A Synthesis of Knowledge of Potential Durability of Concrete

Long-Life Concrete: How Long Will My Concrete Last?

Peter C. Taylor, PhD
October 2013

Sponsored through
Technology Transfer Concrete Consortium (TTCC) Pooled Fund Study TPF-5(159) with funding from Colorado, Illinois, Iowa, Kansas, Michigan, Minnesota, Ohio, Oklahoma, and Pennsylvania

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There is an ongoing discussion about moving toward performance-based specifications for concrete pavements. This document seeks to move the discussion forward by outlining the needs and the challenges, and proposing some immediate actions. However, this approach may increase risk for all parties until performance requirements are agreed upon and, more importantly, how the requirements can be measured.

A fundamental issue behind pavement construction activities is that the owner/designer needs to be assured that the concrete in place will survive for the intended period (assuming there are no changes in the environment or loading) and, therefore, that full payment should be made. At the same time, each party along the supply chain needs to be assured that the material being supplied to them is able to meet the required performance, as is the product/system they are delivering.

The focus of this document is a discussion of the issues behind this need, and the technologies that are available, or still needed, to meet this need, particularly from the point of view of potential durability.

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INTRODUCTION

There is an ongoing discussion about moving toward performance-based specifications for concrete pavements. However, this approach may increase risk for all parties until performance requirements are agreed upon and, more importantly, how the requirements can be measured. This document seeks to move the discussion forward by outlining the needs and the challenges and proposing some immediate actions.

A fundamental issue behind pavement construction activities is that the owner/designer needs to be assured that the concrete in place will survive for the intended period (assuming no changes in the environment or loading) and, therefore, that full payment should be made. At the same time, each party along the supply chain needs to be assured that the material being supplied to them is able to meet the required performance, as is the product/system that they are delivering.

The focus of this document is a discussion of the issues behind this need, and which technologies are available, or are still needed, to meet this need, particularly from the point of view of potential durability. The phrase “potential durability” is used because, despite the best efforts to deliver a high-quality mixture, poor workmanship may ruin it and/or the environment experienced is not the same as that assumed at the time that the mix design was settled upon.

Traditionally, we have measured strength, slump, and air content at the point of delivery. Why? Because we could and because, initially, these were adequate indicators of potential durability. However, current mixtures contain admixtures that confound correlation between slump and water content (the parameter we really care about), while supplementary cementitious materials remove any relationship between strength and permeability (Figure 1), thus calling into question the benefit of accepting a batch of concrete based on these parameters alone.

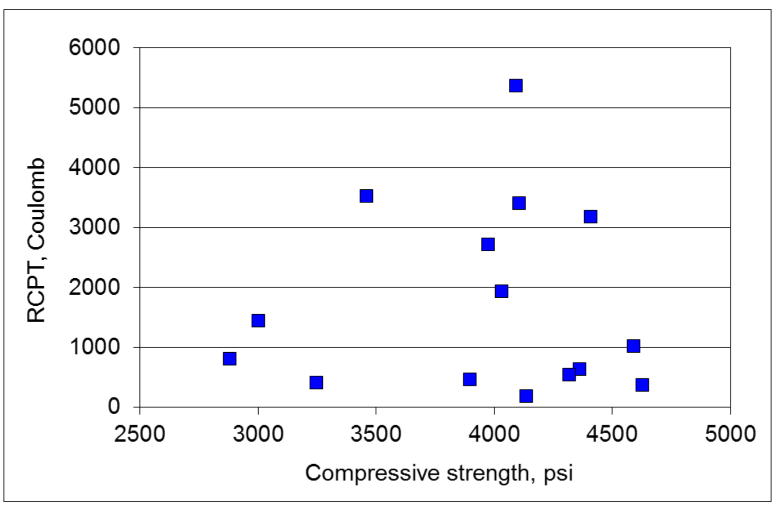


Figure 1. Poor correlation between compressive strength and RCPT data (Data from Grove et al. 2008)

Mixtures are increasingly complex and may contain up to four binders including ground limestone, along with multiple admixtures. Demands on mixtures are also increasingly stringent, including the need for early loading and the ability to resist aggressive deicing salts in cold regions. All of this means that we are unable to continue to do things we have always done while expecting pavements to be long lasting.

Longevity of a given batch of concrete is dependent on a number of factors including the following:

- Environment it is exposed to
- The mixture including ingredients and their proportions
- Workmanship in mixing, transporting, placing, and curing the concrete
- Loading and the resultant stresses

The last topic is not discussed in detail in this document because it is outside the scope of this document.

The discussion starts with the mechanisms that potentially cause failure in concrete pavements. This discussion is followed with a look at the measurements needed to be sure that the risk is acceptable and to note the difficulties of applying some of these measurements in a contractual environment, and identify the gaps that exist in the process. Recommendations are then made on new approaches that can be implemented and on new and needed research to fill the current technology gaps.

HOW DOES CONCRETE FAIL?

Durability of concrete may be defined as the ability of the concrete to survive the environment to which it is exposed. This section discusses the mechanisms that may cause distress in a concrete system.

Internal Attack

Some failure mechanisms are based on products expanding within the concrete microstructure. Because hydrated cement paste is very stiff, and weak in tension, small expansions can result in extensive microcracking and damage. Mechanisms that cause internal expansion are discussed in the following sections.

Alkali Aggregate Reaction (AAR)

A chemical reaction can occur between certain types of aggregate, alkali hydroxides, normally from the cement, and water that leads to the slow formation of a gel in and around the aggregates (Figure 2) (Kosmatka and Wilson 2011).

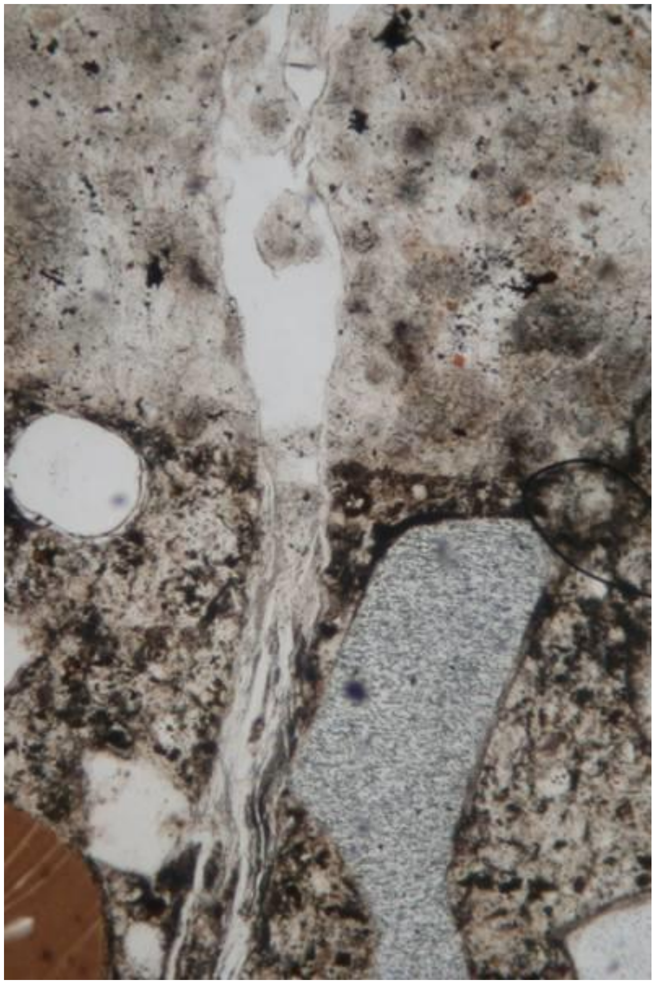


Figure 2. Alkali–Silica Reaction (ASR) gel extending from a crack in an aggregate particle

This gel is expansive when it absorbs water and can lead to significant damage in a concrete system over a period of years. Ideally, the risk can be mitigated by a number of actions, or a combination thereof as follows:

- Avoid use of reactive aggregates. This is not always possible when alternative aggregates are not available within a reasonable range.
- Keep the concrete dry. Again, this is often not possible because, even in the desert, ground water will tend to collect under slabs-on-grade elevating the relative humidity in the concrete above the levels needed to promote the reaction.
- Use appropriate dosages of supplementary cementitious materials (SCMs). This is a common approach, although it's contingent on knowing how much SCM is needed for a given aggregate.
- Include lithium-based admixtures in the concrete, converting the gel to a non-expansive form.

