in the air void system. If problems occur, they can often be resolved by changing the source or dosage of cementitious materials, or type of chemical admixture.

The replacement dosage for SCMs (fly ash and GGBFS) should be compatible with the needs for strength and durability. The desired SCM content should be established considering the importance of early strengths, durability concerns, the curing temperatures, and the properties of the SCMs, the cement, and other concrete materials.

Approved Water to Cementitious Materials Ratio

The approved water cementitious ratio is that submitted with the laboratory mixture proportioning submittal. The laboratory proportioning study is also where the strength correlation is determined. The water cementitious materials ratio is a key element that has an impact on concrete strength as well as concrete durability. Therefore, the ratio cannot be exceeded in the field. Field mixing is commonly more efficient than laboratory mixing; therefore, field mixes typically require less water than the laboratory study indicates, which is acceptable.

Strength Correlation Data

The proposed specification allows the contractor the option of using flexural strength or splitting tensile strength testing to determine concrete strength at the specified age. If the contractor elects

to use splitting tensile strength testing, he needs to develop a one-point correlation between the flexural strength and the splitting tensile strength for the specified age of testing. The one-point correlation should be developed as soon as the final mixture proportions have been established based on the laboratory testing.

The contractor should note that the development of the correlation data may require an extra month beyond the completion of the mixture proportioning study.

Acceptable Adjustments in Mixture Proportions

Some minor changes in the concrete mixture proportions are permissible on a routine basis if these changes do not have a detrimental impact on concrete durability or strength. These changes may be considered acceptable without requiring multiple reviews by inspectors, especially if these minor variations may vary during the day. The emphasis with the concrete mixture proportioning is to achieve a consistent end product, rather than rigidly-established material proportions.

Shortages of cement or other concrete-making ingredients may occur during the construction season. If any changes in type, source, or brand of cementitious material, admixtures, or aggregate source need to be made, trial batches need to be carried out to verify that the required properties are retained.

Certain minor adjustments to the concrete mixture proportions (e.g., air entraining and water reducing admixtures) may be necessary due to changes in the weather and to maintain the required workability and air content. However, if air content is increased or water is added above the design w/cm ratio, the concrete strength may decrease.

Minor variations in aggregate proportions in the field do not have a significant impact on the strength correlation.

5.0 EQUIPMENT

5.1 Concrete Batching Plant

Concrete is a manufactured product, the quality and uniformity of which depend upon the control exercised over its manufacture. The concrete batch plant needs to be in good condition, operate reliably, and produce acceptable concrete uniformly from batch to batch. The National Ready Mix Concrete Association (NRMCA) QC3 (Plant Certification Check List) process is the recommended standard and should be used for projects where it is anticipated a batch plant will be dedicated to the project, either on- or off-site.

It is not required that the NRMCA QC3 certification be prepared by a professional engineer; the specification identifies the qualifications for the inspector. A NRMCA QC3 certificate is not required, only that the checklist be completed and be acceptable.

The plant should be inspected prior to the start (or re-start) of each paving project and when uniformity or strength problems are encountered during production.

5.1.1 Plant Certification

If an existing plant or ready-mix operation is to be used, some state DOT certifications are equal to or more stringent than NRMCA QC3 and may be used. It is incumbent upon the engineer to determine if the state DOT requirements are permissible and edit the specification accordingly.

Plants that are moved should be checked using the NRMCA QC3 process.

Plants without Certification

The contractor should complete NRMCA QC3 checklist for each concrete plant to be used for the work. Each plant shall pass in all categories.

Trucks for truck-mixed concrete, if used, also need to pass the NRMCA QC3 checklist. The NRMCA provided certificates are not required.

The NRMCA QC3 checklist should be performed not less than 6 months from the start of production paving. In addition, the checklist inspection should be repeated if the plant is relocated.

The NRMCA QC3 checklist is not required to be completed by a registered professional engineer. However, personnel performing the inspection in accordance with the NRMCA QC3 checklist shall provide documentation of knowledge of batch plant operations and concrete production. A Statement of Qualifications shall be maintained for all personnel involved in the inspection process.

5.1.2 Mixers

Most central plants in the US are drum mixers with a tilting drum, non-tilting drum, or reversing drum. There is also a horizontal shaft type mixer that is available that uses two rotating shafts with paddles. All the plant types are acceptable provided the mixture design parameters are achieved. Plant data recorders shall record all of the concrete mixture batch weights.

The mixers should be inspected for hardened concrete around blades. Concrete is mixed by shearing. For drum mixers, the higher the fall from the top of the drum, the better the mixing action. If the blades are worn or have concrete buildup, the materials will not be carried as high in the drum and this will reduce mixing efficiency.

For truck mixers, the delivery tickets should show the information as provided for in NRMCA QC3. This will allow rapid determination at the site if any water can be added to the mixture.

5.1.3 Concrete Uniformity Tests

Concrete uniformity testing is required prior to the start of paving using ASTM C 94. Uniformity testing is required for all batch plants that are moved or are set up for the project.

Uniformity testing determines the ability of the mixer to mix the concrete and to establish minimum mixing times. Uniformity tests compare differences in concrete sampled at approximately 15% and 85% drum discharge. Differences shall be less than the maximum allowable differences stated in Appendix 1 of ASTM C 94/C 94M. The tests include the following:

- Unit weight
- Air content
- Slump
- Coarse aggregate content
- 7 day concrete average compressive strength
- Water content

The number of revolutions for truck-mixed and shrink-mixed concrete should be determined by uniformity tests in accordance with ASTM C 94/C 94M.

Moisture Control

Aggregate moisture control is an important process control item and can affect the consistency of the concrete production. Concrete with varying aggregate moisture content will exhibit difficulties during placing and finishing operations and may also exhibit low strength. Therefore, it is important that the contractor manage their aggregate stockpiles well and monitor the aggregate moisture regularly.

It should be noted that batches of concrete with variable water to cementitious materials content will exhibit poor durability. This is also the reason for not allowing water additions to truck-mixed concrete beyond the allowable w/cm ratio for that concrete and for not allowing water addition by spraying ahead of and behind the paving equipment.

5.2 Concrete Hauling Equipment

NRMCA QC3 provides guidelines on items to inspect for hauling equipment. It is beneficial for field personnel if each delivery truck has a large, clear, unique placard, e.g., No. 1, to improve references for communication between the paver and the plant, to cross-reference batch tickets, and to monitor delivery times.

5.3 Transfer and Spreading Equipment

Use of the transfer and spreading equipment is a contractor option. The contractor is the one most familiar with the capabilities of the paver and the concrete delivery planned for a project.

5.4 Paving Equipment

Paver selection needs to be at the option of the contractor. However, paving equipment for production paving are required to be fitted with internal vibrators and equipped with a vibration monitoring device that indicates the frequency of each installed vibrator.

Slipform Paver

Slipform pavers are generally capable of handling the larger projects where there is sufficient room to maneuver. For thicker sections, typically more than 12 in., some light-weight pavers may need a placer-spreader in front to pre-shape the concrete, otherwise the machine may not have enough tractive force to extrude the concrete or the paver frame may flex and lose flatness control of the pan. There are large machines available that have sufficient tractive force and weight to effectively spread and pave the concrete. The effectiveness of the paver can be determined at the test section.

If the engineer designs the paving joint layout on the plans, care must be exercised in coordinating the paving direction with the grading plans. A slipform paver cannot readily respond to rapid grade changes, such as paving over a crown or through an invert. The paver will

flatten the extreme grade change for the pilot lane. For the adjacent fill-in lanes, the edges of the pan will spall the pilot lane concrete edges.

Sideform Paver

Sideform pavers can achieve an excellent pavement but have a slower production rate and may require more labor than slipform pavers. Highly effective sideform pavers will have similar immersion vibrators and split augers as a slipform paver. It is common to use a slipform paver with side forms. A key issue with sideform pavers is the weight of the machine may damage the edges of the pilot lanes when paving the fill-in lanes. The paver will slide along the concrete and may cause spalls on the transverse joints within about a foot of the pilot lane edge.

Longitudinal Mechanical Float

If a longitudinal mechanical float is used on a paver, it will correct any minor surface issues, but if it is not properly weighted and adjusted, it will cut the surface or pool slurry on the low edge. Pooling the slurry is an indication that the mixture is incorrect or that the float is not adjusted properly. Simply removing the slurry is not the solution; the float must be adjusted and calibrated.

Form Riding Finishers

Form riding machine finishers ride on the forms but do not have the multiple immersion vibrators as do side and slipform pavers. These finishers will be necessary on most jobs, but are typically used for paving the fillets or near buildings where there is insufficient clearance for a paver. Form riding machine finishers include vibrating trusses and roller screeds.

Form riding finishers have a higher tendency for excess paste to accumulate at the surface and joints. Use of these finishers should be discontinued when excessive paste develops at the surface.

Bridge Deck Finishers

Bridge deck finishers with internal vibrators that travel transversely across the slab are acceptable for production paving. However, their use is more effective for placement of thinner concrete pavements. The rate of paving is also slower than slipform paving. Bridge deck finishers have a tendency to develop excess paste at the surface and along longitudinal edges. Use of the bridge deck finisher should be discontinued when excessive paste develops at the surface or along the edges.

Rotary Trowels

Rotary trowels or other equipment that can burn or polish the concrete surface shall not be used to finish the concrete surface.

