

## EXECUTIVE SUMMARY

Well-designed and constructed portland cement concrete (PCC) pavements are inherently durable and are expected to be relatively maintenance free during many years of service. Primarily because of these two properties—durability and low maintenance—concrete has been the material of choice for premium pavements for many years.

Unfortunately, a number of pavement distresses can occur as a result of the interaction between the concrete and the environment in which it serves. In contrast to the common perception held by many engineers that concrete is relatively inert, it is in fact a very complex material whose properties can change significantly with time. Some of these changes can be positive, such as long-term strength gain obtained through continued cement hydration. Other changes can be detrimental to the concrete, resulting in the development of premature pavement distress. Paste deterioration resulting from freezing and thawing, aggregate freeze-thaw deterioration (also referred to as D-cracking), and alkali-aggregate reactivity (AAR) are a few examples of detrimental changes that can occur over time. When these changes manifest themselves on the pavement surface, they fall under the general category of materials-related distress (MRD). The types of MRD that are common to concrete pavement, and thus were of primary concern in this project, are summarized in Table 1.

MRD in concrete pavement is a concern to all State highway agencies (SHAs) in the United States. Although the specific type of distresses may vary geographically, it is clear that a better understanding of these types of pavement failures is an important starting point for the production of pavements having longer expected service lives. A principal driving force for understanding the sources of MRD is an increased awareness on the part of SHAs that such failures occur. However, the ability of these agencies to analyze, diagnose, remedy, and prevent these failures has not been fully developed, and this research project focuses on these general areas.

The objective of this research was to develop guidelines to provide pavement engineers and field and laboratory personnel with a systematic procedure for the identification, evaluation, treatment, and prevention of MRD in PCC pavements. The research is presented in three documents:

- *Volume 1: Final Report* presents the synthesis of background material, describes the development of the guidelines, and briefly introduces the case studies
- *Volume 2: Guidelines - Description and Use.*
- *Volume 3: Case Studies - Using the Guidelines.*

Table 1. Summary of key MRDs in concrete pavements.

Type of MRD	Surface Distress Manifestations and Locations	Causes/ Mechanisms	Time of Appearance	Prevention or Reduction
<i>MRD Due to Physical Mechanisms</i>				
Freeze-Thaw Deterioration of Hardened Cement Paste	Scaling, spalling or map-cracking, generally initiating near joints or cracks; possible internal disruption of concrete matrix.	Deterioration of saturated cement paste due to repeated freeze-thaw cycles.	1–5 years	Addition of air-entraining agent to establish protective air void system.
Deicer Scaling/Deterioration	Scaling or crazing of the slab surface with possible alteration of the concrete pore system and/or the hydrated cement paste leading to staining at joints/cracks.	Deicing chemicals can amplify freeze-thaw deterioration and may interact chemically with cement hydration products.	1–5 years	Provide minimum cement content of 335 kg/m <sup>3</sup> , limit water–cement ratio to no more than 0.45, and provide a minimum 30-day “drying” period after curing before allowing the use of deicers.
Freeze-Thaw Deterioration of Aggregate	Cracking parallel to joints and cracks and later spalling; may be accompanied by surface staining.	Freezing and thawing of susceptible coarse aggregates results in fracturing and/or excessive dilation of aggregate.	10–15 years	Use of non-susceptible aggregates or reduction in maximum coarse aggregate size.
<i>MRD Due to Chemical Mechanisms</i>				
Alkali–Silica Reactivity (ASR)	Map cracking over entire slab area and accompanying expansion-related distresses (joint closure, spalling, blowups).	Reaction between alkalis in the pore solution and reactive silica in aggregate resulting in the formation of an expansive gel and the degradation of the aggregate particle.	5–15 years	Use of non-susceptible aggregates, addition of pozzolans to mix, limiting total alkalis in concrete, minimizing exposure to moisture, addition of lithium compounds.
Alkali–Carbonate Reactivity (ACR)	Map cracking over entire slab area and accompanying pressure-related distresses (spalling, blowups).	Expansive reaction between alkalis in pore solution and certain carbonate/dolomitic aggregates which commonly involves dedolomitization and brucite formation.	5–15 years	Avoid susceptible aggregates, significantly limit total alkalis in concrete, blend susceptible aggregate with quality aggregate or reduce size of reactive aggregate.
External Sulfate Attack	Fine cracking near joints and slab edges or map cracking over entire slab area, ultimately resulting in joint or surface deterioration.	Expansive formation of ettringite that occurs when external sources of sulfate (e.g., groundwater, deicing chemicals) react with the calcium sulfoaluminates.	1–5 years	Use w/c below 0.45, minimize tricalcium aluminate content in cement, use blended cements, use pozzolans.
Internal Sulfate Attack	Fine cracking near joints and slab edges or map cracking over entire slab area.	Formation of ettringite from internal sources of sulfate that results in either expansive disruption in the paste phase or fills available air voids, reducing freeze-thaw resistance.	1–5 years	Minimize internal sources of slowly soluble sulfates, minimize tricalcium aluminate content in cement, avoid high curing temperatures.
Corrosion of Embedded Steel	Spalling, cracking, and deterioration at areas above or surrounding embedded steel.	Chloride ions penetrate concrete, resulting in corrosion of embedded steel, which in turn results in expansion.	3–10 years	Reduce the permeability of the concrete, provide adequate concrete cover, protect steel, or use corrosion inhibitor.