D-Cracking

Some calcareous aggregates possess a microstructure that promotes absorption of water into small pores, but the size of the pores is such that desorption is much slower. This results in the coarse aggregates remaining saturated during freezing, expanding and cracking (Figure 3), which leads to failure of the concrete.

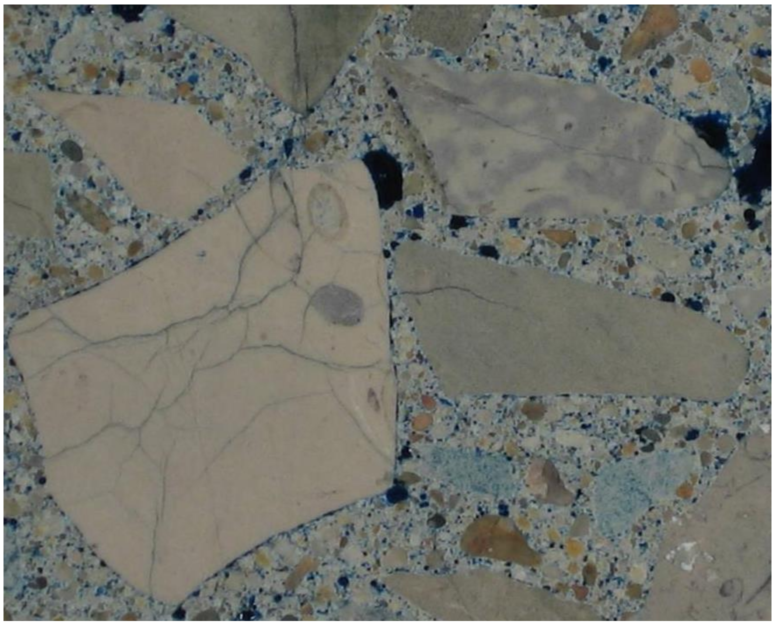
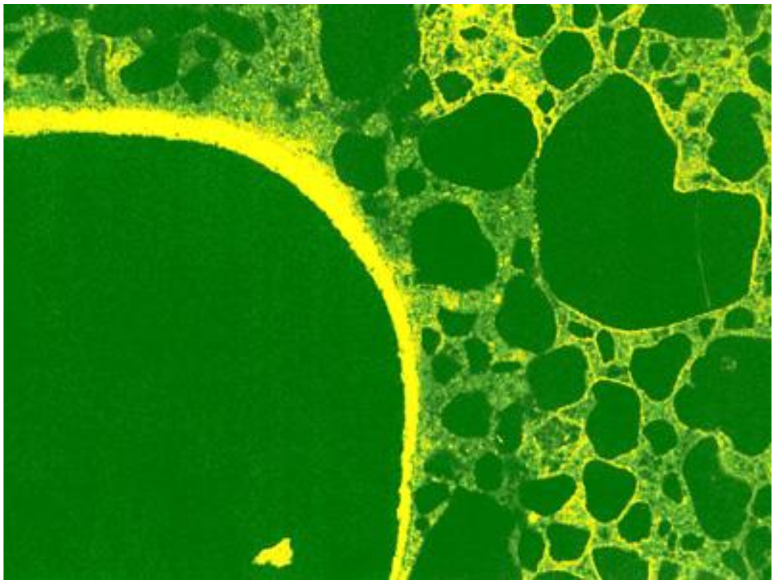


Figure 3. D-cracking aggregates in un-cracked paste

Prevention is achieved only by avoiding use of the aggregate or limiting the amount used in a given mixture (Taylor et al. 2006). Previous guidance included limiting the maximum size of the aggregate, but this may only delay cracking in the concrete rather than prevent it.

Delayed Ettringite Formation (DEF)

Another form of internal attack is known as internal sulfate attack (Detwiler and Taylor 2005). In this case, concrete that is cured at elevated temperatures (>70°C) causes normally-formed ettringite to decompose. At later ages and in the presence of abundant water, the ettringite re-forms, leading to expansion of the paste, and cracking in the concrete (Figure 4).



The (bright) gaps around the aggregate show where the paste has expanded

Figure 4. Transmitted light thin section concrete that has undergone DEF

Prevention is achieved primarily by ensuring that the concrete is kept below 70°C. If high temperatures due to heat of hydration are likely (mass concrete) or steam curing is planned, the chemistry of the cement should be monitored for C_3A, C_3S, Na_2O_{eq}, MgO, and fineness contents (Tracy et al. 2004).

Steel Corrosion

In this case. it is not the cementitious system that is expanding, but steel embedded within it. Iron can expand up to seven times its original volume when fully oxidized (Figure 5) (Detwiler and Taylor 2005).

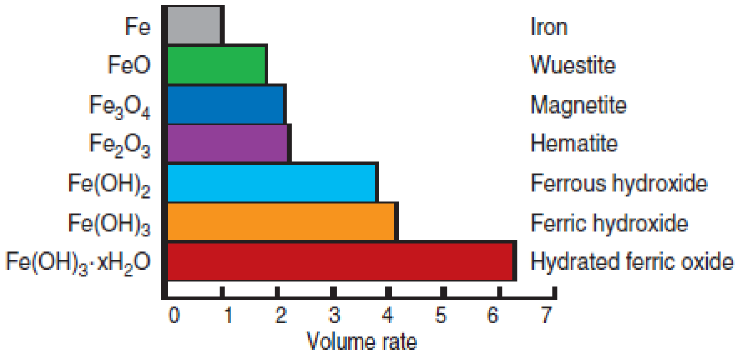


Figure 5. The volume of the corrosion products is greater than that of the original iron from which they form (adapted from Herholdt et al. 1979)

The high pH of the pore solution in concrete will normally develop a protective layer around steel, but, if the concrete pH is dropped due to carbonation or there are sufficient chlorides in the system, the corrosion will proceed. Prevention alternatives include the following:

- Keep the concrete dry, as discussed above
- Prevent the ingress of chlorides and/or CO_2, either by ensuring a lower permeability mixture or coating the concrete with a topical sealant
- Coat the steel with protective layers such as epoxy coatings
- Add corrosion inhibiting admixtures to the mixture

Cold Weather

Concrete that is exposed to freezing weather faces an additional set of aggressive mechanisms.

Freeze Thaw Cycling in the Paste

Saturated concrete that is frozen undergoes damage regardless of the air content. This is because water is attracted to the freezing front and it expands as it freezes, and therefore sets up stresses greater than the strength of the paste. The damage is typically cyclic because, while saturation may be limited to a shallow depth, cracking at the surface will open up the system allowing further penetration of the water. Some deicing salts, such as magnesium chloride, will attract water from the atmosphere, increasing the saturation of the concrete and therefore increasing the risk of freeze-thaw damage.

Prevention is achieved by entraining small air bubbles close together that provide a place for expanding water to move into. Improving impermeability of the paste to limit the rate of water ingress is also beneficial.

Salt Crystallization

A mechanism associated with, but not limited to, cold weather is that of salt crystallization within the pore system (Figure 6).