Internal Vibrators

Concrete needs to be internally vibrated to achieve desired consolidation to ensure adequate strength and durability. The energy imparted by vibration needs to ensure that concrete is neither over-consolidated nor under-consolidated. The energy to be imparted by internal vibration is a function of the concrete mixture, paver speed, vibrator rotor force, vibrator frequency, vibrator spacing, and concrete head.

Slipform and some sideform pavers are equipped with internal vibrators that are typically spaced no more than 18 in. across a paving lane. Bridge deck pavers commonly have one or two vibrators that are mounted on a trolley that traverses across the paving lane. This type of consolidation is adequate for thin pavements, but becomes less effective as the slab thickness increases for heavily traffic pavements.

Vibration Monitoring Device

Vibration monitoring devices, also known as smart vibrator systems, are readily available and their use is considered very cost-effective. These devices monitor the vibrator frequency continuously and ensure that the proper level of vibration energy is imparted into the concrete mixture. These devices also immediately identify poorly-operating or inactive vibrators.

The frequency of a vibrator may be changed by the operator. The common range for concrete vibration is 5000 to 8000 Hz. Need for use of frequencies outside this range indicates that the mixture is not dense graded or there are other workability issues with the mixture. Given that vibrator effectiveness is dependent on vibrator type, mixture properties, slab thickness, and paver speed, the engineer should not specify frequencies or amplitudes.

Many concrete paving machines arriving on an a project have vibrators tuned to high settings for mixtures that are gap graded, have low workability, or are for thinner pavements. Dense graded concretes are significantly more responsive to vibration than traditional gap graded mixes.

Over vibration of dense graded mixtures, especially on fill-in lanes, is a significant contributor to sliver spalls at the joint seal reservoir. The vibrator frequencies at the edges of the fill in lanes normally need to be reduced due to the energy reflected from the pilot lane.

Vibrators should be positioned 4 to 6 in. below the finished surface and positioned at an attitude of 5 to 10 degrees. Vibrators too close to the surface will leave mortar trails that will crack and affect pavement durability.

Vibrator spacing is a function of the radius of action. The radius of action is a function of the vibrator rotor force and vibration amplitude and frequency. The vibrators should be spaced to ensure there is an overlap in the radius of action of adjacent vibrators.

The contractor should demonstrate or determine the optimum frequency and vibration to be used with the project concrete mixture at the test section, based on a designated paver speed. The

contractor needs to be aware that as the paver speed and concrete head vary, the vibrator frequency may need to be adjusted, based on experience or pre-established protocol.

Hand Vibrators

Insertion, operation, and withdrawal of the vibrator should be done with the vibrator in vertical alignment to avoid segregation and sand streaks that will reduce pavement durability. ACI 309 provides guidance on vibrator selection and operation.

Dowel Bar and Tie Bar Inserter(s)

Equipment used for inserting dowel bars in transverse contraction joints and tie bars in longitudinal contraction joints shall be capable of placing bars to specified tolerances. The contractor shall demonstrate and verify bar placement within specified tolerances during placement of the test section and once per lot of production paving.

For two-lift paving, the dowel bars should be inserted by the paving machine used to place the top lift. With this approach, no additional consolidation is applied after the dowel bars are in position. Additional consolidation after the dowel bars are inserted can lead to misaligned dowel bars.

5.5 Texturing Equipment

For production paving, texturing shall be done using automated equipment. The texturing equipment should be capable of providing uniform surface texture in plastic concrete across the full width of the paving lane. The texture may be applied with a brush or broom, burlap drag, or artificial turf finish. The texturing equipment should be capable of providing an average macrotexture depth of 0.04 in., plus or minus 0.008 in., when tested in accordance with ASTM E 965. The texture depth requirement permits the contractor to consider other innovative techniques to apply surface texture.

A hand broom may be used to apply texture on small, isolated handwork areas.

5.6 Curing Machines

Curing should be applied by a curing machine, which provides more uniform coverage than hand spraying. The curing equipment should be capable of applying the curing compound at the specified rate and coverage. The operation of the curing compound should be regularly calibrated in conformance with ASTM D 2995, Method A and spray nozzles should be checked regularly.

Minimum size of paving lane to require self-propelled curing machine may be determined by the engineer. Generally, if the area is large enough to accommodate a slipform or sideform paver, a self-propelled curing machine should be used.

Hand sprayers are intended to be used in isolated areas only and when approved by the engineer.

5.7 Concrete Saws

The concrete saw blade should be matched to the concrete aggregate. Improper saw blade use can lead to joint raveling and spalling. In addition, the saw blade needs to match the arbor. The sawing equipment should be in good operating condition and should not exhibit chattering behavior.

The contractor shall provide sawing equipment adequate in number of units and power to complete the sawing to the required dimensions in a timely manner, for transverse joints as well as longitudinal joints, if applicable. The contractor should provide standby saws in good working order and a supply of saw blades at the site at all times during sawing operations.

5.8 Drills

Drill used to drill dowel bar holes should be sized to ensure that there is no excessive chipping or spalling of concrete around dowel bars.

6.0 WEATHER MANAGEMENT

On most concrete paving projects that extend into several weeks, there is a good possibility that the project will be subjected to extreme weather conditions, defined here as hot weather, cold weather, or unforeseen rainstorms. Adequate precautions need to be taken during these extreme weather events to ensure concrete durability and functionality are not compromised. The weather management plan must be practical and can be implemented under short notice. An inherent requirement of the plan is that the contractor monitor the changing weather conditions and anticipate changes in the weather that may have an impact on the paving operation.

It is wise to stop paving on extreme weather event days if the contractor is not prepared to take adequate precautions as detailed in the weather management plan. Otherwise, the contractor risks potential problems – plastic shrinkage cracking, full-depth cracking in advance of joint sawing, delayed concrete set, excessive curling/warping, and damaged surface concrete.

A written weather management plan is not required for smaller projects requiring less than about 10,000 cubic yards of concrete. However, it is the contractor's responsibility to take necessary precautions to ensure that the extreme weather conditions do not have an impact on their paving operation. Other than the submission requirements for a written weather management plan, all requirements for the protection of the fresh concrete and the placed concrete are the same for small as well as large projects.

It should be noted that the weather management plan needs to incorporate only the elements of the extreme weather conditions that are applicable for the specific project. For example, cold weather paving items need not be included for projects in the southern parts of the US.

A sample weather management plan is provided in Appendix A.

6.1 Hot Weather Paving

See Appendix A.

6.2 Cold Weather Paving

See Appendix A.

6.3 Protecting Concrete from Rain Damage

See Appendix A.

7.0 EXECUTION

7.1 Underlying Material Preparation

The grade is accepted after the base layer is placed, trimmed, leveled, and compacted. Once the grade is accepted, a traffic control plan must be implemented. Heavy construction trucks traveling on the prepared surface can damage the grade. Traffic management must be enforced if logistics require use of the prepared grade by construction equipment.

The variability of the base layer grade will affect the variability of the concrete slab thickness and this variability may have an impact on payment for thickness. Therefore, it is important that the base layer variability be minimized.

7.2 Paving on Stabilized Bases

There are many issues to be addressed in the design to prevent early-age cracking on stabilized bases. The engineer shall incorporate the appropriate slab/base interface treatments into the design, and clearly identify in the plans and specifications.

7.3 Test Section

The test section can be a critical element to enable the contractor to adapt the mixture and paving equipment to the site conditions, and demonstrate to the owner that the acceptance criteria can be achieved using their materials and processes. A test section is not required for small projects that involve less than about 2,000 cubic yards of concrete production.

The test section should be constructed on the first day of paving with a maximum placement of one lot for the selected paving method. The test section width and thickness should be most representative of the production paving area. Ideally, a non-critical area that is also representative of the majority of paving should be selected as the site for the test section. It is expected that some adjustments may be made to the laboratory based concrete mixture proportions as well as some of the contractor's operations to achieve the desired end products.

It is emphasized that the test section is being used to validate the contractor's concrete mixture and paving process, especially with respect to the ability to place, consolidate, and finish the concrete within the limits of the specification requirements. If a contractor is not using a combined aggregate gradation and paving equipment capable of internal vibration, the specification requires that consolidation testing be performed to assess the degree of consolidation by depth.

Test Section Expectation

Contractor is expected to adjust their process and concrete mixture, so when the test section is started, the specified end product is attained.

The test section is rejected if it has deficient or defective pavement areas or the thickness percent within limit value is 55 or less (see Section 9.0 – Acceptance Testing)

There is a concern that adequate consolidation of thick concrete slabs may not be achieved using consolidation techniques other than closely-spaced internal vibrators. The consolidation testing using cores from newly placed concrete pavement will verify if there is excessive segregation, poor consolidation (as manifested by honey-combing or large amount of entrapped air) at the slab bottom or over-consolidation in the upper portion (as manifested by excessive paste at the surface).

7.3.1 Test Section Requirements

The acceptance criteria for the test section are the same as for production paving; however, partial or conditional acceptance is not allowed. Partial or conditional acceptance of a test section is not allowed because the contractor must demonstrate control over all materials and equipment. A project cannot begin without acceptable control of the process as demonstrated at the test section.

A period of time to evaluate the test section is necessary. The time used by the contractor to evaluate the test section and to submit the test section data to the engineer. This evaluation period is mandatory and cannot be waived. It is expected that the contractor and engineer will agree in advance upon the actual time of the test section, evaluation, and response if the paving occurs at odd hours, weekends, or holidays.

