Achieving Better Performance from Concrete Pavements by a Focus on Design and Construction Fundamentals

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Paper prepared for presentation
at the Innovation in Geotechnical and Materials Engineering Session

Of the 2021 Conference of the
Transportation Association of Canada

ABSTRACT

Properly designed and constructed concrete pavements should provide a serviceable life of 50 years or more, without the need for major rehabilitation and with only minimal maintenance interventions required. The main challenge to achieving this outcome is design and construction quality. We frequently see recently constructed concrete pavements develop cracking that can eliminate the economic benefit of having constructed with concrete in the first place. In the case of airfield pavements, the early onset of distress can be much more serious than in the case of highway pavements but in all cases it has significant economic impact on maintenance expenditures and operational safety. While it is not unexpected to have early age plastic shrinkage cracking in concrete pavements and it is recognized as not representing a severe distress, this type of cracking can be eliminated with appropriate concrete mix design and strictly adhering to best practices for concrete placement, finishing and curing. However, it is the development of premature structural cracking that once it occurs is very difficult to repair and thus needs to be avoided, where possible. Based on case studies, this paper explores the range and types of early age distresses that all too frequently occur in even properly designed concrete pavements. By identifying the causes of these distresses, the means for avoiding them becomes clear. The lessons learned point to the imperative of achieving uniform pavement support, of managing and coping with adverse construction conditions, and having in place the appropriate level of independent quality assurance inspection and testing during all critical stages of construction.

1.0 INTRODUCTION

A pavement structure comprising Portland Cement Concrete (PCC) slabs supported on granular or cement stabilized materials is referred to as a concrete pavement. Concrete pavement structures can include two types, rigid and composite pavements. In rigid pavements, the concrete slabs are exposed and in direct contact with traffic loading. Composite pavements are a type of rigid pavement where one or multiple lifts of asphalt are placed on top of the PCC slabs [1].

In addition to the fact that a well designed and constructed concrete pavement can deliver a service life of 50 years or more with limited rehabilitation and/or maintenance efforts required, concrete pavements offer several other benefits:

- Improved load distribution to accommodate static, concentrated, and heavy loads, particularly on subgrade soils with lower bearing strength;
- High resistance to indentation, distortion and rutting;
- Resisting damage from fuel spillage;
- Higher reflectivity than asphalt pavements and so reduced contribution to urban heat island effects; and
- No adverse impact on load bearing capacity at extreme temperatures.

With recent advancements in technology, construction of high quality concrete pavements becomes more cost effective and a feasible alternative to flexible pavements in a wide range of applications. However, to achieve the anticipated benefits of concrete pavements it is critical that the design and construction fundamentals are followed. Failure to adhere to these fundamentals can result in concrete pavements prone to premature distresses, regardless of the type of advance concrete technology used.

The objective of this paper is to refresh the concrete pavement design and construction fundamentals. It provides examples of what can happen if those fundamentals are not followed resulting in early life structural distresses or complete failure of concrete pavements. We also identify the primary causes of such distresses and recommend remedies to minimize the potential for their occurrence.

2.0 CONCRETE PAVEMENT FUNDAMENTALS

Based on our experience mainly from multiple concrete pavement design and construction projects, there are three basic fundamentals for achieving long lasting and high performing concrete pavements. These are as follows:

1. Proper geotechnical investigation;
2. Proper design; and
3. Proper construction.

Proper geotechnical investigation defines the existing subgrade soil types and their condition, particularly soil moisture content and frost susceptibility potential. It also identifies seasonal groundwater variations. In the case of previously developed sites, the subsurface investigation identifies anomalies, such as old fill materials, buried topsoil, or even old foundations. These will all need to be considered in establishing how to create uniform subgrade support conditions.

Regarding proper design, several design methodologies are commonly used for designing concrete pavement structures, including “Guide for Design of Pavement Structures” by the American Association of State Highway and Transportation Officials (AASHTO) dated 1993 [2], “Thickness Design for Concrete Highway and Street Pavements” by the Portland Cement Association (PCA) dated 1995 [3], and “Mechanistic-Empirical Pavement Design Guide” (MEPDG) by AASHTO dated 2008 [4]. Irrespective of the design methodology used, design fundamentals are consistent for all of them, and they include:

- Subgrade types and condition;
- Understanding of current and future traffic loading;
- Surface and sub-surface drainage, and environmental conditions;
- Condition and type of pavement structure layers underlying the concrete slabs;
- Avoiding non-uniformities, particularly the impact of utilities underlying concrete slabs;
- Concrete joints and installation of load transfer devices; and
- Concrete materials properties and material selection, such as selection of durable and inert fine and coarse aggregates, appropriate mix design, air entrainment and mix workability, concrete compressive and flexural strength, and modulus of rupture.