Figure 6. Salt deposits inside a crack

If a salt solution penetrates the microstructure, and then the water is removed either by freezing or by evaporation, the remaining salts may crystalize out and expand depending on the chemistry of the salt. Damage may also be due to osmotic pressures set up by differential salt concentrations between the pore solution at and remote from the freezing front. Surface scaling is also reportedly due to differential movements in the surface ice and the concrete at the surface causing shallow cracking (Valenza and Scherer 2005).

Salt crystallization is also the basis of wicking, where a partially-immersed concrete element may exhibit damage above the surface of the water because salt solutions are absorbed below the fluid surface, transported up by capillary action, evaporating out above the fluid surface leaving salts behind (Figure 7).

Figure 7. Salts wicked up a partially-immersed sample

Like freezing and thawing, damage is reduced by entraining air and by reducing permeability.

Chemical Attack

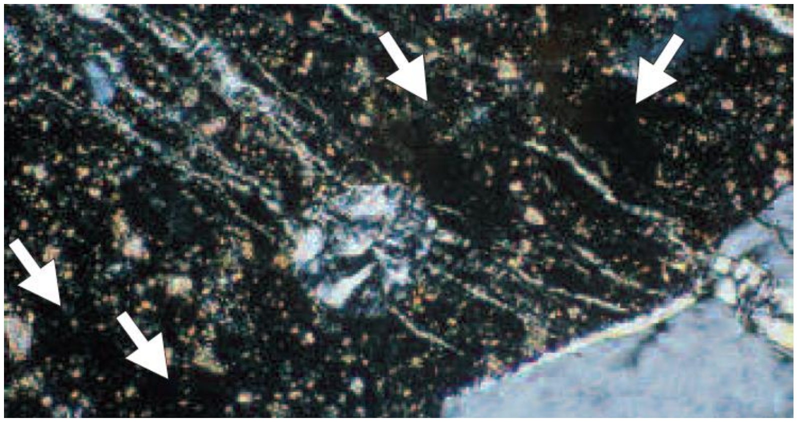
Chemical attack of concrete is limited to a relatively small set of reactive materials.

Soft Water/Acid

A large proportion of hydrated cement paste is calcium; therefore, fluids that dissolve calcium readily such as acids and soft water will attack concrete surfaces. This is normally limited to etching, but samples immersed in a river of almost pure water have been known to fully disintegrate. Protection is enhanced by reducing permeability; but, in severe cases, a high-build coating will be required.

Sulfates

External sulfate attack comprises sulfates in solution reacting with C_3A and C_3A hydration products, forming expansive compounds and decomposing the cement paste (Figure 8) (Detwiler and Taylor 2005). This may be a significant issue for slabs in contact with sulfate-rich soils.



Dark areas (pointed out by arrows) indicate where calcium hydroxide has either been leached out or dissolved to provide calcium for the formation of ettringite in cracks and air voids

Figure 8. Micrograph of concrete subject to sulfate attack

Mitigation is conventionally in the form of reducing permeability of the concrete using low C_3A cements and/or including low-calcium fly ash in the mixture.

Salts

While salts penetrating concrete may be responsible for scaling due to crystallization, they may also promote some chemical-based degradation. Salts in contact with concrete are most commonly present because of the need to reduce ice build-up on pavements, bridge decks, and sidewalks. Such salts are most commonly chloride-based products, including $CaCl_2$ and $MgCl_2$.

These compounds can react with the components of a mixture to form secondary ettringite, Friedel's salt (Figure 9), or calcium oxychloride, any of which may lead to distress within the system.

Measures that limit the ability of these compounds to penetrate the system will reduce the rate of damage accumulation. Potassium acetate has also been demonstrated to cause distress in high concentrations.

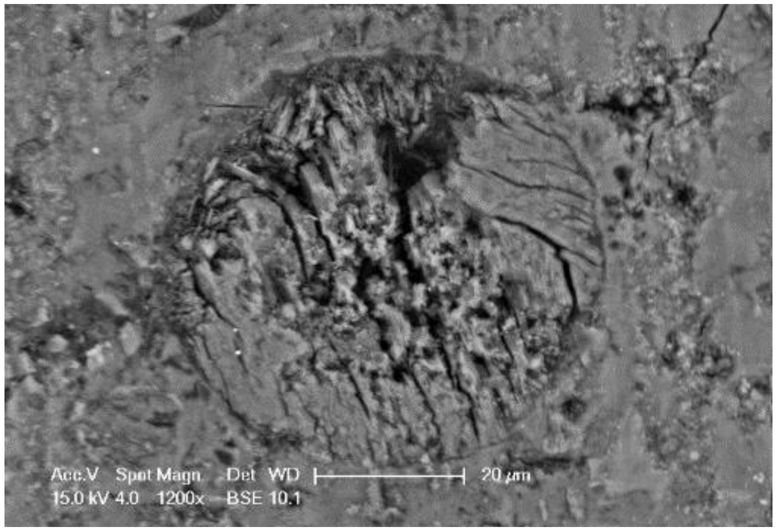


Figure 9. Friedel's salt deposited in an air void (Sutter 2012)

Cracking

Cracking is a common symptom of distress in a concrete system and is the result of changes in volume that are restrained, either externally or internally (Figure 10).

Figure 10. Cracks in a pavement, likely a combination of plastic shrinkage and settlement effects over dowels

Changes in volume can be a result of growth of components or deposits in the matrix, such as alkali silica reaction, or due to thermal and moisture changes. Cracking has the added effect of exposing additional surfaces to the environment, thereby accelerating the reactions causing the distress. Crack prevention requires a range of activities:

- Reduce the drying shrinkage of the mixture, by minimizing paste content (within reason)
- Reduce thermal effects by choosing an aggregate with low coefficient of thermal expansion (CTE)
- Reduce permeability to slow or prevent chemical related mechanisms (must be balanced with the associated changes in shrinkage)
- Cure the system well to maximize hydration
- Control applied loads (as discussed below)

Overload and Fatigue

Any structural material that is overloaded will likely fail. Likewise, many materials that are repeatedly loaded to a significant proportion of their yield stress (or fatigued) will accumulate damage, eventually leading to failure. This is normally controlled by the structural design ensuring that loads imposed are lower than strength, and by ensuring that the support system is adequate. Curling and warping will tend to lead to increased stresses because the slab is effectively unsupported at the edges (Figure 11).

Figure 11. A corner crack likely due to loss of support due to curling

Fatigue is the growth of damage or cracking due to cyclic loading. Typically, any load that is greater than about 50% of the ultimate strength of the material will induce microcracking that can develop with each cycle, eventually coalescing to form a macro crack and eventually failure. This is typically controlled in pavements by designing to keep stresses low enough that sufficient fatigue cycles can be carried over the life of the pavement, particularly at edges and corners.

Typically, a mixture that is resistant to a severe environment will often exhibit greater strengths than required for structural purposes. Other than noting that strength is a poor analog of potential durability, this topic is not discussed further in this document.

WHAT DO WE MEASURE NOW?

The common factor in all of the mechanisms discussed above is water, which either acts as a transport medium for aggressive species or is involved directly in the distress mechanism. In all cases, actions to reduce the transport of fluids through the concrete will reduce the risk or rate of damage. This is why so much attention in the past has focused on permeability measurement as a means of assessing potential durability of concrete. In addition, for the individual mechanisms listed above, the following are the current approaches to estimating the acceptability of a given material or mixture.

Permeability

Permeability is the propensity of a semi-porous material to allow fluids to be transported through it. As such, a low permeability concrete will be at lower risk of all forms of environmental deterioration because the amount of water penetrating the surface is reduced.