Removal of unacceptable portions of the test section is determined by the engineer. Partial payment and corrective action methods can be utilized. If the total length of paving on the first day does not produce an acceptable test section of the minimum continuous length/volume specified, another test section shall be built.

The concrete mixture proportions determined from the test section become the approved proportions for the project. Throughout the paving process, additional minor adjustments may be made in the mixture proportions, but within the limits given in the specification and discussed in the next section. When these minor adjustments are made, a revised mixture proportioning submittal is not required.

7.4 Production Paving Adjustments to the Concrete Mixture Proportions

Shortages of cement or other concrete-making ingredients may occur during the construction season. If any changes in type, source, or brand of cementitious material, or aggregate source need to be made, new mixture proportions will need to be developed by the contractor and approved by the engineer. Certain minor adjustments to the concrete mixture proportions may be necessary due to changes in the weather and to maintain the required workability and air content. However, if air content is increased or water is added above the design w/cm ratio, the concrete strength may decrease.

If a new mixture proportions needs to be developed because of changes in concrete materials, the contractor should be allowed to proceed with paving once the early-age breaks indicate that the new mixture will provide the specified strength at the specified age.

Allowable adjustments in the mixture proportions are given in the specification and are listed below:

1. Individual aggregate proportions may be adjusted as necessary. However, the combined aggregate gradation may be adjusted only within the limits of Para. 8.3.3 – Combined Aggregate Gradation.
2. As necessary, cementitious materials may be increased by up to 10% by mass of the approved mixture proportions. Cementitious material content shall not be reduced from the approved mixture proportions.
3. As necessary, cement may be replaced with the approved SCM in an amount not to exceed 10% of the original SCM mass. When applicable, the contractor's mitigation plan for reactive aggregates shall be re-evaluated.
4. As necessary, any SCM may be replaced with the approved cement. When applicable, the contractor's mitigation plan for reactive aggregates shall be re-evaluated.
5. Quantities of admixtures may be adjusted in accordance with the manufacturer's recommendations.
6. Field adjustment for water is permitted provided that the water-cementitious materials ratio does not exceed the ratio for the approved concrete mixture and is not less than that listed in Para. 4.1 – Concrete Mixture Requirements.
7. For truck-mixed concrete, additional water may be added only once to adjust the workability of concrete, provided the approved water-to-cementitious-materials ratio is not exceeded. The maximum amount to be added shall be adjusted based upon the volume of concrete already discharged. The drum or blades shall be turned a minimum of 30 additional revolutions at mixing speed after water addition.
8. Water addition to the concrete by spraying in front of and behind the paving equipment is not allowed.

7.5 Tie Bar Placement

The tie bars should be placed at mid-depth and centered along the longitudinal joint. However, alignment of tie bars is not critical. Tie bars may be skewed up to 1 in. per 15 in. length of the tie bar. However, the top end of tie bars should not be less than 3 in. from the surface of the concrete slab.

Self-loading tie bar inserters mounted on slipform pavers can be used along longitudinal sawed contraction joints when paving multiple lanes. Injectors push rebar into plastic concrete and vibrate the concrete above bars. Distance meters are used to trigger the tie bar insertion at pre-determined spacing. Longitudinal positioning of bars needs to be observed to ensure that the minimum specified distance from transverse joints is maintained.

Tie bars should not be placed within 15 in. of doweled transverse joints.

7.6 Doweled Contraction Joints

Dowel bars may be installed at transverse and longitudinal contraction joints using a basket assembly or an automatic dowel bar inserter device.

Basket Assembly

Dowel baskets must be securely fastened to the base. Clips are generally adequate when fastening a basket to stabilized base. Long pins are required to fasten baskets securely in granular and open graded bases. The basket assemblies should be pinned at the bottom rung of the assemblies regardless of the length of the pins. Pinning on the top rung can result in dowel bar misalignment due to bending of the top rung from over-zealous hammering of the pins into the grade.

Cutting or crimping of longitudinal dowel basket wires is not necessary. Field experience and theoretical analysis indicate that the tie wires will yield before excessive stress develops in the freshly place concrete. However, the shipping wires need to be cut if the magnetic imaging device is to be used to determine dowel alignment.

Dowel Bar Inserter

Effectiveness of the dowel bar inserter is dependent on the operation of the paver and the inserter unit. Dowel bar alignment and correct location of joints are two critical items. A positive method must be used to mark joint locations to be at mid-location of the inserted dowel bars.

For two-lift paving, the dowels should be inserted by the paving machine used to place the top lift concrete. This will ensure that the dowels are not disturbed by additional consolidation after the dowels are in position.

Dowel bar alignment should be determined at the start of the project and regularly thereafter using a magnetic imaging device.

7.7 Doweled Expansion Joints

Care must be taken to ensure that the specified expansion gap in the expansion sleeve is maintained until the time of concrete placement. Use of sleeves with a foam insert is beneficial.

7.8 Concrete Production

The contractor is responsible for determining the process used for production of concrete. Concrete production involves the following two critical steps:

1. Batching – measuring concrete mix ingredients by mass and introducing them into the mixer.
2. Mixing concrete – thoroughly mixing concrete until it is uniform in appearance, with all ingredients evenly distributed. Concrete may be mixed at a stationary plant at the project site or may be ready-mixed concrete that is batched and mixed off-site. Properly batched and mixed concrete is consistent from batch to batch.

Concrete batching and mixing is demonstrated and validated at the test section. The validated processes should be used during the production paving.

7.8.1 Batch Tickets

The engineer should review the concrete batch tickets regularly to verify that the approved proportions of materials are used for concrete production and, in the case of truck-mixed concrete, water is not being added without exceeding the approved water-to-cementitious-materials ratio.

7.9 Hauling

The haul time is defined as from addition of cementitious material until the time that the paving equipment has passed over the concrete. This is different than the time in ASTM C94 that ends when it is deposited in front of the paver. Maintaining a limit on the haul time is very important as excessive haul times can affect the properties of fresh concrete, which may affect the long-term durability of the concrete. The allowable haul times are as follows:

1. Normal Weather Conditions
 - a. Non-agitating trucks – 45 minutes
 - b. Agitating trucks – 105 minutes
2. Hot Weather Conditions (concrete deposited at the paver is at a temperature $>85^{\circ}\text{F}$)
 - c. Non-agitating trucks – 30 minutes
 - d. Agitating trucks – 90 minutes

Note that the specified haul times are 15 minutes longer than allowed in ASTM C 94.

7.10 Paving

Concrete may be placed using transfer and spreading equipment or placed directly in front of the paver. Transfer and spreading equipment use is the recommended method.

The disadvantages of directly unloading in front of the paver are as follows:

1. Trucks backing into the paver may disturb non-stabilized bases, utility structures, stringlines, or forms.
2. Dowel baskets need to be placed just ahead of the paver – placing dowel baskets just ahead of the paver may not allow time to verify dowel bar alignment or verify that baskets are securely fastened to the base. Safety of laborers fastening baskets in areas between the forward moving paver and backward moving dump trucks needs to be considered.
3. Additional time for staging and positioning of trucks may be necessary.

Concrete should be deposited on grade within reasonable time after the addition of mixing water. When placed, there should be time remaining for consolidation, strike-off, and finishing before initial set. The consistent delivery of concrete is necessary to minimize stopping and starting of the paver. If paving operations are stopped to wait for concrete from the batch plant, additional trucks must be used or the paver speed should be slowed.

Concrete Consolidation

Adequate concrete consolidation is essential to long-term pavement performance. As discussed previously, concrete is extensively tested as-delivered, in the plastic state. In addition, strength specimens are prepared using the as-delivered concrete. The assumption is that the concrete as-placed will exhibit the same characteristics of a well consolidated concrete as tested in the laboratory during the mixture proportioning phase and as reflected in the strength specimens.

Adequate consolidation of concrete is very important for strength and durability. Inadequate consolidation results in lower concrete strength and honeycombing. Inadequate consolidation can be due to the following:

1. Poorly-functioning or dead vibrator
2. Paver speed too high
3. A concrete mixture with poor workability

Over-consolidation can lead to freeze-thaw durability problems if the air void system is adversely altered and can also result in excessive paste at the surface. Over consolidation can be due to the following:

1. Excessive vibrator frequency, especially along edges in fill-in lanes
2. Reducing paver forward speed without an adjustment to vibrator frequency
3. Concrete mixture with poor workability

The requirement of optimized combined gradation and use of internal vibration ensures that the concrete is well consolidated with proper paver operation.

Finishing, Surface Correction and Testing

Concrete finishing is a critical step in the paving process. Concrete finishing is the hand finishing that is typically applied to obtain a smooth surface necessary to correct any unevenness behind the paver. Concrete finishing efforts are to be kept to a minimum. Ideally, the correct concrete mixture will result in an acceptable surface finish behind the paver.

A 12 ft straightedge is used to check the fresh concrete surface behind the paver or finishing machine. This check needs to be continuous to ensure the machine is functioning properly. Common irregularities are transverse bumps across the lane and longitudinal dips within 2 ft of the edge. It is important for the straightedge to be checked with a stringline to ensure it is straight. If the paving machine is properly calibrated, the most common cause for surface irregularities are stopping/starting the paver, frequently a result of waiting for concrete delivery.