The research approach was to conduct a thorough review of existing literature to establish the state-of-the-practice for the field evaluation, sampling, laboratory analysis, treatment, and prevention of concrete pavement MRD in concrete pavements. From the information gathered, draft guidelines were developed and a field and laboratory study was conducted on six real world pavements suffering unidentified distress(es) in order to test the applicability of the draft guidelines. These guidelines were then modified accordingly.

The three guidelines, which are provided in Volume 2 of this Final Report, provide the primary product of this study. To assist in dissemination of the information contained in the guidelines, a technology transfer package was developed to provide training materials and visual aids needed to conduct a one-day training course.

The literature review suggested what the field evaluation confirmed, that the visual manifestations on the pavement surface of many of these deterioration mechanisms appear similar, especially early in their development. Cracking and staining in the vicinity of joints is an indicator of MRD, but this visual analysis alone does not provide positive identification of what mechanism is at work. For example, it is believed in the past that some cases of external sulfate attack, possibly resulting from deicer impurities, may have been misdiagnosed as aggregate freeze-thaw deterioration (D-cracking).

To address the difficulties of accurate diagnosis, standardized diagnostic methods executed by well-trained personnel are required. This includes training of both the field crews collecting visual information and concrete samples, and the laboratory staff carrying out chemical and petrographic analyses. In some cases, advanced analytical methods based on the use of the scanning electron microscope (SEM) and x-ray diffraction (XRD) may be required to establish what mechanism(s) is at work. This process is illustrated in figure 1. It also must be fully understood that the complexity of the problem might be so great that the best result of a diagnostic investigation is a prioritized list of probable causes.

As mentioned, the guidelines were applied at the six sites with the cooperation and support of the SHAs. Both *Guideline I – Field Distress Survey, Sampling, and Sample Handling Procedures for Distressed Concrete Pavements* and *Guideline II – Laboratory Testing, Data Analysis, and Interpretation Procedures for Distressed Concrete Pavements* were evaluated. The third guideline, *Guideline III – Treatment, Rehabilitation, and Prevention of Materials-Related Distress in Concrete Pavements*, was not applied and is presented as a state-of-the-practice based on a review of the available literature. In general, the guidelines seemed to direct the necessary work well and provide a systematic method of gathering and recording data.

The first guideline presents a systematic approach for performing a field distress survey, sampling the distressed pavement, and sample handling procedures. In applying this guideline, it was noted that in many instances the construction records for the selected sites were incomplete or limited. In part this may be due to the age of the pavements. However, it may be indicative of a systemic lack of methods and procedures for accurately recording construction data. Even data

as fundamental as the job mix formula for the mix design was unavailable in many cases. Information such as climatic conditions during placement is non-existent. Improving data collection, most probably by an automated data collection system during concrete placement,