Proper construction involves following best practices for concrete pavement construction, including subgrade preparation, compaction and proofrolling, granular layer or cement stabilized base placement and compaction, and concrete slab construction and curing. Having sufficient independent quality assurance (QA) inspection and testing during the construction phase is also essential to address any unexpected conditions that arise and to monitor all phases of the work for compliance to the required specification.

Photographs 1 to 3 show examples of how the critical elements of a concrete pavement structure should appear when the fundamentals are followed. Photographs 1a and 1b illustrate an example of a well-constructed and uniform cement stabilized base that has supported the overlying heavily loaded concrete slabs for over 60 years. Note that in Photograph 1b after excavation the chunk of cement treated base (CTB) is shown on top of the concrete, but it shows that after 60 years the CTB was still in good condition and well adhered to the concrete. Photograph 2 shows a newly constructed concrete pavement that has been constructed on uniform support provided by well compacted granular base, consolidated and finished properly, cured with double application of curing compound, and sawcut at the right time and to the right depth to eliminate random shrinkage cracking. Photograph 3 shows properly sawcut and sealed longitudinal and transverse joints.

Photograph 1a – Well designed and constructed concrete pavement supported on good quality cement treated base, Photograph 1b – Good condition of excavated cement stabilized base after 60 years of service under an airport pavement (Note that in the photograph the pavement chunk has been overturned so that the cement treated base is on top of the concrete slab)

Photograph 2 – Properly constructed concrete slabs. Note uniform finish and well constructed control joints

Photograph 3 – Properly sawcut and sealed longitudinal and transverse joints.

Inadequate consideration of the fundamentals will likely lead to premature development of pavement distresses and reduction in pavement service life. The following section of this paper provides examples of distresses that can develop in concrete pavements if the fundaments are not followed.

3.0 CONCRETE PAVEMENT PREMATURE DISTRESSES

Soft subgrade soils beneath a concrete pavement (Photograph 4) if not properly addressed prior to placing the base course will provide insufficient and inconsistent support, which can result in differential slab movement. This can cause early longitudinal cracking, transverse cracking, and corner breaks in concrete slabs, and can also lead to faulting at joints. The movement of the slabs at the joints under load application can result in pumping of fine materials from underneath the concrete slabs and creates voids over time [5]. Faulting also occurs due to a lack of load transfer devices, such as dowel and tie bars, at the concrete joints. However, it should be noted that the purpose of load transfer devices is not to address inconsistent support since irrespective of the joint details, the pavement still remains a ground-supported structure.

Photograph 4 – Soft subgrade soil that failed proofrolling. Further work is needed prior to placing base course.

Subgrade soil condition including its moisture content, drainage and susceptibility to frost action should also be considered when designing concrete pavements. Additional subsurface drainage may need to be installed or in extreme cases, a portion of the frost susceptible soil may need to be removed and replaced with select subgrade or granular material. Photograph 5 shows an example of a concrete pavement that has severely heaved and then the failure was repaired with a hot-mix asphalt overlay. However, the repair did not work, and the heave bump reappeared the following winter, and the asphalt also distorted and cracked. Since this was an airside pavement, it created foreign object debris risk potential. In this case, the permanent fix requires improved localized subdrains possibly in conjunction with some replacement of the problematic soils.

There are three conditions for the frost heaving to occur: frost susceptible soils, sub-freezing temperatures and the presence of water. Removing water by installation of a proper subsurface drainage system is often considered to be the most practical and effective. If localized frost heaves are repaired, tapers may be necessary to achieve a gradual transition.

Photograph 5 – Frost heaving of concrete slabs unsuccessfully repaved with asphalt overlay

Voids can develop beneath a pavement for a number of different reasons; however, they generally occur when the fines in the granular material directly underlying the bound pavement layers is removed by pumping and washed away. Such voids generally form under both concrete and composite pavements. The evidence of pumping of fines, as seen in Photograph 6 is a good indicator that there are likely voids under the concrete slabs. Such voids will continue to progress until the root cause is addressed.