Excessive Hand Finishing Behind the Paver

The concrete surface does not need to be very tight and every small blemish on the surface does not need to be corrected. Hand finishing behind the paving equipment must be kept to a minimum. A properly adjusted and operated paving machine will provide the desired surface grade. Hand finishing behind the paving equipment must be kept to a minimum to fill any small holes and trim excess concrete from the corner. A properly proportioned concrete mixture with a properly adjusted and operated paving machine will provide the desired edges and surfaces.

7.11 Texturing

Concrete texturing is the most common technique used to provide concrete with required skid resistant pavement surface. Texturing is applied while the concrete is still in a plastic condition. The texture may be applied with a brush or broom, burlap drag, artificial turf finish, or tining.

Texturing for new construction may also be applied by grinding the hardened surface. When grinding is used to apply surface texture, it is also used to make appropriate surface profile corrections.

7.12 Curing

Curing is an important process for constructing durable concrete pavements. Curing of concrete is defined as the maintenance of adequate moisture and temperature conditions for a period of time immediately following finishing. Proper curing allows the development of required physical properties in the concrete. Poor curing practices can result in excessive curling, early-age cracking, surface deterioration, low early strengths, and reduced durability. Most of the damage caused by poor curing is irreversible. The start of curing and the maintenance of curing for the specified period are critical items.

Curing should be initiated as soon as possible after placing the concrete to prevent excessive water loss and drying of the surface. Curing compounds work by sealing the concrete surface and reducing the rate of moisture loss. Rising bleed water can become trapped under a prematurely finished surface layer. Bleed water that rises after the application of a curing compound can disrupt the curing membrane and can form a lens that causes spalling or delamination. Bleeding typically stops at about the time of initial setting when the aggregate particles interlock with cement hydration products. Slipform paving concrete typically does not bleed until 20 minutes after concrete placement and may never bleed. For slipform paving concrete, the evaporation rate almost always exceeds the bleed rate of the concrete.

Curing should not be applied to pavement surface that has standing water as a result of a rainfall. Application of curing compound over standing water will not be effective. Curing compound should be applied as soon as the standing water has evaporated and the surface is still damp.

Evaporation retardants may be applied immediately after placing and before texturing work to limit the risk of early drying in hot and high evaporation conditions.

For extreme weather events (hot weather and cold weather concreting), the curing procedures established under the Weather Management Plan should be followed.

Curing Material Coverage

Curing application needs to be uniform and at the specified rate. Large paving surfaces will lose water rapidly. Inadequate curing application may result in a variety of early-age cracking and durability issues. If the application does not appear uniformly white, it needs to be re-sprayed.

Hand Spraying

A two coat application, the second in direction at right angle to the first, is necessary to ensure proper coverage.

7.12.1 Curing Protection

Membrane curing needs to be protected from damage to be effective. Curing compound can be damaged by traffic on the pavement surface. For this reason, no traffic except that required for sawcutting should be permitted for the first 12 hours. Curing compound needs to be re-applied if damaged from rain or traffic within 72 hours of initial application.

7.13 Form Removal

Forms should not be removed prematurely. If removed prematurely, the concrete edges may be damaged. The specification requires that forms shall not be removed until the concrete has attained a compressive strength of 500 psi. Concrete strength can be most economically monitored by using maturity sensors, as prescribed in the specification.

It is necessary that curing compound be applied along the exposed faces of the concrete immediately after form removal. Otherwise, weak paste may develop along the exposed concrete faces, possibly contributing to joint spalling.

7.14 Sawcutting

Joint sawing and sealing is an art rather than a science. It requires an experienced crew to carry out the associated tasks correctly. Although improved guidelines for estimating the time at which sawing can begin are available, the timing of sawing, speed of the saw, condition of the blade, condition of the sawing equipment, and care of the operator all combine to influence the final product. In addition, blade type should match the aggregate type. Use of improper blades can result in joint raveling.

Too early sawing can result in joint raveling and tearing of the concrete and late sawing can result in slab cracking. Therefore, the contractor should be aware of the available sawcutting window. The factors that can have an impact on the sawcutting window include the following:

1. Sudden temperature drop (approaching cold or rain front)
2. High wind, low humidity
3. High friction base
4. Bonding between base and slab
5. Porous base (e.g., permeable asphalt treated base)
6. Retarded set
7. Delay in curing application

Skip sawing of transverse joints may be considered for long paving lanes, provided the skipped joints are sawed right after completion of initial sawing of every second joint. Sawing of intermediate longitudinal joints should commence at the same time as the sawing of transverse joints.

All contraction joints should be saw cut. Use of joint forming inserts should not be allowed, irrespective of project type or size.

7.15 Sealing Joints

Sealing joints in concrete pavements is optional. Studies have shown that unsealed jointed concrete pavements have similar performance to that of concrete pavements with sealed joints.

Joint sealants come in a variety of types. The performance of joint sealants is sensitive to proper installation and routine maintenance.

Pavements constructed in wet freeze-thaw environments should not use joint sealant designs that leave a void beneath the backer rod. This void is prone to saturation and freeze-thaw deterioration.

7.16 Opening to Construction Traffic

Contractors need access to a recently placed concrete pavement for a number of reasons, a primary reason being construction of fill-in lanes. In this case, a number of different construction equipment may need to use the recently placed pavement.

In addition, certain areas may need to be opened to traffic at an early age. This can be addressed directly by the engineer by specifying high early strength concrete and/or by making appropriate adjustments in the pavement's structural section.

With respect to construction traffic, the following items need to be addressed:

1. Damage to the curing system
2. Damage to the pavement surface
3. Damage to transverse and longitudinal joint edges
4. Structural damage to the concrete slab
5. Damage at the dowel/concrete interface

Damage to the Curing System

There is a general consensus that construction traffic, except for joint sawing equipment, should not be allowed on a freshly placed concrete until the curing membrane has completely dried. This period is typically considered to be about 24 to 36 hours. In addition, it is necessary that any curing membrane that is damaged by construction traffic during the specified curing period (typically 72 hours) be immediately repaired.

Damage to the Pavement Surface

Early use of a concrete pavement can damage the pavement surface. However, this concern is superseded by the concern related to the structural damage to the pavement. If the construction equipment use will not result in structural damage to the concrete, it is unlikely that the equipment will result in surface damage to the concrete. However, special precautions may need to be taken to ensure there is no damage from paver tracks riding along the concrete pavement edges.

Damage to Transverse and Longitudinal Joint Edges

Early use of a concrete pavement can damage transverse and longitudinal joint edges. Similar to the concern related to damage to the pavement surface, this concern is superseded by the concern related to the structural damage to the pavement. If the construction equipment use will not result in structural damage to the concrete, it is unlikely that the equipment will result in joint edge damage.

Structural Damage to the Concrete Slab

The concern with structural damage to the concrete pavement is in relation to the development of excessive stresses in the concrete slab that may result in early-age cracking or may affect the long-term performance of the pavement. It is therefore necessary to keep the bending stresses that develop as low as possible in comparison to the strength level at time of use. This requires that the actual stress level that develops due to specific equipment and for a given pavement section be taken into account. For example, the stress levels in the concrete slab due to a haul truck riding on an 12 in. thick slab will be much less than for the same truck riding on a 10 in. thick slab. Similarly, the stress levels will be much less for a pickup truck.

To minimize any detrimental effects of the construction traffic loading, it is necessary that these stress levels (typically along an edge) be maintained at a level much less than the concrete strength at time of use. In other words, the concrete strength at the time of early loading should be much higher than the anticipated stresses.

Typically, a stress multiplier of 2.0 is used to determine a minimum strength level for unlimited stress applications without resulting in damage. However, a stress multiplier of 2.5 is recommended to account for curling/warping stresses and accuracy in determination of early-age in situ concrete strength. The calculated edge bending stress multiplied by 2.5 is referred to as the “Zero Fatigue Stress.” Thus, if an edge stress of 120 psi is computed for a haul truck for a 12 in. thick project pavement, the concrete flexural strength level would need to be at least 300 psi (zero fatigue stress value) at time of use by the haul trucks.

The proposed specification provides the contractor the option of waiting until the in-place concrete flexural strength is 450 psi or demonstrating by the approved computation method that their construction equipment will not result in excessive stresses on the pavement. In any case, the flexural strength of the concrete cannot be less than 300 psi to minimize damage at the joints (aggregate interlock or dowel bar bearing stress damage – see next section).

Damage at the Dowel/Concrete Interface

A concern with early use of the pavement is with high dowel bearing stresses at the dowel/concrete interface. For a 20,000 lb haul truck tandem axle load, the dowel bar shear load can exceed 3,000 lbs for the corner dowels (about 1,200 lbs for interior dowels) for trucks riding along the edges. The corner dowel loads decrease if the trucks are kept away from the edge/corner. The 3,000 lb dowel load can result in about 3,000 to 4,000 psi dowel bearing stress and can be accommodated by mature concrete. However, this load level is considered very high for a recently placed normal concrete. The simplest way to mitigate this concern is to keep heavy traffic at least 2 ft away from the slab longitudinal edges.

Bending Stress Computation

Slab bending stress may be computed for the critical construction equipment using one of the following procedures:

1. Use of ACPA’s computer program StreetPave

2. Use of approved slab-on-grade finite element analysis software, such as, ISLAB 2000 and JSLAB
3. Other methods approved by the engineer

Thinner pavements result in higher zero fatigue stress for the same construction equipment. Therefore, thinner pavements require higher strength development before opening to construction traffic.