The difficulties in measuring this property in concrete include the following:

- It changes with continued hydration of the system over time. Slow hydrating systems, such as those containing fly ash, may show high values at even up to 56 days, but very low values at one year. Such delays mean that meaningful measurement in a quality management system is difficult.
- It is strongly influenced by the moisture state of the sample, which in turn is difficult to measure. Accelerated drying techniques will tend to damage the sample by causing internal cracking and therefore skew results toward a false poor result.
- The permeability of a given system will vary with depth from the surface, because of the effects of curing on hydration and drying on micro-cracking. Therefore, there will be a difference in results if measurements are taken at the surface or from below the surface of field samples. The surface may represent the actual condition but will vary significantly, while sub-surface testing will indicate potential for the mixture but does not represent effects of curing and exposure.
- Similarly, field surfaces, samples made in the field but stored and tested in a laboratory, or laboratory-prepared and -tested samples may all provide significantly different data.
- Reasonably-rapid tests of water permeability involve imposition of significant pressures that are unlikely to be experienced by the concrete, except perhaps in a tall water-retaining structure. Sorption tests are representative of the likely exposure, but are prone to significant scatter. Gas permeability tests are also considered.

European practice is to use the Torrent device that can be used reportedly in the field (Figure 12) (Romer 2005).

Figure 12. Torrent test cell (Proceq)

The Torrent device is comprised of an outer vacuum chamber that isolates the inner test area from the environment and helps to grip the equipment to the surface. The device measures water movement under pressure.

An alternative approach to direct measurement of permeability is to investigate an analog such as the electrical conductivity. This has some logical basis because ionic charge is far faster in fluids in the pore system than in the solids of the hydrated cement paste. The classic approach to this is the so-called rapid chloride penetrability test (ASTM C 1202) that measures current transmitted across a sample under a 60V DC potential. This test has been popular for some time despite its limitations and poor repeatability.

Alternatives have been proposed including a resistivity approach (Streicher and Alexander 1995, Scali et al. 1987, ASTM C 1760). A device finding growing acceptance is the so-called Wenner probe that measures resistivity between four probes a known distance apart (Figure 13) (Rupnow and Icenogle 2011). This test is rapid and operator insensitive, making it desirable for regular evaluation and is being balloted at ASTM at the time of writing.

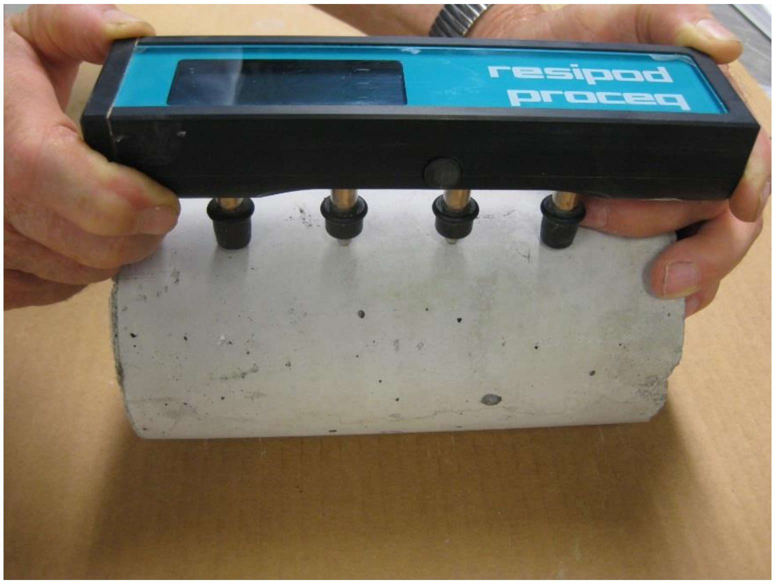


Figure 13. Resistivity measurement device

Another method being considered at ASTM is to monitor rates of desorption of a saturated sample (Baroghel-Bouny et al. 2007). The test will take at least five weeks to conduct, depending on how quickly samples can be saturated by immersion.

All of these approaches are sensitive to the degree of hydration and moisture state of the sample, which are difficult to control or measure. Electrical approaches can also be skewed by mixtures containing ionic compounds such as shrinkage-reducing admixtures or corrosion inhibitors, reporting poorer potential performance than is valid.

A thorough review of test methods has been reported by Castro et.al. (2010). No test has been accepted generally because of the limitations discussed above.

Alkali Aggregate Reactivity

Two sets of evaluations are required with the first to assess the reactivity of a given aggregate and the other to determine the risk of deleterious expansion in a given mixture with or without mitigation efforts such as inclusion of fly ash.

Based on work funded by the Federal Highway Administration (FHWA) (Thomas et al. 2008), the American Association of State Highway and Transportation Officials (AASHTO) has published a protocol that addresses testing needs for alkali-aggregate reactivity (AAR) risk evaluation (AASHTO PP 65-11).

Aggregate reactivity is assessed by the following:

- Field performance history
- Petrographic assessment
- Chemical composition for carbonates
- Accelerated tests:
  - Mortar bar (ASTM C 1260)
  - Concrete prism (ASTM C 1293)

Preventive measures are assessed by the following:

- Laboratory testing
  - Accelerated mortar bar (ASTM C 1567)
  - Concrete prism (ASTM C 1293)
- Consideration of the following:
  - Reactivity of the aggregate
  - Type and size of structure
  - Exposure conditions
  - Composition of cementitious materials

This approach is a compromise between the need to obtain reliable data and to obtain data quickly. The biggest issue with the mortar bar and concrete prism tests is that the latter is the more reliable approach, but it takes two years to complete, which is difficult to accommodate in traditional contractual processes. The most reliable approach is to expose large blocks, but that takes even longer to conduct.

D-Cracking

Testing for the risk of D-cracking is normally based on some combination of the following:

- Past performance in the field
- Laboratory freeze-thaw tests of concrete specimens (ASTM C 1646 with ASTM C 666)
- Rapid pressure release method (Janssen and Snyder 1994)
- Iowa pore index test (Marks and Dubberke 1982)
- Mercury intrusion porosimetry to measure the capillary pore system more precisely

Some specifications may refer to the sodium sulfate or magnesium sulfate test, ASTM C 88/AASHTO T 104, but this test is sometimes misleading due at least in part to the fact that the mechanisms of attack are not the same as in freezing and thawing.

Freeze-Thaw

The traditional approach to assessing freeze-thaw durability is the ASTM C 666 test, which involves rapid freezing and thawing of samples of concrete in water and observing the damage incurred in the sample over 300 cycles (Figure 14).

Figure 14. Damage in a beam after an ASTM C 666 test

Concretes performing well in this test reportedly perform well in field applications, but concretes failing the test may still have satisfactory field performance. Acceptance limits vary by agency.

Scaling

Resistance to salt scaling is determined using the ASTM C 672 test. Specimens are flooded with salt solution and cycled from freezing for 16 to 18 hours to laboratory air for 6 to 8 hours for 50 cycles. The condition of the surface is rated visually. This test is considered to be severe, with concretes performing satisfactorily in the field despite failing the ASTM C 672 test.

Another test is being prepared to submit to ASTM (Hooton and Vassilev 2012) based on the Bureau De Normalisation du Québec approach that reportedly shows a better correlation with field performance. This method requires slightly different finishing and curing requirements for the samples.

Sulfates

There are no tests to evaluate the ability of a mixture to resist sulfate attack. Current specifications are based on evaluating the cementitious system in pastes and mortars rather than the concrete.

Chemical Attack

There are no standardized approaches to evaluating resistance to chemical, acid, or soft water attack.

Shrinkage

Drying shrinkage of beams is normally tested in accordance with the requirements of ASTM C 157. However, the standard test requires that samples be moist-cured for 28 days, then dried for 64 weeks, making it impractical for acceptance purposes. Many agencies call for variations of the method in which the soaking and drying periods are adjusted, along with when initial readings are taken.

Care must be taken to be explicit about reporting and accommodating these changes when comparing data from different sources. Another factor that limits the usefulness of this test is that initial readings are taken at or after the first 24 hours, while chemical shrinkage is likely to occur before this time, meaning that a significant contributor to total volumetric change is not being assessed. The delicate handling of the beams and the equipment also makes it difficult to conduct the test in a field setting.

