Framework for Design and Construction of Long-Life Concrete Pavements

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Abstract

In the past, concrete pavements were routinely designed and constructed to provide low-maintenance service life of 20 to 25 years. In fact, the majority of the U.S. interstate and the primary system were designed on the basis of the 20 to 25 year initial service life. Experience has shown that pavements in high volume traffic corridors need to be designed and constructed to provide longer service life because of the difficulties in performing effective repair and rehabilitation activities along these high volume highway corridors. In addition, the public is no longer tolerant of frequent extended lane closures to perform repair activities. It is becoming an established practice in the U.S. to require that concrete pavements provide low-maintenance service life of 40 plus years. PCC pavements can meet this specific requirement if proper considerations are incorporated in the design and good construction practices, including use of sound concrete making materials, are followed.

This paper provides an overview of current U.S. practices and efforts at optimizing pavement design features and construction practices to minimize early age failures and provide long-term low-maintenance service in excess of 40 plus years. The paper also provides a framework for ensuring that the critical design and construction features that impact long-term service are recognized and accounted for. The design and construction features discussed include features that improve slab cracking and deflection responses, features that minimize maintenance operations, and construction features that assure long-life pavement.

Introduction

In the past, concrete pavements were routinely designed and constructed to provide low-maintenance service life of 20 to 25 years. In fact, the majority of the U.S. interstate and the primary system were designed on the basis of the 20 to 25 year initial service life. Experience has shown that pavements in high volume traffic corridors need to be designed and constructed to provide longer service life because of the difficulties in performing effective repair and rehabilitation activities along these high volume highway corridors. In addition, the public is no longer tolerant of frequent extended lane closures to perform repair activities. It is becoming an established practice in the U.S. to design and construct long-life concrete pavements that provide low-maintenance service life of 40 plus years. According to many U.S. highway agencies, “use of long-life pavement strategies has been proven to be a cost-effective tool in minimizing maintenance costs and reducing user delays to the

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motoring public". As an example, the California Department of Transportation (Caltrans) requires use of a 40-year service life for designing pavements along a highway corridor where the 20-year projected average annual daily traffic equals or exceeds 150,000 vehicles or average annual daily truck traffic equals or exceeds 15,000 trucks (California DOT, 2004). The goals of the U.S. long-life concrete pavement program are as follows:

1. Increased initial service life - 40 to 60 years
2. Lower life cycle cost
3. Decreased construction time
4. Fewer maintenance closures
5. Construction of better initial ride
6. Reduced wet-weather accidents
7. Use of efficient construction equipment & procedures (get in and get out as quickly as possible; sustainability considerations)
8. Use of improved QA/QC procedures – to allow monitoring of the concrete quality as the paving progresses, not days or weeks later.

While much progress has been made in the last few decades to extend the service life of concrete pavements and to reduce overall life-cycle costs, many challenges remain and new challenges surface. Some of these challenges include:

1. Constrained highway agency budgets.
2. Increasing traffic volumes and restrictions on construction work zones.
3. Wet-weather safety requirements.
4. Tire/pavement noise considerations.
5. User demands for a smooth and comfortable ride.
6. Local shortages of good quality aggregates.
7. Sound understanding of factors that affect concrete pavement behavior.
8. Optimization of concrete pavement features to meet design requirements.
9. Development and characterization of durable concrete mixtures.
10. Environmental effects on short-term and long-term concrete pavement behavior and performance.

Summary of U.S. Practices

This section provides a summary of current U.S. practices related to concrete pavement technologies and details some key advances and innovations introduced in the last few years.

Concrete Pavement Types

Several types of concrete pavements have been used in the U.S. These include the following:

Jointed Concrete Pavements (JCP) – In the U.S., the primary concrete pavement type is jointed plain concrete pavement (JPCP). In the past, transverse joint spacing varied from about 4 to about 6 m and depended on geographic location. The present practice is to use a joint spacing of about 4.5 m, irrespective of location within the U.S. The concrete pavement thickness ranges from 150 to 200 mm for streets, 200 to 250 mm for secondary roads and 300 to 350 mm for the primary (including the interstate) system. Dowel bars at transverse joints and stabilized bases are generally specified for pavements carrying medium to heavy truck traffic. In the past, jointed reinforced concrete pavements (JRCP), with transverse joint spacing ranging from about 12 to 24 m and steel reinforcement ranging from about 0.15 to 0.25%, were used by a few agencies. No U.S. agency actively uses JRCP as a standard pavement type.