In Situ Strength Determination

If the concrete pavement is to be used by construction traffic within a few days of construction, it is necessary to monitor in situ concrete strength. Concrete strength may be monitored by testing strength specimens cured at the project site or by use of maturity testing. Use of maturity testing is strongly recommended, as this technique is reliable and reasonably-easy to implement.

8.0 QUALITY ASSURANCE

Quality Assurance may be defined as “all those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service.”

Contractor Quality Control (QC) is the system used by a contractor party to monitor, assess, and adjust their production and/or placement processes to ensure that the final product will meet the specified level of quality.” QC activities are performed by the contractor. The goal of a process control program is to provide testing, monitoring, and reporting of information to document adequately that the contractor is meeting the project specifications and to allow the contractor to make timely adjustments to the construction process. The contractor needs to develop a written project specific Quality Control Program plan that is available for review and approval by the owner. The program should address all elements that affect the quality of the pavement, as required by the General Provisions.

Agency acceptance includes “all factors used by the Agency (i.e., sampling, testing, and inspection) to evaluate the degree of compliance with contract requirements and to determine the corresponding value for a given product.” Acceptance is the responsibility of the transportation agency.

Overall Process Control Philosophy

- Provide necessary safeguards to ensure that owner receives an end product with the specified characteristics
- Recognize that a certain amount of variability exists in materials, construction process, and testing
- Material is rejected or process is stopped when the trend indicates that the end product requirements are not being met
- Minimizes placement of marginal or non-acceptable concrete
- Process control requirements are not arbitrary nor punitive

The specification also requires the contractor to perform all acceptance testing. The Quality Control plan should also address the conduct of acceptance testing.

The components of a good contractor QC plan are as follows:

1. Introduction
 - Project Description
 - Key Contact Information (contractor, owner, and owner’s representative)
 - Contract Plans and Specifications Highlights
2. Purpose of QC plan
3. Organization chart – Clearly delineating the flow of responsibility from ground up to top management

- QC roles (testing laboratory, contractor, etc.)
- Project personnel
- 4. Duties and Responsibilities
 - QC manager
 - Project engineers
 - Technicians/inspectors
- 5. Inspections (Include tests required and frequency and acceptance criteria)
- 6. Process control testing
 - Testing plan
 - Report submittals
- 7. Contractor acceptance testing
 - Testing plan
 - Report submittals
- 8. Deficiencies reporting
- 9. Conflict resolution
- 10. Defective pavement repair
- 11. Changes to the QC plan
- 12. Appendices (as needed).

The QC plan needs to be clearly written to minimize the potential for misunderstanding. The plans also need to be reviewed for ambiguity with respect to sampling locations, number of tests, test procedures, special provisions, and acceptance limits. It is important that copies of all test procedures referred to in the plan be readily available at the project site or at the project test facility.

The contractor management needs to support the QC process fully. Without the support of management, urgent deadlines and outside pressures may dominate the project activities and the QC testing and inspection could suffer.

Process Control Testing Concept

The process control testing requirements are based on multiple tests before materials are rejected or paving operation stopped. Typically, tests are routinely performed at the frequency specified for each test. If a test results in a failure, a second test is conducted on the same batch of materials. If the second test results in a failure, tests are conducted at a higher frequency. If more tests result in failure, the paving operation is stopped or the materials are rejected, as applicable. This practice ensures that materials are not rejected or the paving process is not stopped based on individual tests. It is the pattern of failed tests that is of concern.

8.1 Testing Personnel

The specification requires technicians to be certified for strength testing. This is especially important when using beams for acceptance testing.

If the state DOT has a concrete technician certification program, certification from that program is also acceptable. The key elements are that the testing personnel are experienced in testing the particular elements of the concrete; otherwise, test discrepancies will arise.

8.2 Testing Laboratory Requirements

The contractor may use an in-house or hired laboratory. The testing laboratories used by the contractor are required to meet the requirements of ASTM C 1077 that relate to the minimum technical requirements for laboratory equipment utilized in testing concrete and concrete aggregates for use in construction. The contractor's curing process for strength specimens need to meet the requirements of ASTM C 31. The local state DOT's concrete laboratory certification is also acceptable. AASHTO accredited laboratories may also be used.

Field storage and curing environment for strength specimens during the first 24 hours is very critical and proper measures must be taken. Improper curing during the first 24 hours can lead to lower strength at 28 days. Use of commercially-available or contractor-fabricated controlled curing chambers is strongly recommended. In addition, proper procedures must be followed for transporting and final curing of the strength specimens.

8.3 Quality Control Testing

The contractor is responsible for controlling the process. The test section is to demonstrate the process is under control, and the production paving requires maintenance of that process. The process control testing should be a major component of the Quality Control Plan. The Process Control plan should also identify the appropriate corrective action from measured responses.

8.3.1 Accuracy of Plant Batching

During production paving, the accuracy of batching for all weighed concrete ingredients shall be rechecked in accordance with the provisions of NRMCA QC 3 document at the specified frequency. Accuracy of batching does not imply recalibration of the scales, but it is the checking of the desired quantity against the actual quantity, making required adjustments, and recording the activity. Most modern plants have the capability to print the target weight versus the actual weight for each load.

8.3.2 Aggregate Quality

Aggregate quality at the plant site is impacted by stockpile management methods. NRMCA QC3 requires stockpile management methods to be developed and followed. Issues that should be addressed include the following:

1. Preventing contamination and clay balls by having a stockpile foundation. The foundation may be the bottom 1 or 2 ft of the pile or a hard paved surface.

2. Drainage should be away from the stockpile.
3. Separation between piles to prevent cross contamination.
4. Labeling of the stockpiles and plant bins by the material names that the delivery truck and loader operators are accustomed to.

All aggregate materials have the potential to segregate. Proper stockpiling methods are required to prevent segregation. In no case shall materials be allowed to free-fall more than 3 ft from a conveyor. Two acceptable methods include numerous small cones and loader-built piles. For the first method, numerous cones about 3 ft in height are built adjacent to each other. The next layer of cones are built to fill the space between the first cone layers. The process is continued to the desired height. This is easily accomplished with a telescoping radial stacker that is computer controlled.

For loader built piles, the first layer should not be higher than the maximum dump of the loader. Equipment shall not be allowed to travel on top of the aggregate pile to prevent degradation. Stockpiles should not be built with trucks, loaders, or dozers driving up a slope and dumping or pushing over the end of the pile. This creates some of the worst segregation.

The following ASTM C 33 aggregate quality tests are required to be performed on the day of test section construction and on every seventh day of paving thereafter:

1. Deleterious substances in accordance with ASTM C 33, Table 3, for the portion of the combined aggregate retained on the No. 4 sieve
2. Deleterious substances in accordance with ASTM C 33, Table 1, for the portion of the combined aggregate passing the No. 4 sieve
3. Flat and elongated pieces for aggregate retained on the No. 4 sieve

8.3.3 Combined Aggregate Gradation

Grading for each aggregate type shall be determined at least once before start of paving for each day of paving in accordance with ASTM C 136 on samples representative of that day's paving. The mathematical combined aggregate gradation shall be determined using the aggregate proportions of the established concrete mixture. At the beginning of a project, it may be advantageous to the contractor to conduct additional gradations at the midpoint of each day's paving until the variability from the supplier is determined.

The purpose of the combined aggregate gradation determination is to make any adjustments to the individual material batch weights to remain within combined gradation requirements. This requires that positive stockpile management methods must be used. More specifically, it is considered a deviation to feed the plant from the same face of the stockpile that is being replenished, as the actual gradations will not be known.

For projects that have limited stockpile sites at the plant, it is common to build a dedicated stockpile at another location, such as at the quarry or vacant lot. The dedicated stockpile can be

the one that is managed where replenishment occurs in a different location than the face used to haul to the plant site. For these off-site stockpiles, it would be reasonable to conduct the daily gradations at that location if the plant site cannot store even one day's production.

8.3.3.1 Workability Factor and Coarseness Factor

The combined-aggregate grading shall be used to determine the Workability Factor (WF) and the Coarseness Factor (CF). The combined-aggregate grading tolerance is plus or minus 3 points for the WF and plus or minus 5 points for the CF from the production paving proportions established at the test section. These limits are reasonable and if a combined gradation exceeds these, one or more of the materials has changed substantially.

8.3.3.2 Combined-Aggregate Gradation Controls

These provide the assurance that the individual aggregate proportions will be adjusted to maintain a consistent combined gradation, which will provide a consistent product for production.

8.3.3.3 Aggregate Moisture Content

Aggregate moisture content has a strong influence on the w/cm of the final mixture. It is therefore important that the moisture content of the aggregate is monitored and appropriate adjustments made to the water added to the mixture. If it is observed that the workability of the mixture is changing then aggregate moisture content should be determined more often than specified. The stockpile should be carefully managed to minimize variability, particularly in the fine aggregate.

8.3.4 Air Content

The purpose of the specified process control testing is to ensure that only a minimal amount of marginal concrete with poor air system is placed.

8.3.5 Concrete Temperature

The purpose of the specified process control testing is to ensure that only a minimal amount of marginal concrete with excessively high temperature is placed.

8.3.6 Hand Finishing

Hand finishing of the edges and corners of the concrete surface behind the paving equipment to remediate excessive edge slump is limited to 25% of the edge per slab panel. Hand finishing of the edges and corners in excess of 25% of the edge per slab indicates the process is not within

the specified level of conformance and the contractor should make the necessary adjustments in the concrete proportions and construction process.