An alternative approach is to use the so-called ring test, in which a ring of concrete is cast around a steel cylinder (Figure 15) (ASTM C 1581).

Figure 15. A ring shrinkage specimen

The steel is instrumented with strain gauges to monitor stresses induced by the shrinking concrete and to signal when cracking occurs. Readings can be taken as soon as the sample is cast, allowing collection of data that are not available in the C157 test.

The outer form can be removed as soon as the concrete is set, and selected surfaces of the concrete can be sealed to control the direction of drying.

CHALLENGES TO EFFECTIVE MEASUREMENT

While the list of distress mechanisms outlined above is relatively short, the reactions are complex and slow, making measurement and prediction of failure difficult. Some of the challenges to effective measurement are discussed in this section, explaining why test methods have not been adopted yet.

Concrete is Not Uniform

Ingredients in a concrete mixture vary in size from about 25 mm (1 inch) down to about 10 nm (Figure 16).

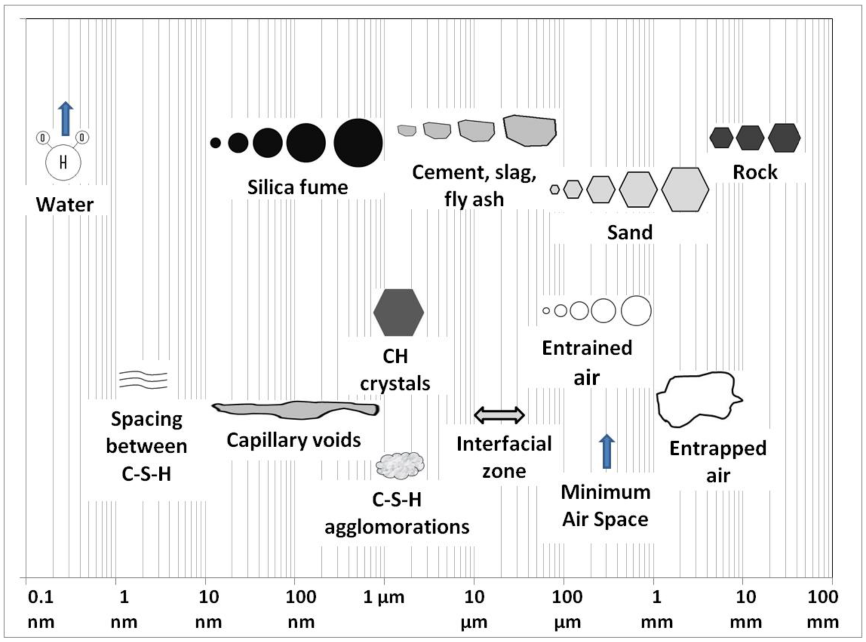


Figure 16. The range of particle sizes in concrete

In addition, the hydrated cement paste is non-uniform and unique formations can be observed down to the nanometer scale. The system may therefore be considered a heterogeneous mixture of greatly varying materials at all scales, requiring that samples or probes need to take into account the local variability inherent in the system.

Further complicating this situation is that responses to the environment, such as curing, will further increase non-uniformity. This has been observed at sawn joints where moisture may penetrate a few mm from the saw face, thus increasing saturation at a local scale, and increasing risk of frost related deterioration. Measurement systems therefore need to be appropriate to the layer/scale being assessed.

Most permeability-type tests use samples prepared from below the surface of the concrete, primarily to reduce the variability induced by surface drying. This does not necessarily represent the concrete that is exposed to the weather. Likewise, the common approach available at present to assess saturation is to dry, then saturate, a core and record changes in weights. This may not be sufficient to assess saturation at 5 mm from a concrete face.

On a macro scale, concrete will also vary from batch to batch because of variations in stockpile moisture, chemistry of the ingredients, and operating temperatures, among other factors. This is normally addressed by frequent testing aimed at observing and compensating for such variations. At present, it is often an operator with an experienced eye who is the first to note that something about a mixture has changed.

Reactions are Slow

Several of the mechanisms that lead to distress in concrete involve slow chemical reactions that may take several years to exhibit. Conducting tests to determine acceptability of materials or mixtures therefore requires that the mechanisms be accelerated. The common methods of accelerating deterioration are either to heat the system or to increase concentrations of critical reagents.

The negative to this approach is that, by changing reaction rates, the nature of the reactions may also change, potentially leading to invalid findings. This is typically exhibited in the ASTM C 1260 mortar bar test to assess alkali-silica reactivity (ASR) risk. The test duration is shortened from two years of the ASTM C 1293 concrete prism to two weeks, but reports are indicating that the test correlates with slower tests a fraction of the time (Thomas et al. 2007) (Figure 17).

The error goes both ways, meaning that, in some cases, a false positive result is reported, and, in other cases, a false negative result. This means that the test cannot be used conservatively in practice for unknown materials.

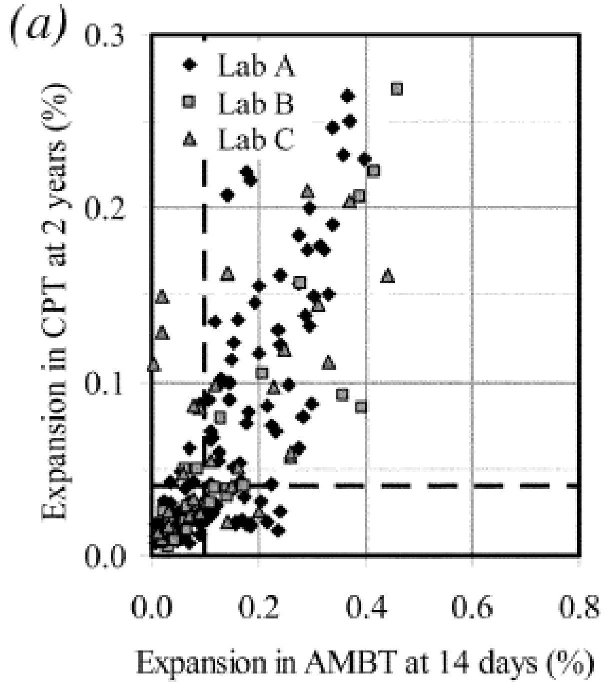


Figure 17. Data illustrating relative performance of mortar bar (AMBT) and concrete prism (CPT) tests

The alternative to running a failure mechanism to completion is to observe initial rates of reaction and to extrapolate the trends out to the desired lifetime. The risk inherent in this approach is that small errors in testing or inherent variability in the test may have significant impacts on the predicted life of the system. In short, predicting condition at 40 years based on a 7 or 28 day test may not be reliable, especially in systems where the rates of reaction change over time.

In general, there is very little information that correlates long-term field performance with the tests currently, except, perhaps, for ASR, which has been the focus of intensive study for a long period of time. Efforts to develop such a correlation by investigating existing pavements or structures are often hampered by insufficient records of materials, practices, and conditions at the time of construction, or that the records are destroyed after 5 to 10 years.

An alternative is to consider the nature of the materials, such as their chemical composition or porosity, to assess their risk of deterioration. This is the approach in investigating D-cracking where the porosity of the aggregate seems to provide a means of assessing risk of failure.

Concrete Changes Over Time

Hydration of concrete is initially rapid, but slows over time. The reaction, while slow, is still continuing enough to keep changing properties such as permeability for months or years after initial mixing. This is especially marked in mixtures containing supplementary cementitious materials (SCMs), where permeability continues to drop significantly through 365 days and beyond. This fact further complicates prediction of long-term performance based on very short-term testing, because the rates of change are sensitive to changes in system chemistry, dosages, and curing.

Current practice is to try to measure permeability at 56 or 90 days in systems containing SCMs, but this is practically problematic for acceptance because removing concrete placed several months ago will have significant impacts on any construction site, if indeed, the contractor is still there.