Continuously Reinforced Concrete Pavements (CRCP) – Since the 1960's, thousands of kilometers of continuously reinforced concrete pavements (CRCP) have been constructed in the U.S. These pavements have typically provided 20 or more years of service life without requiring major rehabilitation. CRCP is a concrete pavement with continuous longitudinal steel reinforcement and no intermediate contraction joints. The steel induces transverse cracking and then keeps the cracks tightly closed ensuring a high level of load transfer across the cracks. CRCP is designed to develop transverse cracking at a spacing of about 0.6 to 2.0 meters. In the U.S., current practice is to use CRCP thickness the same as for an equivalent jointed doweled concrete pavement. The steel content ranges from about 0.65 to 0.75% of the cross sectional area of the pavement. The steel is usually pre-placed over transversely placed steel bars that rest on chairs. Although CRCP may have a slightly higher initial cost, life cycle cost analysis typically identify CRCP as a very cost-effective pavement alternative for long-term service. Several highway agencies in the U.S. use CRCP as a pavement of choice for high volume and heavy truck traffic highways.

Prestressed Concrete Pavements (PCP) – Conceptually considered very cost-effective, this pavement type never gained widespread popularity in the U.S. A few experimental highway projects were constructed during the 1970's and 1980's. These pavements typically included the following features:

1. Slab length of about 75 m to about 130 m
2. Expansion joint between individual slabs
3. Effective prestress at mid-slab of about 0.5 MPa
4. Slab thickness of about 150 to 175 mm
5. Stabilized base

These pavements have generally performed well and have required only minimal maintenance to correct early age distresses resulting from poor construction practices. This pavement type has not generated much interest in the U.S. because of the higher initial costs and the need for a pavement contractor/subcontractor familiar with prestress construction techniques. Also, the construction of these projects requires more care in fabricating and constructing the transverse expansion joints between adjacent prestressed slabs.

Precast Concrete Pavements **–** Precast paving is beginning to receive more attention in the U.S. due to its potential for use in the rapid repair and rehabilitation environment. It is currently considered an experimental technique, but is seeing application on production paving projects. This technique is being considered for full-depth repairs at deteriorated transverse joints and is used also for larger area (e.g., toll booth facilities) and longer length mainline rehabilitation. For mainline rehabilitation, the following two approaches may be used:

1. ***Conventional panels*** **–** Precast panels of conventional length (e.g., 4.5 m long) and thickness and a lane wide are laid adjacent to each other on a prepared base with a positive means of load transfer provided at transverse joints.
2. ***Post-tensioned panels*** **–** Precast panels of shorter than conventional length (e.g., about 3 m) and full width (2 lanes wide plus shoulder), but thinner, are laid adjacent to each other on a prepared base. A group of these panels are post-tensioned to provide an effective slab length of 80 to 100 m. An expansion joint is provided between adjacent post-tensioned panels.

Although the discussion in this paper is applicable to different concrete pavement types, this paper primarily addresses long-life considerations for only the jointed plain concrete pavements.

Long Life Concrete Pavement Requirements

The quest for long life concrete pavements necessitates a much better understanding of design and construction factors that affect both the short-term and long-term concrete pavement performance. Essentially, this requires that there be a better understanding of how concrete pavements deteriorate or fail. Concrete pavements deteriorate over a period of time as a result of distresses that develop due to a combination of traffic and environmental loading. Typical distresses that can develop include the following:

1. ***Cracking*** **–** typically transverse cracking, but longitudinal, random, and corner cracking may also develop due to poor design and construction practices. Cracking is typically referred to as a stress based distress.
2. ***Joint faulting*** **–** joint faulting may develop with or without outward signs of pumping. Faulting is typically referred to as a deflection based response. Joint faulting is significantly affected by the type of load transfer provided at transverse joints.
3. ***Spalling*** **–** spalling may develop along joints or cracks. Spalling may develop due to poor joint sawing practices, incompressibles in joints or cracks (poor sealing practices), and/or poor quality concrete.

4. ***Materials related distress*** **–** the more significant materials related distress may include alkali-silica reactivity (ASR) and D-cracking in freezing environment.
5. ***Roughness*** **–** pavement smoothness is affected by the development of various distresses in the concrete pavement. The effect of each distress type is additive and results in pavement roughness over a period of time.