The more concrete is worked and finished, the more likely it is to bring excess paste to the surface. The longitudinal edges of a slab are in a high stress zone. Stresses result from the sawing of longitudinal joint seal reservoir, from saw blade chatter that may occur, from tensile stresses due to joint seal pull, and from surface stresses from snow plows. These stresses contribute to the development of spalls at the longitudinal joints.

Snow plow spall damage occurs at transverse and longitudinal joints. Transverse spalls are either from the cutting edge spalling the joint or from the blade bearing pads, behind the blade, crushing the joint. Normal plow operations have the blade traversing the joints at an angle, so the potential is minimized. These are mechanically caused spalls and are typically not the responsibility of the contractor provided the concrete was placed in conformance with the specifications.

Longitudinal joint snow plow damage is usually due to mismatch of the joints, a more frequent issue for slipform paving than for sideform paving. When paving the fill-in lane, if the paver pan rests on the pilot lanes, there is a strong possibility that the weight of the machine will crush the edge of the pilot lane. Therefore, common practice is to set the pan about 1/4 in. above the pilot lane surface, which is where the joint mismatch occurs. To avoid violating the criteria, finishers will work the outer 18 to 24 in. of the fill in lane to match the pilot lane, thereby creating the excess paste that contributes to the development of the sliver spalls.

Another aspect that is not good practice is to use a higher water to cementitious materials ratio for the fill-in lanes. This is viewed as a construction expedient by increasing the workability, reducing work force requirements, and increasing production. The risks are segregation and excess paste accumulation at the joints. Part of the safeguard against this practice is the requirement of the minimum water to cementitious materials ratio contained in the specification.

A common practice that is often overlooked is the settings of the outer vibrators. The outer two or three vibrators are often set very high for paving the pilot lanes to ensure the edge stands. However, for a fill-in lane, the vibrator efficiency is greatly increased because the energy reflects off the pilot lane. Therefore, the outer vibrators need to be turned down for the fill-in lanes to avoid segregation and excessive paste accumulation.

All of these issues are contributing factors to the limitation on hand finishing behind the paver. The requirement will be applied to slipform and sideform paving. The use of cutting straightedges, which are channels several feet long and attached to a handle, is not considered hand finishing. Hand finishing is the use of floats, trowels, darbys, edgers, or tools with similar functions, and to work the edge to fill in voids left from the paver. Hand finishing also includes the use of boards or forms to prop up, repair, or restore the free edge.

When the mixture is matched to the paving method and the climate, there is no need for excessive hand finishing. The ability to match these elements is the primary reason that the contractor is afforded complete control of the process and adjustments to the process are allowed. The test section is the arena to demonstrate the process is in control. It is recognized that there is an occasional disruption in the process and that some hand finishing is required, which is addressed by the maximum limitation in the specification. However, continuous hand finishing indicates the paving elements are not matched and/or the process is not in control.

8.4 Control Charts

Control charts provide the contractor and the engineer an easy to digest summary of the key construction processes. Control charts are excellent tools to track trends and anticipate problems. The benefits of using control charts include early detection of problems, monitoring variability, and establishing process capabilities.

Similar to other documentation on a construction project, control charts are only useful when updated and adjustments implemented on a timely basis. The CQC plan should address the detailed procedures, identifying which items require control charts, the information to be presented on each control chart, the required posting time, and the distribution of information.

The aggregate grading and aggregate moisture contents are the largest sources of variability in the concrete. These items should be tracked regularly using control charts.

As a minimum, the contractor is required to maintain linear control charts for combined aggregate WF and CF values, air content, and concrete temperature.

Corrective Action

Corrective actions should be implemented before the process becomes out of control. The process control testing should identify developing trends in key construction activities. If the trends indicate recurring quality problems, the contractor should take appropriate actions to bring the processes back into control. Continual feedback of the process is therefore necessary.

9.0 ACCEPTANCE TESTING

The acceptance testing process involves testing conducted to determine the degree of compliance with contract requirements and is typically linked to pay items, and may involve corrective work and removal and replacement of defective items.

The proposed specification requires acceptance testing to be performed by the engineer as well as the contractor. The engineer's testing is performed on hardened concrete and is not subject to the contractor's schedule. In addition, the engineer's testing does not require laboratory facilities. The contractor's acceptance testing items should be incorporated in the contractor's QC plan.

Acceptance Testing Philosophy

The intent of acceptance testing is not to discriminate absolutely between good and bad end product. Otherwise, we would be testing every cubic yard of concrete and every square yard of the pavement. The intent of acceptance testing is to discriminate sufficiently to minimize the contractor's risk of good end product being rejected and the owner's risk of a bad end product being accepted. The balance between rejecting a good product and accepting a bad product is maintained by type and extent of testing and rules used to accept test results.

The test requirements must have direct relevance to concrete pavement performance. Arbitrary tests should never be specified. The impact of acceptance items on pavement performance is illustrated below:

1. Thickness and Concrete Strength → Affects Structural/Fatigue Cracking → Impacts Structural Performance
2. Concrete Air Content → Affects Freeze-Thaw Response → Impacts Durability
3. Straight Edge/Grade/Edge Slump → Affects Geometry and Surface Drainage → Impacts Functional Performance (Safety)
4. Dowel Alignment → Affects Early Cracking and Load Transfer at Joints → Impacts Structural Performance
5. Cracking and Spalling → Affects Serviceability → Impacts Structural and Functional Performance
6. Material Requirements → Affects Material-Related Distresses → Impacts Durability and Functional Performance

9.1 Control Charts

The contractor should prepare control charts for acceptance testing to track trends and anticipate problems related to the acceptance testing items.

9.2 Lot Size

Two project sizes are delineated in the specification: less than 10,000 cubic yards and larger than 10,000 cubic yards. The break points are not rigid and should be selected by the engineer. It is recommended that a lot equal 2,000 cubic yards. Each lot is required to be divided into five sublots.

9.3 Department Performed Acceptance Tests

The following are the engineer-performed acceptance tests:

1. Cracking
2. Joint spalls
3. Dowel bar alignment

The acceptance tests discussed next are required to be conducted on a subplot basis, unless otherwise noted.

9.3.1 Cracking

Two types of cracking are designated in the specification, as follows:

1. Shallow cracking
2. Deeper cracking

Shallow cracking is defined as cracking that is 2 in. or less in depth. Shallow cracking may be closely spaced, random, appear in a spider-web form, or be a series of parallel cracks that may be at a diagonal to the paving direction. Typically, shallow cracking is plastic shrinkage cracking that develops due to loss of water from the concrete surface before the concrete completes releasing bleed water. Thus, the importance of the use of the moisture evaporation chart (see Appendix A). The key defining issue is the depth of cracking. If the crack depth is less than 2 in., the severity of the distress is low and epoxy repairs can resolve the problem. Cracks deeper than 2 in. indicate that the process was not under control. Pavement areas with cracking deeper than 2 in. are considered defective.

9.3.2 Joint Spalls

Joint spalls are larger or deeper than sliver spalls and are typically the result of equipment damaging early-age concrete. Usually, these distresses are isolated and can be repaired using proper methods and regular concrete mixtures.

Key issues are that exotic spall repair materials are generally not effective due to the differences in the coefficient of thermal expansion with the concrete and the repair material. It has been

observed that regular concrete, with a smaller aggregate size appropriate for the repair area, will perform better than most of the proprietary materials. The keys to performance are proper preparation, proper concrete mixture, and effective curing. Improper repairs will seldom last one year, and failure is usually by debonding, which can be determined by sounding.

9.3.3 Dowel Bar Alignment

Dowel bar alignment is a critical item and must be checked on a regular basis. Dowel misalignment does have a significant effect on pavement performance. The dowel misalignment categories are illustrated in Figure 2.

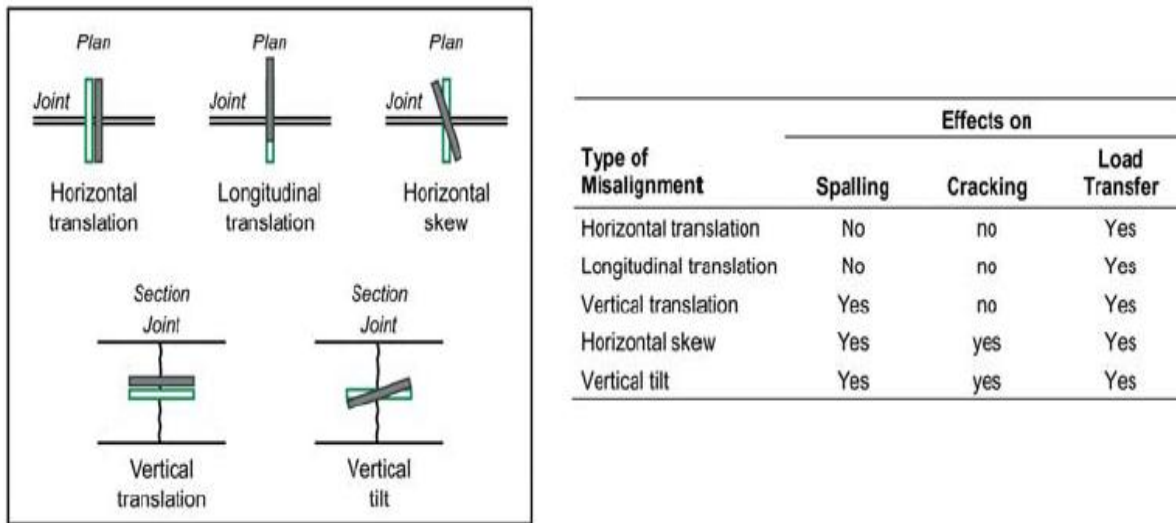


Figure 2. Dowel bar misalignment categories

Dowel bars should be placed within the allowable tolerances. Improved dowel bar alignment testing methods are now available. These methods provide accurate information on the misalignment categories identified above. However, evaluation of this information should be done carefully.