The other complicating part of evaluating concrete in the field is that it always cracks, and the crack spacing and width will significantly impact the ability of fluids to penetrate the system. A mixture that appears wonderful in the laboratory, may exhibit a high risk of cracking in the field, thus negating the benefits.

Finally, all tests currently available to assess permeability are extremely sensitive to the moisture state of the sample. In the lab, it is relatively easy, but slow, to bring a small sample to a known state of moisture, but this is impossible in the field, which, combined with the inability to measure the degree of saturation in the field, makes calibration of field tests a significant hurdle. Compounding this situation is that concrete in the field may exhibit large local variations in the moisture state (Figure 18).

Figure 18. Illustration of local differences in moisture state in a single slab

The Environment is Not Constant

The point here is to emphasize that real concrete is never exposed to a constant laboratory environment. Not only does the moisture and temperature change daily and annually but, as noted above, there are localized variations caused by wind exposure, shading from the sun, and local drainage. For example, with sawn joints in pavements and slabs on grade, the concrete immediately adjacent to the joint may experience far more severe exposure than the rest of the slab due to water and salt solutions trapped in the joint. All of these variations make modeling and prediction complex.

Workmanship Issues

The other factor that makes life prediction challenging for concrete is that it is fabricated outside a factory. This means there are added layers of variability introduced by inconsistencies in weighing, mixing, placing, consolidating, finishing, and curing practices from batch to batch.

Transfer of responsibility and risk between batch plant operator, contractor, and owner may make it necessary to know the quality of the system at each of these handover points.

Testing

A number of other factors influence the acceptability or practicality of test approaches.

Cost

A significant barrier to more meaningful testing of concrete is that of cost. Many tests tend to require expensive equipment, trained operators, and careful storage of samples. If a significant amount of concrete is to be evaluated on delivery, testing costs can escalate rapidly. On the other hand, failure is expensive, thereby justifying the expense of effective testing. Any consideration of effective testing must include a review of the costs compared with the potential benefits thereof.

Reliability

The precision of the test methods must also be considered. All tests are prone to some variation due to factors such as different operators, environment, variability in the instruments, or influences that cannot be controlled.

In some cases, the inherent variability may be large, such as the ASTM C 1202 chloride penetration test in which the acceptable variation between tests of the same sample by two operators is 46%. This means there is a high probability that good concrete will be rejected or bad concrete accepted. Such tests can be used only to monitor trends, unless a statistical approach is used when using them for acceptance purposes.

Speed and Timing

Ideally, a test should be complete before concrete is discharged from a truck because, unless the performance is catastrophically poor, it is unlikely to be removed. This in turn is influenced by variability through the volume of a truck, but ASTM C 172 requires that samples be taken only from the middle of the load as it is discharged from a rotary drum truck or from five locations from a dump truck after discharge.

The other factor is the time it takes for a test to be completed. An example is the air-void-analyzer; while considerably faster than a C457 Microscopic test, it still takes about 30 minutes to run, by which time the concrete has been placed, leveled, and possibly finished.

It may be that a poor result can be accepted in a limited number of deliveries, as long as there is a change in processing at the batch plant, but the faster a result is obtained, the more beneficial the testing will be.

Impact on the Finished Product

A barrier to conducting tests behind a paver is that many of the tests require extracting at least a cubic foot of concrete, which ruins the surface of the pavement to the dismay of the contractor and owner alike (Figure 19).

Figure 19. Concrete surface after a sample has been removed from behind the paver

On the other hand, tests conducted on samples taken in front of the paver do not take into account the effects of the paving operation. Consideration may be given to occasional testing before and after the machine to calibrate changes, followed by regular testing in front, such as is recommended for air content testing. An alternative approach may be calibration of changes in a test strip built before construction starts.

What Do We Want to Measure?

Having discussed the barriers to effective testing, this section discusses some answers to the questions raised.

One approach may be to move away from in-line testing. The philosophy behind this approach would be to investigate thoroughly the properties of a series of mixtures in the laboratory to find the system that meets the needs of the project, including strength gain and potential durability. Once a mixture has been selected, the sensitivity of the required performance parameters should be assessed against the likely variability to be observed on site due to changes in materials properties and proportions (Bickley et al. 2006).

The final testing required on site, then, is to prove that the mixture delivered is within the limits already determined. This may be limited to verifying the types and proportions of the ingredients in the mixture along with workability and air content that do vary significantly from batch to batch. While this may increase the cost of preconstruction testing, the costs of "as received" testing should be controlled while the probability that the system will survive should be increased.

A parallel to this is to consider the testing a purchaser conducts when taking delivery of a new vehicle. The purchaser may conduct extensive research to choose a vehicle that has the required power, seating, load capacity, and reliability. Having chosen the make and model, all that is decided at the dealership is the color and the accessories, while assuming that the critical parameters in the vehicle delivered are as advertised, backed up (one hopes) by factory quality systems. One significant difference when taking delivery of a pavement is that it is effectively impossible to return it and demand a new one if there are serious defects.

The other factor that is not well addressed by this approach is that, while it may improve/ensure quality of the mixture at the point delivery, it does not take into account the potential changes that may be imposed between delivery and final placement. This remains a challenge.

Parameters that may be evaluated either in the preconstruction stage and/or at delivery include the following.

Mixture Proportions

Before the model discussed above is to be useful, there is a need to be able to determine the mixture proportions of fresh concrete. The critical parameters would be cement and cementitious material contents, and water content.

Water content can be assessed using the AASHTO T 318 microwave test in which fresh concrete samples are dried in a microwave and the mass loss is determined. The test is sensitive to the moisture state of the aggregates at the time of batching, but can be useful in monitoring trends at a given batch plant.

Attempts have been made to use a portable x-ray fluorescence (XRF) device to measure cementitious materials content and was found to be reasonably accurate for paste, but the errors reported in mortars, let alone concretes, were unacceptable (Taylor et al. 2012). Consideration may also be given to spiking ingredients with tell-tale materials such as colored beads that can then be used to provide a quantitative measure of their dosage (Moss 2012).

Workability

Workability is a loosely defined term referring to the ease with which concrete can be handled, placed, and consolidated. The standard approach is to use the slump test, but many writers have indicated that this test is only beneficial as an indication of uniformity of a mixture between batches.

Fundamentally, three parameters are involved when considering workability:

- Yield Stress – This is the property evaluated by the slump test and is a measure of what it takes to get a mixture moving. Low yield stress is desirable for a structural concrete, so that forms can be filled, while high yield stress is preferred for slipform paving, because of concerns with edge slump.
- Viscosity – This is a measure of what it takes to keep a mixture moving, or to accelerate it. A typical example of a high-viscosity fluid is honey.
- Thixotropy – This is a measure of how the system reacts to applied energy and is observed typically in differences in the rising and falling curves of a rheology plot.

The last parameter is likely the most useful for slipform paving mixtures because it is desirable that a mixture is fluid when under vibration, but static when vibration is removed. At present, there are no good tests to assess this property for stiff mixtures, although work is underway to find approaches to plot flow against applied energy. Such a plot is likely to provide an effective means to characterize a mixture for its use in a given paving machine. Mix proportioning can then be conducted with the aim of hitting a desired curve.

One approach being investigated, at Oklahoma State University, is known as the box test, in which a mixture is placed in a wooden cubical form and vibrated for a fixed time. The form is then removed and the surface finish is evaluated in terms of honeycomb and edge slump (Figure 20) (Ley et al. 2012).

Figure 20. Box test sample after removing the forms

Other work, at Iowa State University, is looking at modifying the vibrating slope apparatus to overcome some of the limitations of the original test, or to attach a vibrator to a Kelley-ball.

Closely associated with workability is the occasional need to investigate how well a sample of concrete has been consolidated. Poor consolidation will result in a significant amount of entrapped air, leading to lower strengths and increased permeability. It is normally assumed that adequate vibration will lead to adequate consolidation, but there are occasions where disputes may arise on this point.