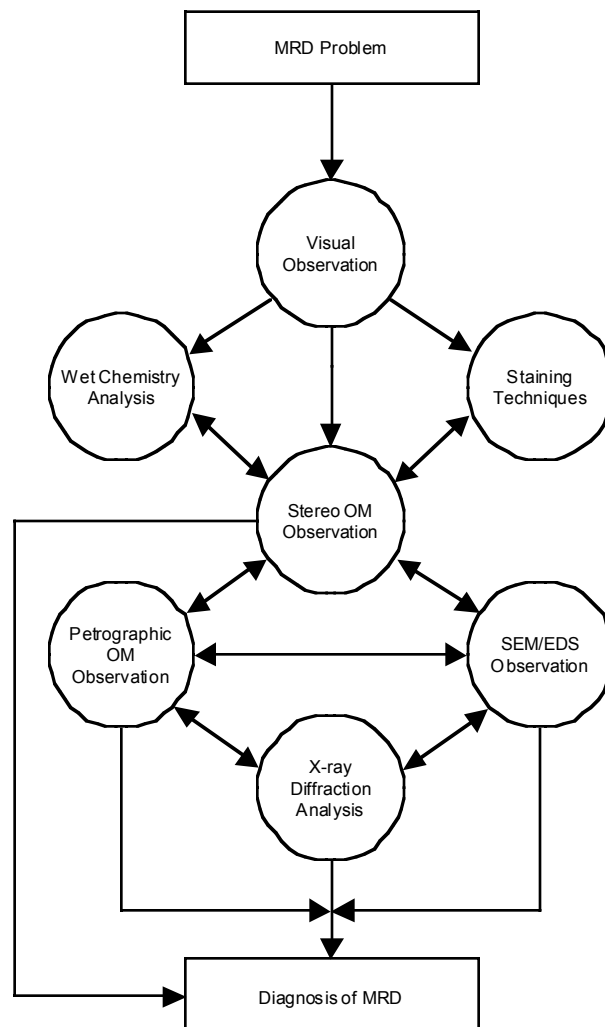


Figure 1. Fundamental process for analyzing a concrete MRD sample.

could greatly add to the information available to help diagnose the causes of pavement distress, including MRD. It is suggested in Guideline III that SHAs adopt a more rigorous data collection and storage methodology in line with what is presented in ACI 126.1R, *Guide to a Recommended Format for the Identification of Concrete in a Materials Property Database*.

The application of Guideline I provided a detailed assessment of the current condition of the pavement. This not only provides the current information needed for analysis, but also provides a baseline for monitoring the rate of pavement deterioration when compared to data gathered in the future. This greatly improves the ability of the engineer to maintain the pavement and extend

its life, while providing a means to judge the effectiveness of various treatments. This also illustrates one positive aspect of the developed guidelines. They are intended to be applied together, but can easily be applied separately at different times. As an approach, a SHA may use Guideline I as a means of screening pavements and prioritizing maintenance and reconstruction after the specific MRD(s) present has been identified.

The second guideline is the heart of the research effort, as it proposes an approach to laboratory analysis and diagnosis of MRD. The recommended laboratory procedures provide a systematic method for analyzing distressed concrete based on diagnostic flowcharts and tables, which provide a step by step approach to use when trying to determine the exact cause of MRD. Clearly there will be cases where the guidelines fail to isolate the cause to any one MRD mechanism and, in many cases, multiple MRD mechanisms will be identified as possible contributors to the observed distress. However, it is believed that in most cases the data collected using the methods discussed in Guideline II provided a more complete understanding of the distress mechanisms at work. Based upon the results of this evaluation, the majority of cases were resolved. In four of the six case studies used to evaluate the guidelines, definitive and most probable causes of MRD were established. Of the other two, one was identified through execution of the guidelines as not likely being affected by an MRD. It is noted that the laboratory investigation conducted on this site bore out this conclusion, even though early stages of MRD were observed, but were not yet (and may never be) associated with microcracking. In the last site presented, a diagnosis could not be reached using the guidelines, as it became evident early in the evaluation that a different approach would need to be taken to investigate the problem.

The researchers were satisfied with Guideline II in terms of its efficacy and broad applicability. However, in a couple of instances, techniques not proposed in the guideline were employed. Specific examples are the use of epifluorescence microscopy as a means of estimating the effective  $w/c$  for the concrete and the use of a flat bed scanner as a low cost imaging tool. Neither of these techniques is precluded by the guidelines and, further, the methods proposed in the guidelines were never intended to be the sole methods of analysis or interpretation. They are simply designed to provide guidance for the common methods.