Photograph 6 – Pumping of fines through longitudinal and transverse joints

Effective joint design is a key component of a properly designed concrete pavement. In addition to a regular network of expansion/contraction joints, additional joints may be needed depending on the geometry of the slabs and the locations of discontinuities and cut outs. The inclusion of isolation joints in a concrete pavement may be necessary where differential movement may occur between the slab and an adjacent structure, such as may occur when a slab abuts a concrete foundation base for a generator. Additional joints are also required to avoid situations where irregular shaped slabs are needed. The isolation joints should provide complete separation between the two different structures allowing them to move independently. Joints will also be needed where right angled cut outs will give rise to stress concentrations at the abrupt change in geometry. If a proper isolation joint is not constructed around discontinuities in the slab, such as columns, maintenance holes and inset lights, cracking and slab breakage will occur at the point of stress concentration or where the adjacent structure impedes the normal seasonal movement of the slab. The isolation joint should extend though the entire depth of the concrete slabs. Photograph 7 shows cracked concrete slabs adjacent to a concrete column due to lack of an isolation joint. The differential movement caused the concrete slab to crack and break into multiple pieces.

Photograph 7 – Not Providing Isolation Joint

Photograph 8 shows an example of concrete slab damage with two maintenance holes in very close proximity, without isolation joints around the circular cut-outs. Due to a lack of effective isolation joints and likely inconsistent support due to failure to adequately compact the service trench backfill, as well as poor design, the slab shattered into pieces within a year requiring costly repairs.

Photograph 8 – Concrete slab shattered into pieces due to failure to adhere to good design and construction fundamentals

Poor concrete aggregate selection and failure to confirm compliance to CSA standards can also be the source of performance problems. Photograph 9 shows an example of concrete failure caused by Alkali-Silica Reactivity (ASR). ASR caused swelling, cracking and expansion of the concrete. Some aggregates containing reactive amorphous silica react with the cement paste having high alkalinity and produce an expanding gel. This expanding gel over time causes deterioration in the form of swelling and ultimately cracking in the concrete pavement in the presence of moisture and warm temperatures [1].

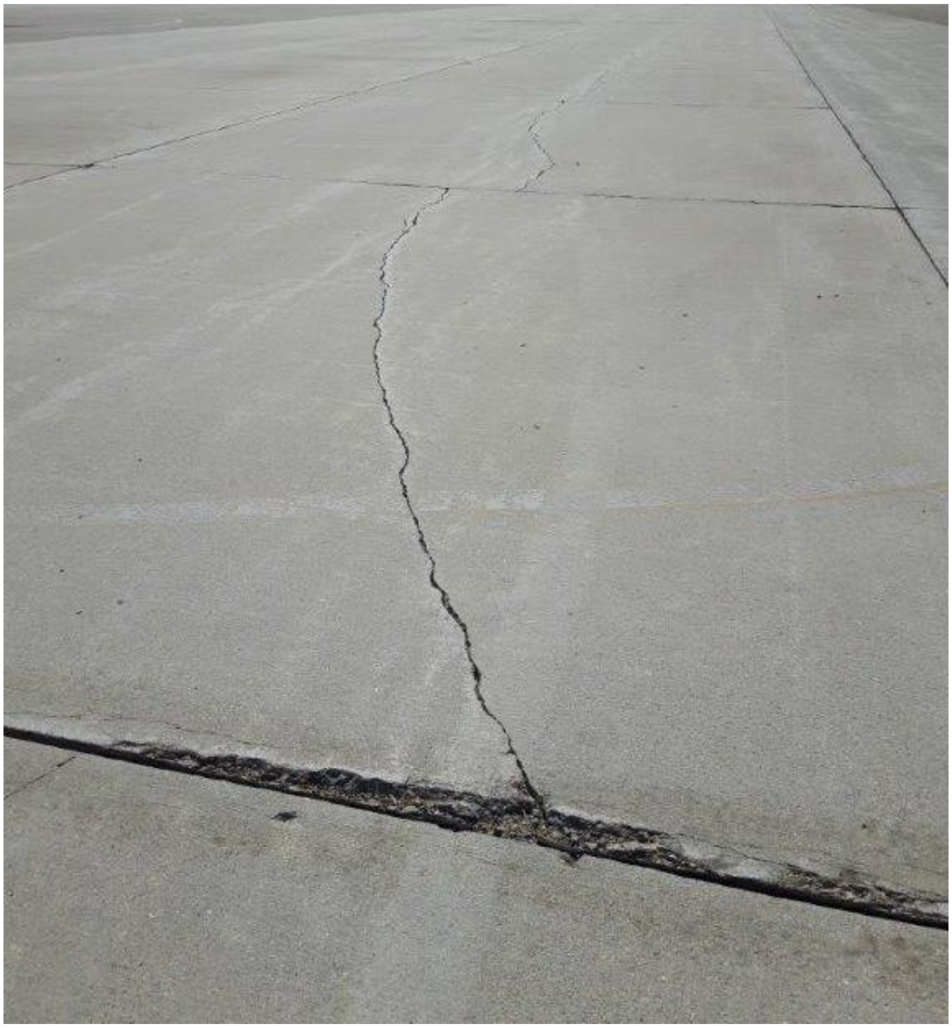
Photograph 9 – ASR-induced swelling of concrete under asphalt overlay.