Nuclear approaches are available to report the density of concrete in situ (ASTM C 1040), but they are rarely used and pass-fail criteria do not appear in specifications. There may be value in developing a method to assess effectiveness of consolidation, based on density, or maximum bubble size, along with realistic acceptance criteria (Figure 21).

Figure 21. A core with large air voids (Is it sufficiently consolidated?)

Air Void System

Ideally, the air void system should be assessed after placement because the system is sensitive to a wide variety of workmanship-related factors.

To minimize damage to the pavement incurred in removing samples from behind the paver, it may be sufficient to calibrate the change in air content during processing for a given mixture/machine system, and then to conduct regular testing in front of the paver. At the same time, knowledge of the air void system delivered for a given air content is essential, along with a thorough understanding of the factors that will affect the system. Such factors will include the cementitious chemistry and composition, admixture type (both air-entraining admixture/AEA and water-reducing admixture/WRA), mixture temperature, sand gradation, and mixing energy.

There is a need for a quick and simple device that will indicate the structure of the air void system in fresh concrete. A device called the Super Air Meter (SAM) is being developed at Oklahoma State University that shows promise of being able to do this (Figure 22). Work is needed to validate its performance in the field.

Figure 22. Super Air Meter (SAM)

Alkali Reactivity

Aggregate and mixture reactivity need to be tested reliably and quickly and, at present, there is no test that can do both. AASHTO has published a protocol (AASHTO PP 65-11) that comprises the best approaches available at present.

Consideration may be given to assessing the permeability and mineralogy of the aggregates along with the chemistry of the pore solution in a given mixture, rather than depending on expansion-based tests (Olek et al. 2013). Such an approach is complex but still seems fundamentally sound if the details can be worked out.

Permeability

As already discussed, the tests used currently to assess permeability are either slow, extremely dependent on sample maturity and conditioning, and/or use indirect approaches such as conductivity.

Consideration may be given to using a falling head permeameter that uses water over a saturated sample, similar to the gas permeameters used to assess pre-dried samples. This approach is under investigation.

The resistivity approach is finding acceptance and is being standardized. Resources are needed to help in its implementation.

A caveat with this approach is that correlation between permeability and scaling resistance is poor (Hooton and Vassilev 2012).

Saturation

Despite the sensitivity of many test methods to the degree of saturation in a sample, there is no standard approach to measuring degree of saturation for concrete mixtures. Some work has been reported using electrical devices that monitor resistivity between fixed probes (Guthrie and Yaede 2013), while other devices that monitor capacitance are being developed.

It is likely that such devices will need to be calibrated for a given mixture, but they will make it easier to assess in situ the permeability of a given sample at a given location. This will facilitate assessment of the effects of construction practices on the quality of the slab in place.

These devices also have the potential to be buried in slabs and can also be used to report saturation at selected locations, such as near saw-cuts. In such an application, these devices may provide a means for early warning that future damage is possible as moisture content reaches critical levels (Li et al. 2012), thereby allowing remedial action to be taken early.

WHAT DO WE NEED?

The discussion so far has listed the difficulties and challenges that have prevented development of more effective test methods and, thus, performance-based specifications for long-lasting pavements. By structuring this discussion, it is hoped that we can now start addressing the needs with the greatest probability of success and through a logical process.

To reiterate, the needs include the following:

- Tests that measure the critical parameters
  - Permeability (gas, conductivity, etc.) – This need is being addressed in work under TPF 5(179)
  - Workability – This need is being addressed in work under TPF 5(205)
  - Air void system
  - Mixture proportions in fresh concrete
  - Saturation (locally)
  - Cracking resistance
  - Consolidation
- Calibration of tests with lifetime
  - Permeability with regard to freeze-thaw cycles, scaling, corrosion over time
  - Saturation over time under exterior conditions
  - Effects of salts on cracking and frost resistance
- Modeling of the effects of mixture ingredients and proportions on critical performance parameters
  - How much can we err and still be OK?
  - Effect of sand gradation/properties on workability
- Understanding of effects of workmanship on lifetime
  - Water added to mixture
  - (Over) vibration
  - Finishing
  - Curing
- Innovative materials that contribute to durability, with reduced environmental impact
  - High SCM mixtures
  - Limestone cements
  - Non portland cements
  - Internal curing
  - Recycled concrete as aggregate
  - SCMs from alternative sources
- Specifications that use the tests effectively – either in enforcing sound quality control (QC) or in Acceptance procedures
- Education about all of the above – for everyone involved from executive to site laborer

WHAT'S THE PLAN?

The list of needs above is significant and, in many ways, unlikely to be fully met. It is therefore logical to put into place what we can immediately and to begin working on activities that have the highest priority.

Use What We Have

There are a number of technologies that are available for monitoring concrete that are not in everyday use, such as the resistivity test. The needs are as follows:

- Educate agencies and contractors about these technologies, how to use them, what they're for, and why they are important
- Conduct demonstrations at construction sites and conferences
- Develop model specification language
- Start collecting data to learn about variability and, in the long term, correlate these data with performance
- Establish a process to accelerate implementation of new technologies as they come available

Many of these tools are potentially effective for improving QC because they can be used to flag a change in the system. However, they may not provide a direct indication of what has changed or how serious it is. Such tools, or those with poor precision, may not be appropriate for Acceptance. Agencies may encourage use of such approaches, but enforcing their use, and enforcing changes in materials or processes, may be difficult contractually.

The largest challenge facing us, then, is finding or developing rugged methods that can be used for Acceptance purposes. Approaches that are available include the following.

Calorimetry

Simple semi-adiabatic calorimeters provide an effective means for uniformity of cementitious systems to be monitored and for potential incompatibility of the system to be caught early. If a sample of fly ash, cement, and water is mixed and placed into test as it is delivered to the batch plant, it is likely that changes to the system that will affect constructability may be observed within a few hours, allowing batches or placing practices to be modified. This can be a valuable QC tool.

Workability Based on Effort to Turn Drum

A systematic approach to monitoring the effort required to turn the mixing drum will also flag non-uniformity of mixtures from batch to batch. A protocol of remedial actions needs to be developed and implemented to ensure that water-cementitious material (w/cm) ratios are not exceeded, while uniformly-workable concrete is supplied in each load.

Microwave Test

The fundamental controlling factor that governs mixture performance is the w/cm. While a mixture design may call for a given w/cm, it is difficult to be sure that the mixture delivered has not been modified to maintain workability. While the AASHTO T 318 method is sensitive to aggregate moisture state, it can be used to monitor change between batches. It also has the benefit of being a tool by which the work can be monitored, and that every action is reported to help improve performance, independently of the reliability of the test method.

Unit Weight

Monitoring unit weight is another low-cost yet effective means to measure variability. Unit weight will flag excess water or large variations of air in the mixture. Used in combination with other test data, it can be at the heart of a QC plan.

Super Air Meter (SAM)

This device shows promise in reporting the critical parameters of the air void system in fresh concrete and, as such, should be evaluated for implementation in the field for Acceptance purposes.

Air Void System behind the Paver

The increased instability of the air void system means that it may not be sufficient to simply measure properties in front of the paver. It is recommended that periodic measurements be taken behind the paver to calibrate and account for changes occurring during processing.

P-Wave or Thermal Measurements for Setting Time and Saw-Cutting Window

It has been reported that calorimetric approaches are useful in predicting the saw-cutting window for the slab as it is placed (Whitaker 2012). This reduces the risk of late sawing (and therefore cracking), while reducing the costs of operators waiting to start their work. Work is underway to assess the usefulness of using an acoustic approach to achieving the same end (Taylor et al. 2013). Such devices can be used at the site and take into account the weather on that day for the mixture as delivered.