Dowel alignment should not be rejected based on individual dowel bars. Dowel alignment data should be considered based on a whole joint and a group of adjacent joints. If a problem is determined with dowel misalignment during construction, the contractor should immediately stop paving and remedy the problem before continuing.

9.4 Contractor-Performed Acceptance Tests

The following acceptance tests are to be performed by the contractor:

1. Thickness
2. Strength

Testing is conducted on a subplot basis; however, acceptance of the pavement is on a lot basis. Each lot is to consist of five sublots.

9.4.1 Percent within Limits

The PWL shall be determined in accordance with procedures specified in AASHTO R-9 and R-42.

The specification provides for acceptance of the pavement based on the method of estimating percentage of material within specification limits (PWL). All test results for a lot will be analyzed statistically to determine the total estimated percent of the lot that is within specification limits. The PWL is computed using the sample average (\bar{X}) and sample standard deviation (S_n) of the specified number (n) of sublots for the lot and the lower specification tolerance limit, L , for the particular acceptance parameter. From these values, the Lower Quality Index, Q_L , is computed and the PWL for the lot is determined as the percentage of the material above the lower specification tolerance limit.

The lower specification tolerance limit, L , for flexural strength and thickness are as follows:

- Flexural Strength: $0.93 \times \text{Specified Strength}$
- Thickness: Lot Plan Thickness in Inches less 0.50 in.

The lower specification tolerance limits incorporate the normal variability in the respective measures.

9.4.2 Thickness

Acceptance of each lot of in-place pavement shall be based on PWL.

The sampling, testing, and acceptance procedures for thickness are defined in the specification. The thickness of a pavement can be tested in several ways. It can be checked by using paving stringline as a guide, performing destructive testing by taking cores from the concrete pavement, or surveying elevations before and after placement. Coring is the preferred method. If core testing is used for thickness verification, the cores (typically 4 in. in diameter) need to be labeled and stored, preferably on-site, until the end of the project.

9.4.2.1 Sampling

Standard specification item.

9.4.2.2 Thickness Acceptance

Standard specification item.

9.4.3 Strength

Concrete pavements are designed based on flexural strength; however, there is a reasonable correlation between flexural strength and compressive strength. To reduce costs, it is therefore preferred to determine acceptability based on compressive strength of test cylinders.

9.4.3.1 Concrete Strength using Cylinders

Standard specification item.

9.4.3.2 Strength Acceptance

Standard specification item.

9.4.4 Smoothness Testing

The final pavement surfaces where the posted vehicle speed is 30 mph or greater shall be measured using an Inertial Profiler System (IPS) and the International Roughness Index (IRI) in accordance with the procedures detailed in AASHTO R-54. The use of an IPS system that uses only a point laser is not recommended. The recommended IPS is a system that uses a line laser.

The contractor shall furnish a properly-calibrated, documented, and department-certified IP. The IPS shall export raw profile data in an unfiltered ERD file format and produce a profile trace of the surface tested (profilogram). The IPS shall conform to the Class 1 requirements of the most recent revision of ASTM E950 and must be certified by the department.

The contractor shall furnish an operator, trained in the operation of the particular IPS and knowledgeable in the use of the most recent version of the ProVAL software. All profiler operators shall pass a proficiency test and possess a current certification issued by the department.

Areas of localized roughness will be identified using the ProVAL “Smoothness Assurance” analysis, calculating IRI with a continuous short interval of 25 ft and the 250 mm filter applied. Only the right wheel path will be used to determine areas of localized roughness. The longitudinal limits of the corrective work shall be taken from the ProVAL “Grinding” section within the “Smoothness Assurance” analysis, using the “Default Grinding Strategy” option.

10.0 DEFICIENT AND DEFECTIVE PAVEMENT

Defective pavement that is of the greatest concern is that which will reduce ride quality or fail to last as long as it should. Failure is often in the form of cracking or joint deterioration. When specified tolerances are exceeded and defective pavement areas result, it is imperative that strict repair standards be enforced. Pavement areas that are not in compliance with the specification requirements are designated as follows.

1. Deficient pavement – localized pavement areas that exhibit minor levels of non-compliance, such as the following:
 1. Shallow cracking
 2. High spots
 3. Joint spalls

Deficient pavement areas can be left in place after corrective treatment and are not considered to impact long-term pavement performance.

2. Defective pavement – pavement areas that cannot be corrected and left in place. Defective pavement areas require removal and replacement. Defective pavement areas include the following:
 1. Deeper cracking
 2. Excessive joint spalls
 3. Excessive edge slump
 4. Low areas that impede surface drainage
 5. Severely rain-damaged areas

10.1 Deficient Pavement

10.1.1 Shallow Cracking

Shallow cracking, which is 2 in. or less in depth as determined by cores, can remain in place after treatment by application of free-flowing capillary methyl methacrylate by a skilled installer. Shallow cracking is not considered a structural deficiency and does not affect long-term pavement performance.

10.1.2 High Spots (Localized Roughness)

Areas of localized roughness will be identified in accordance with AASHTO R-54, using the ProVAL “Smoothness Assurance” analysis and calculating IRI with a continuous short interval of 25 ft and the 250 mm filter applied. Only the right wheel path will be used to determine areas of localized roughness. The longitudinal limits of the corrective work shall be taken from the ProVAL “Grinding” section within the “Smoothness Assurance” analysis, using the “Default Grinding Strategy” option.

High spots shall be ground. Grinding equipment that causes excessive raveling, aggregate fractures, spalls, or disturbance of the transverse and/or longitudinal joints shall not be permitted. Grinding shall remove the high spot deficiencies and shall not create surface conditions that will trap surface water runoff. Corrective work required shall be performed before thickness determinations, joint sealing, and grooving operations.

Prior to commencing corrective work by grinding, the ProVAL Grinding Simulation, with an 18 ft wheelbase grinder and a maximum grinder depth of 0.3 in. (7.62 mm), must indicate a predicted improvement to the 25 ft IRI value for sections proposed to be ground. If the grinding simulation does not predict improvement for a section, that section must be corrected by a method other than grinding or the appropriate deduction in Section 12.1 will apply.

Corrective work by diamond grinding may result in thin pavements. The Department shall determine if this condition needs to be verified by coring. Additional coring for thickness verification shall be at no cost to the Department. Thin pavement sections after diamond grinding may result in thickness price deductions.

Unless otherwise approved by the Department, corrective work shall be by an approved surface diamond grinding device consisting of multiple diamond blades.

10.1.3 Joint Spalls

Minor amounts of joint spalls can be corrected by using the partial depth patching technique. The key steps for the partial depth patching are described in the specification. Partial depth patching requires great care. Some of the key items to note are as follows:

1. Surface preparation is critical. The prepared surface must be sound and clean.
2. A joint forming insert must be used.
3. The repair material must be compatible with the base concrete. When a proprietary repair material is used, the manufacturer's directions must be strictly followed.

10.2 Defective Pavement

Defective pavements are those pavement areas that are considered to pose a safety hazard or to result in future performance problems. Because it is more difficult and more costly to perform repairs to defective pavements after the pavements are operational, it is necessary that all defective pavement areas be corrected by removing the affected pavement areas and replacing with concrete meeting project requirements.

The key steps for slab removal and replacement are given in the specification. The removal and replacement may be required to be performed on a fast-track basis. In such a case, use of a concrete mixture that results in high early strength may be required. The contractor should have such a concrete mixture developed and submitted to the engineer at the start of production paving.

11.0 MEASUREMENT

Standard specification item.

12.0 PAYMENT

Standard specification item.

APPENDIX A. SAMPLE WEATHER MANAGEMENT PLAN ITEMS

The following is an example of an acceptable weather management plan. This plan may be used with edits and expanded as necessary by the contractor to meet the needs of the contractor's concrete mixtures, haul units, evaporation modeling method or software, paving hours, and other items that are project specific.

CONTRACTOR XYZ WEATHER MANAGEMENT PLAN

Project: XYZ

Location: XYZ

Submitted By and Title: XYZ

Date: XYZ

The following project specific plan details actions that will be taken during concrete placement in hot weather, cold weather, and times when a rainstorm is imminent.

1.0 Hot Weather Paving

Hot weather paving is defined as paving when the concrete temperature is greater than 85°F or the moisture evaporation rate at the concrete surface is greater than 0.20 lb/ft²/hr (0.10 lb/ft²/hr for concrete mixtures containing fly ash or slag), as determined using the American Concrete Institute (ACI) moisture evaporation rate chart. During hot weather, the following actions will be taken:

- 1) **Mixing Requirements** - Paving will be suspended when the concrete temperature exceeds 95°F, mitigation measures to prevent the concrete temperature from exceeding 95°F when measured directly in front of the paver include:
 - a) Chilled water shall be used to prevent the concrete temperature from exceeding 95°F as measured directly in front of the paver.
 - b) Night placement may be initiated during prolonged periods of hot weather.
 - c) Aggregate stockpiles may be sprinkled lightly to cool the outside of the stockpile.
 - d) The use of specific supplementary cementing materials may be reconsidered.
- 2) **Hauling Requirements** - No provision for alternative haul units is included. Non-agitating dump trucks will be used for all placements. The actions detailed in Section 1 will be used for controlling the concrete temperature.
- 3) **Placing Requirements:**
 - a) A water truck shall be utilized to sprinkle the subbase ahead of the area where concrete is deposited. The subbase will be kept damp with no areas of standing water.
 - b) When side forms are used, they will be sprinkled to maintain a surface temperature below 120°F.