It is realized that it would be impossible or impractical to design and construct concrete pavements that exhibit very little or no distress. Distress development over the pavement's service life is expected. However, the rate of distress development is managed by incorporating sound designs, durable paving materials, and quality construction practices. In the U.S., the recommended threshold values for distresses at the end of the pavement's service life are as follows:

Table 1 – Recommended Threshold Values for Concrete Pavement Distresses

Distress	**Threshold Value**
Cracked slabs, % of total slabs	10 to 15
Faulting, mm	6 to 7
Smoothness (IRI), m/km	2.5 to 3.0
Spalling (length, severity)	Minimal
Materials related distress	None

In the past, when concrete pavements were designed for 20 to 25 year service life, the above distress threshold values were considered as the design requirements. Currently, these same threshold values are being applied to the design of concrete pavements for 40 to 60 year initial service life. The question that is raised is what changes are we making in the design and construction technologies that allow us to confidently design and construct concrete pavements that will provide the extended service life of 40 to 60 years. How are we fine-tuning existing technologies and/or incorporating new technologies to ensure the long service life?

The pavement performance trends are illustrated in Figure 1. As shown, the distress threshold values listed in Table 1 would result when the pavement serviceability has reached the threshold level, the level at which the pavement no longer efficiently or safely serves the driving public. In the past, the threshold level were expected to be reached at about 20 to 25 years. The level would be reached earlier if the pavement incorporated design or construction deficiencies. For long life pavements, the threshold would be expected to be reached at 40+ years.

The extension of pavement service life to 40+ years requires, as a minimum, the following to occur:

1. Low levels of traffic and environmental related stresses in the concrete slab relative to in-place concrete strength

2. Low levels of traffic and environmental related concrete slab deflections (deformations)
3. High level of load transfer effectiveness at transverse joints over the 40+ year service life
    a. No dowel bar corrosion
    b. No voiding around dowel bars due to high dowel/concrete bearing stresses
4. No design or construction related early age failures
5. Durable concrete surface with the desired surface texture characteristics
6. Initially smooth construction.

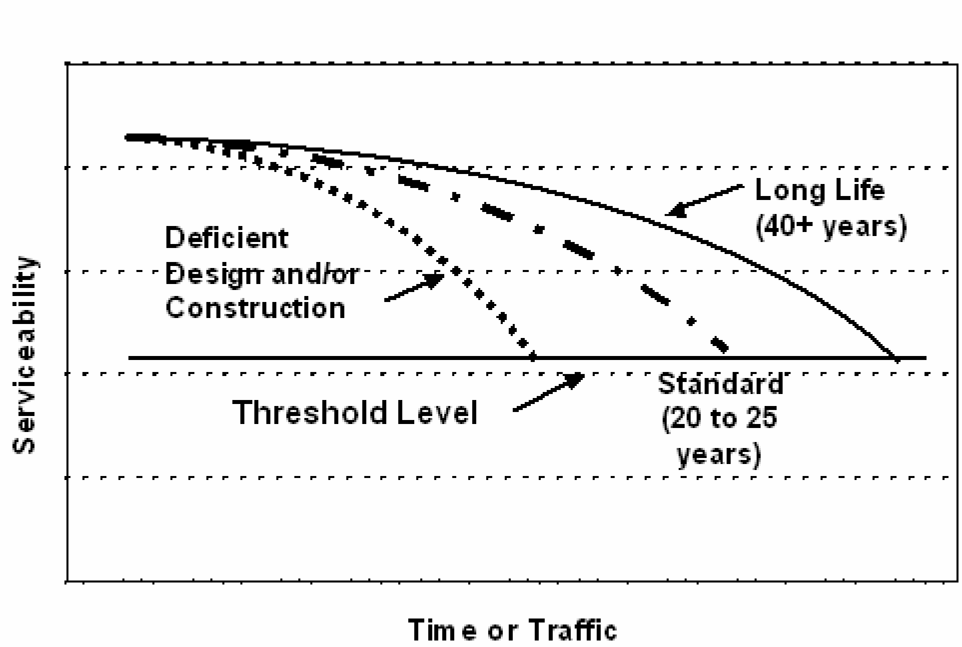

Figure 1 – Pavement Performance Trends

The above requirements can only be met through sound pavement design, use of durable materials, ensuring quality in construction, and timely maintenance. Design and construction of a successful concrete pavement requires attention to many details, some requiring very little attention to do them correctly and others requiring complex technical know-how and operational discipline to do them correctly.