For engineers working on this project, Guideline II proved to be very useful for helping them understand the process of laboratory analysis. For many engineers, this process is a mystery, and misunderstandings can result if the person interpreting or otherwise using the data does not understand the procedures used. When following the guideline, the choice of tests was understood and the engineers knew that the laboratory personnel progressed through the diagnosis without stopping at the first distress identified.

Unfortunately, for laboratory personnel familiar with the various analytical techniques, the guidelines were reported to be too confining. Laboratory personnel examining concrete are, in general, slow to rush to judgment. The inherent variability in concrete, and the limited sampling possible from most pavements, makes it difficult for an analyst to make yes/no decisions about

observations, as is required in the diagnostic flowcharts presented. Laboratory personnel are more comfortable with decisions that are not absolute or are somehow weighted for their significance. As the recipient of the data, the engineer has to understand that absolute decisions are rare and that, in the end, the petrographer or analyst can only provide them with their best judgment. However, the laboratory personnel need to understand the engineers needs. Namely, they need to make yes/no decisions about replacement or rehabilitation and therefore, require the clearest possible diagnosis from the laboratory in order to proceed. Performing the laboratory analysis in accordance with Guideline II helps remove ambiguity and provides a comprehensive look at all possible distresses.

A strong point of Guideline II is that it does not force the diagnosis to resolve at one specific cause. Numerous MRD mechanisms can be active and each should be clearly identified, without bias. The guidelines serve as an interface between engineers and laboratory personnel. Although some MRDs will not be unambiguously diagnosed by using the guidelines, the more common distresses will be identified. Even when absolute diagnosis is not possible, the guidelines help the engineer understand the likely possibilities and the tests available to diagnose the problem further by contracting with outside laboratories.

The third and final guideline was based upon the review of available literature. The results of this review suggest that the various strategies used to treat pavements affected by MRD are not very effective. Most treatments are short-term fixes, such as the application of surface sealers in an attempt to slow the ingress of moisture and deleterious compounds. Some suggested treatments, such as the use of lithium salts in treating alkali silica reactivity, show promise. But in general, long-term treatment of a pavement seriously affected by MRD almost always requires major rehabilitation, either through rubblization and overlaying or complete reconstruction.

Thus, the best method to treat MRD is to prevent it. In new construction, it is recommended that an approach be adopted in which the overall quality of the concrete is emphasized. Strength (especially 7-day or 28-day) is only one measure of quality and it is important that other factors, such as permeability, also be considered. The literature strongly emphasized that the use of short-term strength testing (7-day or 28-day) may be complicit in the increased observation of MRD, and that the emphasis should be shifted to producing dense, impermeable concrete having relatively defect-free insoluble paste microstructural characteristics. This requires the use of durable, non-reactive aggregates arranged to minimize the paste fraction. The paste should have low permeability and solubility. The use of high-quality fly ash or ground granulated blast furnace slag may offer advantages in achieving the desired concrete properties. And care must be exercised during all phases of construction to ensure that the concrete reaches its full potential.

To construct truly durable concrete pavements, it is believed that SHA incentives will need to be modified by changing construction specifications and practices to focus on long-term durability, de-emphasizing rapid construction and short-term strength gain unless project constraints absolutely demand “fast track” construction. It is realized that this will lead to an increase in initial costs, putting concrete pavements at a competitive disadvantage if life cycle costing is not

considered. Therefore the revision of SHA policies must not be restricted to the engineering level, but also must include a commitment to accept higher initial costs to achieve high-performance, durable concrete pavements that will provide many years of maintenance-free service. Without this commitment, it is unlikely that proposed changes can be implemented.

In closing, this project has led to the development of three guidelines that should be useful to both SHAs and the private sector to assist in the diagnosis, treatment, and prevention of MRD in concrete pavements. It is acknowledged that the guidelines are not the final authority on this issue, but are simply an attempt to provide standardization and guidance. In future years, it is likely that the body of knowledge in this area of study will continue to grow, and it is anticipated that the guidelines will grow as well, reflecting advancements in laboratory equipment, procedures, and interpretive abilities.