- c) The ambient conditions for relative humidity (%), concrete temperature (°F), and wind velocity (mph) will be measured and recorded every 30 minutes during concrete placement. These measured values will be used to determine the evaporation rate (lb/ft²/hr) utilizing Chart 1 (in Figure A at the end of this appendix) or appropriate software.
 - d) The anticipated placement and finishing techniques listed in order are as follows:
 - 1) dump concrete in front of the paver, 2) consolidate and extrude the pavement using a slipform paver, 3) hand finishing using mops and straightedges, 4) burlap drag, and 5) curing. When the evaporation rate exceeds 0.20 lb/ft²/hr (0.10 lb/ft²/hr for concrete mixtures containing fly ash or slag) *and* the curing application is more than 20 minutes behind the burlap drag, the pavement will be fog-sprayed immediately behind the burlap drag to prevent plastic shrinkage cracking.
 - e) Windscreens and/or shades as referenced in ACI 305R-99 will not be used.
 - f) The use of an evaporation retardant will be considered if the potential for plastic shrinkage cracking is considered to be high.
- 4) Necessary Concrete Placement in Hot Weather:
- a) When schedule conflicts with traffic cannot avoided, concrete temperatures above 95°F will be allowed for placements that are less than 200 ft long. Under these conditions, evaporation retardant will be sprayed at the manufacturers recommended rate between the finishers and the burlap drag and again directly behind the burlap drag.

The above sections are in accordance with standard practices and applicable recommendations of ACI 305R-99.

2.0 Cold Weather Paving

Cold weather paving is defined as paving when the air temperature is 40°F and dropping and/or the temperature of the surface on which the concrete is to be placed is less than 32°F. During cold weather, the following actions will be taken:

- 1) Mixing Requirements - Paving will be suspended when the concrete temperature is less than 50°F, mitigation measures to prevent concrete temperatures lower than 50°F when measured directly in front of the paver include:
 - a) Heated water shall be used to maintain the concrete temperature above 50°F as measured directly in front of the paver.
 - b) An approved accelerating admixture may be used to promote earlier sawing than would otherwise be possible.
 - c) Approved mixes containing Class F Fly Ash will not be used.
- 2) Hauling Requirements - No provision for alternative haul units is included. Non-agitating dump trucks will be used for all placements. The actions detailed in Section 1 will be used for controlling the concrete temperature.

- 3) Placing Requirements - Concrete will be placed only when the subbase temperature is 32°F or greater and the ambient temperature is at least 40°F. Placement will cease any time the subbase temperature is less than 32°F or when the ambient temperature is less than 40°F.
- 4) Protection of Concrete:
 - a) Concrete pavement surface temperature shall be maintained at or above 32°F for a period of 72 hours or until in-place concrete compressive strength of 500 psi is attained. As necessary, the pavement shall be covered with one layer of polyethylene sheeting and two layers of burlap or curing blankets.
 - b) Maturity sensors that record the temperature of the pavement at 15 minute intervals will be placed in the edge of the pavement approximately 2 in. below the surface in the first and last 200 ft of placement. These sensors will be monitored to determine when the maturity equivalent of 500 psi is achieved. Protective insulation may be removed after the pavement reaches the maturity equivalent of 500 psi and the pavement temperature is essentially in equilibrium with the ambient temperature.
 - c) Protective insulation will be temporarily removed to enable joint sawing at the earliest possible time.
 - d) Pavement will be opened to traffic in accordance with the proposed specification requirements.

The above sections are in accordance with standard practices and applicable recommendations of ACI 306R-88.

2.1 Protecting Concrete from Rain Damage

The following steps will be taken, as necessary:

- 1) Paving will be canceled or ceased when rain storms are imminent. Weather radar will be monitored at the project office at a minimum of 1 hour intervals when the forecast probability of precipitation is 40% or greater.
- 2) 14 rolls of 4.0 mil polyethylene sheeting, 20 ft by 100 ft, will be stored on the curing machine for use in protecting the pavement from rain damage. In addition, an adequate number of 12 ft by 2 in. by 8 in. boards will be stored on the form truck for use as ballast to prevent the polyethylene from being removed by wind. The quantity of polyethylene is based on the following estimate:
 - a) Average initial set time = 3.5 hours
 - b) Average plant production = 250 cubic yard per hour
 - c) Placement dimensions – 25 ft wide by 18 in. thick \approx 1.4 cubic yard/lineal foot of paving
 - d) $3.5 \text{ hours} \times 250 \text{ cubic yards/hour} \div 1.4 \text{ cubic yard/lineal foot} = 625 \text{ ft}$ of exposed pavement that has not reached initial set.
- 3) Polyethylene sheeting will be removed after the rain storm to enable curing operations and joint sawing.
- 4) Cores of rain damaged pavement will be taken at intervals of 100 ft center to center.

Remedial actions for rain damaged pavement shall conform to the proposed specification requirements related to diamond grinding or remove and replace.

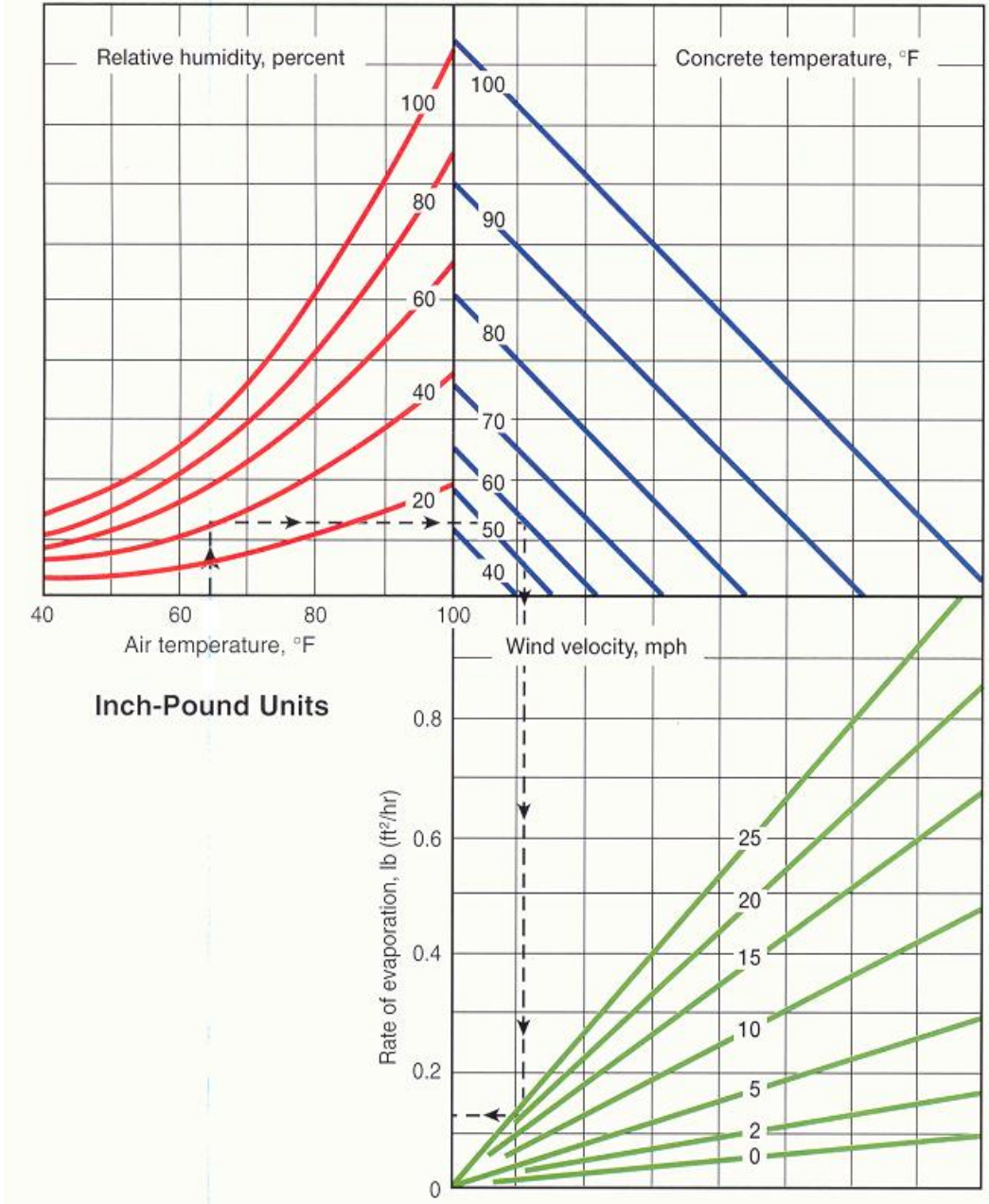


Figure A. Chart 1 rate of evaporation as affected by ambient conditions (courtesy PCA)