Concrete Pavement Features for Long Life Service

As discussed previously, concrete pavements have routinely been designed for 20 to 25 years of initial service life. The effort now is being directed at incorporating improvements in the design and construction features that would, without much risk, provide concrete pavements with initial service life of 40 to 60 years. Well-designed and well-constructed concrete pavements do not exhibit noticeable distress until after about 15 to 20 years and the discriminating influences of any innovations may not manifest until after 20 to 25 years. As a result, the concrete pavement design engineer has a challenging task when designing and specifying long-life pavements. The innovative features that may be incorporated in the pavement design or construction specifications would need to be based on engineering analysis or extrapolated from results of accelerated short-term testing. The luxury of long-term field-testing and validation of innovative features is not available to the concrete pavement design engineer.

A few of the key concrete pavement design, materials and construction features that impact the achievement of long service life (40 to 60 years) are discussed next.

Features that Improve Cracking Response

Early age cracking – Premature cracking (transverse, longitudinal, corner, random) in jointed concrete pavements can develop due to complex interactions of many factors. These factors include:

1. High level of restrained axial stresses (due to slab/subbase friction) relative to strength gain during the early age.
2. High level of restrained curling and warping stresses relative to strength gain during the early age.
3. Early traffic loading in presence of low strength concrete.
4. Non-uniform subgrade swelling.
5. Late and/or shallow joint sawing.
6. Relatively high variability in concrete strength, slab thickness, and/or sawcut depth.
7. Poor interface condition between the stabilized base (including permeable bases) and the concrete slab.
8. Long transverse joint spacing.
9. Paving in hot, windy, low humidity ambient conditions, without taking adequate precautions.
10. Excessive dowel bar misalignment.

Over the years, various forms of guidelines have been developed to help design engineers and contractors minimize the occurrence of premature cracking and to repair such cracking. As such, with proper planning and attention to details, early age cracking can be prevented in concrete pavements designed for long life service.

Progressive Cracking – This is typically mid-slab transverse cracking and is also referred to as fatigue cracking. Progressive cracking can be controlled to manageable level by ensuring low levels of traffic and environmental related stresses in the concrete slab relative to in-place concrete strength. The recently developed mechanistic-empirical design procedures (e.g., the U.S. 2002 Guide (TRB, 2004), currently (2005) under evaluation) allow consideration of many pavement design features for specific site conditions and traffic loading. Based on use of these design procedures, the following design features are recommended:

1. ***Concrete slab thickness*** – For major urban and rural highways, a minimum slab thickness of 300 mm should be considered. For heavy truck volumes, an appropriately thick slab, 320 to 350 mm thick, should be considered on the basis of the pavement design procedure computations.
2. ***Widened lane and/or tied concrete shoulder*** – Use of widened outside lane or a tied concrete shoulder is a standard practice for long life concrete pavements. Lane widening involves extending the outside lane by about 0.6 m. The widening keeps the truck loading away from the edge and results in lower slab stresses. The tied shoulder is typically about 3 m wide or full lane width and same thickness as the mainline pavement. A superior version of this feature is using the combination of a widened outside lane and a tied concrete shoulder.
3. ***Joint layout*** – Joint layout is a critical design item. As discussed earlier, poor joint layout can result in early age cracking. Poor joint layout (e.g., longer transverse joint spacing) can result in higher curling stresses leading to development of load related cracking at an earlier age because of higher combined stress levels. The effect of joint spacing can now be considered by the new mechanistic-empirical design procedures. In the U.S., the use of a 4.5 m transverse joint spacing has become standard for doweled joints and slab thickness equal to or greater than 300 mm., and is recommended for long-life concrete pavements.
4. ***Base type and drainage considerations*** – Although concrete pavement design procedures tend to be insensitive to base type stiffness, it is important to use a non-erodible base with the desired structural properties. Bases recommended for long-life concrete pavements include cement-stabilized base (or lean concrete base) or asphalt treated base. The cement-stabilized base does not need to be very strong (compressive strength of 5 to 8 MPa at 28 days). If a permeable base needs to be used, then use of a stabilized permeable base is recommended. The permeable base does not need to be very permeable. Permeability in the range of 200 to 300 m/day is considered adequate. Base stability should not be sacrificed to achieve higher levels of permeability.