The risk of ASR damage can be mitigated by the use of supplementary cementitious materials. Good surface and subsurface drainage, minimizing contact of concrete slabs with de-icing chemicals, and sealing cracks at the pavement surface can help reduce the severity of ASR deterioration.

D-cracking also known as durability cracking is another form of deterioration in concrete pavements that is caused due to improper selection of coarse aggregates used in the concrete mix. D-cracking presents as a series of hair line cracks along concrete joints and occurs when coarse aggregates are susceptible to freeze-thaw deterioration [5]. Since this type of cracking is primarily observed in concrete with larger coarse aggregate size, i.e. 37.5 mm, consideration can be given to using smaller top size aggregates, i.e. 20 mm, in the concrete mix [1]. Photograph 10 shows an example of concrete pavement D-cracking.

Photograph 10 – D-cracking of concrete pavement

The presence of underground utilities below concrete slabs may create uneven support which in turn can result in concrete cracking. Embedding conduits in concrete pavements will reduce the effective concrete thickness and represents a zone of weakness in the slab that makes it prone to preferential cracking. Photograph 11 shows full depth longitudinal cracking that developed due to the presence of an old utility trench under the concrete pavement.



Photograph 11 – Full depth longitudinal crack due to the presence of a utility trench under concrete slabs

Poor construction of the support layers underlying concrete slabs, such as granular materials, cement stabilized base, and subgrade soil may result in inconsistent support for the slabs. It is important to have a well compacted, smooth, and uniform layer immediately beneath the concrete slabs. Using a debonding agent between concrete and a cement stabilized layer is good practice as it will allow the concrete to freely expand and contract and prevent cracking occurring outside the joints.

Providing a uniform support layer beneath the concrete slab is also critical due to the fact that inconsistent support beneath concrete slabs allows the slabs to pivot or tilt and causes cracks to develop full depth. This cracking could be in the form of corner breaks, longitudinal, and transverse cracking. Photograph 12 and Photograph 13 illustrate a full depth corner break and longitudinal crack that developed due to inconsistent support.

Photograph 12 – Severe corner break due to inconsistent support

Photograph 13 - Full depth longitudinal crack due to inconsistent support

Photograph 14 shows another example of poor construction. Poor concrete consolidation and finishing techniques resulted in drying shrinkage, surface cracking and surface voids which will lead to progressive surface deterioration.

Photograph 14 - Poor concrete consolidation and finishing work

4.0 CONCLUSIONS

In conclusion, long-lasting concrete pavement requires a thorough understanding of geotechnical conditions, concrete materials behaviour and the structural aspects of design. It also requires good knowledge of construction procedures and adherence to best practices at all stages. It is not sufficient to simply calculate the concrete slab thickness or use computer aided software to carry out finite element analysis.

For achieving long-lasting concrete pavements, the design and construction fundamentals are equally as important as the methodology selected to design the concrete slab thickness. Based on our experience there are three main design/construction aspects that require consideration that are as follows:

1. Providing uniform and smooth support for the concrete slabs. For heavily loaded pavements cement stabilized base offers greater reliability;
2. Selection of concrete mixes that incorporate high quality and durable aggregates that are not alkali silica reactive, and ensuring that the concrete mix meets the workability requirements to allow placement and consolidation, and with appropriate air, compressive strength and flexural strength to deliver long term durability; and
3. Constructing proper joints (construction, expansion/contraction and isolation) and efficient load transfer devices (dowels and tie bars), to avoid random cracking that increases maintenance costs and significantly shortens the service life.

Careful consideration of the above noted design aspects, following construction best practices and having adequate quality assurance (QA) inspection and testing during the construction phase should result in concrete pavements that provide the desired long service life and value for money.

5.0 REFERENCES

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5. American Society for Testing and Materials (ASTM D-5340), “Standard Test Method for Airport Pavement Condition Index Surveys”, October 2020