Resistivity

This methodology shows great promise with the caveats that sample moisture state and age can influence results. It is rapid and reasonably idiot-proof, making it among the best permeability assessment tools that we have at present and is in use for Acceptance in Florida and Louisiana. Correlation with long-term performance needs to be developed.

Sorption

Mechanistically, this is a rational approach, but it requires a long preparation process that takes time and, again, correlation with long-term performance is still to be developed. It is a good prequalification test because it is sensitive to mixture variability and curing (Ballim et al. 1994).

Record Keeping

Independent monitoring of batch records may be an effective means of finding a compromise to some of the issues discussed above. Commercial systems are available for ready-mix operations in which proportions, water addition, and workability are recorded by an external party. Such data can be monitored and incorporated into an effective QC and Acceptance plan.

Build Test Beds and Monitor

Work at the MnROAD test facility has gone a long way to improve understanding of foundation design and to evaluate innovative construction techniques. However, test cells tend to be replaced after about 10 years. There is a need to place slabs with detailed records, instrument them thoroughly, and watch them over the next decades to collect data to calibrate lifetime with the measurements available now and those developed in the future.

It is recommended that such beds be urban streets in regular use that carry real traffic, are exposed to the climate zones that we are interested in, and are treated with the de- and anti-icing salts selected by the city or jurisdiction in which they are built. Devices can be embedded to monitor chloride ingress, vertical displacements with changing seasons, stresses, and traffic counts, at a minimum.

Critical to this approach is to think longer term than the average four-year PhD horizon. The data must be maintained in such a manner that the next generation of researchers continuing our work in 20 or 30 years can use it to calibrate their models.

Data storage is inexpensive, but changing technologies may mean we need to translate it periodically (i.e., data on floppy disks may still exist, but there are no longer many disk readers around to access it).

Rethink the Specifications

Specifications need to be modified continually to embrace the current state of knowledge and technology. Coupled to this is a need to educate users as discussed above. A significant barrier is a fear of the unknown and a reluctance to take on risk, which can best be addressed by making the unknown known.

Consideration needs to be given to a suite of specifications that allow sophisticated suppliers to take on risk with adequate reward, without compromising quality.

Specifications should not be built around patches applied to past failures, because such approaches may lead to unintended consequences. Incentives should also be developed carefully to reward the things that are really needed.

Educate

The need for continuing education at all levels is enormous. Not only is the concrete pavement system complex and changing, the demands on the system are growing and the ability to absorb error is shrinking, while people are moving through the hierarchy of organizations. This means that expertise is being lost to retirement or promotion.

There is a need to institute and maintain an effective education program across all parties and at levels that provide continually-updated information on current best practices that are appropriate for each audience.

The availability of internet-based systems must be exploited to meet this need efficiently using web-based training, and electronic publications and applications that can be accessed from the field.

Develop New Tests

Work needs to continue in developing and proving tests that measure critical properties more effectively including the following:

- Workability (including thixotropy)
- Air void system in fresh concrete
- Permeability
- Alkali silica reactivity and D-cracking risk
- Moisture content in situ
- Consolidation

As discussed above, such tests need to be rapid, repeatable, cost effective, and correlated with long-term performance.

Develop and Evaluate Materials

While portland cement is still the most cost-effective material available today, there are a number of researchers investigating alternative cementitious materials. The key factor to their acceptance is going to be the ability to evaluate them for their long-term performance, and at the point of delivery. Tests that are built around the chemistry of portland cement, may not be relevant or appropriate for other cementitious systems.

Likewise, sources of good aggregates may be limited or decreasing in some locations, encouraging the use of alternative materials such as recycled concrete.

Next Steps

The current state of knowledge and immediate needs are summarized in Table 1.

Table 1. Summary of tests required and future actions

	Hardened Properties (Acceptance)						
	Frost resistance	**Salt resistance**	**Permeability**	**ASR**	**D-Crack**	**Shrinkage**	**Strength**
Tests now	C 666	C 672 BNQ	Resistivity RCPT Sorption Gas perm	Mortar bar Concrete prism Block	IA Pore Chemistry Pressure release C 1646	Bar Ring	Cylinder Beam
Tests needed	Saturation	??	Water perm	??	??	??	NDT
Next	Test	Implement	Implement	Test	Test	??	??

	Fresh Properties (QC)			
	Workability	**Setting**	**Segregation**	**Density**
Tests now	Slump Rheology	Penetration UPV Calorimetry	None	Unit weight
Tests needed	Thixotropy	-	??	Consolidation
Next	Test	Implement	Test	Test

	Proportions (Both)			
	w/cm	**AVS**	**SCM**	**Admixtures**
Tests now	Microwave Petro	Air pot AVA	Petro / XRF	FTIR
Tests needed	???	SAM ???	???	???
Next	Test	Implement	Test	Test

The following program of work is suggested to start meeting the needs described above.

Tasks

- Implementation

  Implementation of current knowledge is best achieved by proving to practitioners that such changes are cost effective, sustainable, and with acceptable risk. Traditionally, such actions take more than 10 years, but recent experience with the following process has shown promise in shortening the lead time:

- *Demonstrations*, either in the form of pilot projects built or field-based workshops where equipment can be used. Regional meetings that allow neighbors to learn from each other are particularly effective.
- *A loan program* that allows agencies to borrow and assess equipment before committing the capital to purchase it. Such a program exists through the FHWA.
- *Training* is needed at all levels, from convincing managers that the cost-benefit ratio is acceptable, through practitioners and specifiers to adapt contracts and practices, to field staff who must do and use the new systems. Training is most effective in face-to-face sessions so that questions and concerns can be raised and experiences shared, not only by the trainer but by members in attendance. Web-based and training-on-demand resources can be used if travel costs are prohibitive.
- *Guidance documents* are essential as references so that users can refresh and augment their learning as they gain experience or encounter difficulties. Documents must be available in printed form as well as electronically to address the needs of different generations. Such documents must be aimed at the level of the reader to make best use of their time.

- Guide Specifications

  Guide specifications that can be used by agencies as they begin to accept and adopt innovative methods and materials are required. Such specifications should be consistent with the overall goals of the agency, so that unintended consequences are avoided. As such, these specifications need to be reviewed annually by a group comprised of state, supplier, contractor, consultant, and academic communities. An initial document has been prepared by the National Concrete Pavement Technology (CP Tech) Center.

- Test Methods

  The task of developing good test methods is complex and needs to be taken on with collaboration between researchers and practitioners, not only to prioritize the needs, but also to review the outcomes. Fundamental to this task is sufficient funding as discussed below.

- Test Beds

  Calibration of test data with long-term performance requires installation and monitoring of test locations. A plan is needed to understand the scope of a successful effort, select appropriate locations, find qualified researchers, and collect and store data.

Funding

The needs discussed in this synthesis cannot be addressed in a single project. It is suggested that a program be set up to help set priorities and coordinate funding sources including the following:

- Federal agencies (U.S. Department of Transportation, Department of Energy, Department of Defense) and, Second Strategic Highway Research Program
- State Agencies, Transportation Pooled Fund Program, National Cooperative Highway Research Program
- Materials manufacturers, associations, and suppliers
- Paving industry

The Concrete Pavement (CP) Road Map is a good start for this need, but it needs to be enhanced with a focused effort looking at the topics addressed in this synthesis. The National Concrete Consortium is in a good position to provide much of the guidance needed. Means are needed to leverage the funding that is available and to ensure the most effective tasks are addressed first.

CLOSING

The challenges are large, yet the opportunities are larger. The need for long-lasting pavement systems is growing as budgets decrease, traffic increases, and sustainability becomes more important. Increasing complexity of concrete mixtures and the demands being placed on them means that "business as usual" is no longer acceptable.

On the other hand, the resources available are also growing significantly, particularly computing power, data storage, and communications tools, meaning that tasks that were difficult a generation ago can now be tackled.

Let's get going.

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