   The U.S. practice is to maintain separation between the cement-stabilized base and the concrete slab. This is based on past experience and the practicality of ensuring effective bonding between the stabilized base and the concrete slab. The separation between the base and the concrete slab is assured by use of two coatings of a wax-based curing or asphalt emulsion application on the stabilized base, use of a plastic membrane or geo-textile fabric, or use of about 20 mm of hot mix asphalt concrete.
5. ***Load transfer mechanism*** – An effective means of load transfer across transverse joints is necessary for long-life concrete pavements subjected to medium to heavy truck traffic. Effective load transfer across joints reduces

the potential for corner cracking. The standard practice to ensure load transfer across joints is to use round dowel bars. The dowel bars need to have the following characteristics:

a. Be corrosion-resistant. The standard practice in the U.S. is to specify use of epoxy coated dowel bars. However, the effectiveness of the epoxy coating beyond 20 to 25 years in service is considered suspect. As a result, other dowel bar types are being looked at. Several recent projects have been constructed using stainless steel clad dowel bars. These bars are about three times the cost of epoxy-coated bars. The use of solid stainless steel bars, although used in test installations, is considered too costly. Dowel bars made using fiber-reinforced polymers are also under investigation, but the long-term effectiveness has not yet been demonstrated.
b. Provide high level of load transfer across the joint. A load transfer effectiveness of over 70% needs to be maintained over the 40+ years of the initial service life. This can be done by using the right-size dowel bars, spaced appropriately. For long-life pavements subjected to medium to heavy truck traffic, use of 36 to 38 mm diameter bars is recommended for slab thickness of 300 mm or larger.
c. Provide adequate bearing area. The critical dowel bars (outside corner locations) transfer over 1,200 kgf of load across the joint and do this for millions of repetitions. If the concrete bearing stress around the dowel is relatively high, a void may develop over a period of time. This would result in reduced load transfer effectiveness at the joint. The use of properly sized dowel bars to reduce concrete bearing stress around the dowel bar (e.g., 36 to 38 mm diameter dowel bars for slab thickness of 250 to 300 mm and 42 to 44 mm bars for slab thickness of 300 to 250 mm) and good quality concrete are considered necessary to resist the voiding effect over the extended 40+ year service life.

   Using the same logic, it should be pointed out that the dowel bars should not incorporate any built-in looseness due to use of thick plastic sheaths or thick plastic paint. In addition, the dowel bar load transfer capability should not be compromised during construction by not providing sufficient embedment length on each side of the joint (minimum of 175 mm) and not providing sufficient concrete cover around the dowel bar (minimum of 75 mm).

6. ***Concrete properties*** – Progressive cracking in concrete pavement develops when the repeated load related stresses are relatively high in relation to the in-place concrete strength. Concrete strength of about 4.5 MPa at 28 days is considered adequate to withstand the effect of the repeated load related stresses over the 40+ years of service life. Use of

much higher concrete strength is not necessary as most concretes continue to gain strength over time, thus alleviating the long-term impact of repeated load related stresses. Durability related properties of concrete are considered more important than the strength properties. Concrete mix designs need to emphasize durability and workability instead of focusing too much on strength requirements.

Features that Improve Deflection Response

Concrete pavement deflections need to be maintained as low as possible. Deflections under heavy truck traffic should not exceed 1 to 2 mm. This requires that any curling or warping deformations must be kept to a minimum. Excessive slab deflections due to truck loading can result in pumping and faulting distress. Most of the features discussed in the previous sections for cracking response are applicable for reducing slab deflections. These features include:

1. ***Slab thickness*** – A minimum slab thickness of 300 mm should be considered. For heavy truck volumes, an appropriately thick slab, 320 to 350 mm thick, should be considered on the basis of the design procedure computations.
2. ***Widened lane and/or tied concrete shoulder*** – Use of widened outside lane or a tied concrete result in lower slab deflections at the critical corner locations.
3. ***Base type and drainage considerations*** – A stiff stabilized base is necessary to maintain slab deflections at a low level over the 40+ year initial service life, especially for pavements subjected to medium to high volume of truck traffic. The base needs to be non-erodible.
4. ***Load transfer mechanism*** – An effective means of load transfer across transverse joints is necessary to ensure that slab corner deflections are kept low for pavements subjected to medium to heavy truck traffic. The discussion related to dowel bar requirement in the previous section is applicable here also.

Features that Minimize Maintenance Operations

Special attention needs to be paid to the following three features to ensure that the concrete pavements require only low-maintenance over its service life:

Initial Smoothness – Recent experience in the U.S. has established that concrete pavements constructed smother remain smoother over a long period. New concrete pavements should be constructed to a smoothness level corresponding to the International Roughness Index (IRI) of about 1.2 m/km. The degradation in smoothness over the pavement’s service life should not exceed about 0.05 m/km per year on the average. This low rate of degradation in IRI can be achieved if cracking and faulting distresses are controlled and the concrete is durable.

Durable Surface Texture – A durable surface texture is needed to minimize wet-weather accidents. Until recently transverse tining was the standard procedure for achieving a durable surface texture. Because of noise related concerns, the U.S. practice is now shifting to use of longitudinal tining and other methods. The durability of the surface texture is affected by concrete aggregate type. When softer aggregates have to be used, the texture can be restored at regular intervals by means of surface grinding or surface grooving. Many U.S. highway agencies now routinely plan for concrete pavement re-texturing (by grinding or longitudinal grooving) at about 15-year interval.

Joint Sealing – Joints are sealed to keep water out of the pavement and to keep debris (incompressibles) from getting into the joints. This is a potentially weak link in the concrete pavement system. Although joint re-sealing is considered a routine maintenance activity, it cannot be performed routinely along high volume highways. The resealing intervals need to be extended. Extending the resealing operations also results in less joint re-facing operations. Excessive re-facing can lead to very wide joint widths that impact the performance of the joints and the ride across the joints (due to wheel-slap as the tire moves across the wide joints).

Currently, liquid hot-poured and cold-poured sealants are capable of providing a service life of only 3 to 8 years and use of preformed sealants, properly applied, can provide 12 to 15 years of service life. Long-life concrete pavements along high volume highways would necessitate use of preformed sealants to minimize the number of resealing operations. The current direction towards use of a single-cut joint appears to be very promising. In this case, a 9 to 10-mm wide sawcut is made and the cut may be left unfilled, filled or sealed (using a backer rod). This is a recent innovation and early indications are that the sealed single-cut may provide a cost-effective solution.

Construction Features for Long Life Pavement

Good materials and construction practices are vital for producing long life concrete pavements. Even if a pavement is designed to the highest standards, it will not perform well if it is not constructed well. A pavement that is constructed well using durable concrete paving materials will require less maintenance and repairs over the years. As such, construction requirements and specifications need to be well defined, yet allow for innovations by the contractor.

A fundamental requirement for long-life concrete pavement is that a quality pavement performs well. Quality is an inherent property of a well-constructed pavement. Quality is not a hit or miss proposition. Quality construction requires dedication from the project management down to the execution by labor. The management, as well as the field crews, needs to buy into the concept of quality in construction, not necessarily because it is mandated, but because it is the right approach. The contractor needs to emphasize teamwork and collective accountability for constructing long lasting pavements. The various concrete production, placement, and finishing operations listed below need to be carried out with care and with quality built-in:

1. Concrete production - uniform production
    a. A mix that is workable
    b. A mix that is consistent
2. Concrete quality– long-term durability
    a. No materials related distress
    b. Low shrinkage
3. Desired hardened structural properties (strength, stiffness, thermal).
4. Concrete placement and consolidation – correct techniques
5. Dowel bar placement – properly aligned
    a. To ensure sufficient dowel embedment on each side of the joint
    b. To ensure sufficient concrete cover around the dowel bar; and to
    c. To minimize the effect of dowel skew (tilt)
6. Concrete finishing - minimal manual finishing
7. Curing – timely and adequate
    a. Prepare for extreme weather conditions
8. Joint sawing – timely and to correct depth
    a. Account for variable window of joint sawing opportunity
9. QA/QC - continuous monitoring of concrete quality behind the paver

Currently, it is not common to evaluate the characteristics of the concrete behind the paver. Efforts are underway to develop and implement test methods that will evaluate the quality of concrete right behind the paver, so any corrective actions that need to be taken can be taken immediately and not after many kilometers of pavement has been constructed. This also applied to timely evaluation of dowel bar alignment.

Summary

This paper summarized the current directions at achieving long-life concrete pavements in the U.S. and establishes the framework for considering design and construction features that are critical to obtaining the 40+ years of service life. Use of long-life pavement strategies is considered to be a cost-effective tool in minimizing maintenance costs for the highway agencies and reducing delays to the motoring public. The consideration of long-life strategies is considered very cost-effective and can result in extending the service life of a concrete pavement from about 20 years to more that 40+ years with an increase in cost of only about 5 to 10% of the overall construction cost.

References

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