Summary of Thirty Years of TxDOT-Funded Research on Coarse Aggregate Issues in Concrete Paving

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ABSTRACT

This paper summarizes a number of research projects funded by the Texas Department of Transportation (TxDOT) on aggregate-related issues in concrete paving within the past 30 years. The main focus of this paper is on coarse aggregates, which normally occupy more volume than other ingredients in concrete. Research on aggregates in Texas can be traced back to 1928, but in the past 30 years, aggregate research funded by TxDOT has focused mainly on the effects coarse aggregates have on the performance of continuously reinforced concrete pavement (CRCP). In the past 10 years, research on aggregate-related durability issues has also been a focal area. Visual condition survey data have been collected since 1974 on rigid pavements across Texas. A 1978 summary report on field surveys showed significant performance variations between pavements constructed with different aggregates, especially between crushed limestone and siliceous river gravel. From 1986 to 1995, an extensive research program was devoted to establishing a design tool and studying the effects of coarse aggregates on concrete paving. A total of 13 reports were produced. The cracking issue of concrete pavement appears to have been adequately addressed. However, the spalling of CRCP remains a challenge for TxDOT. Several research projects have recently been completed or are underway to address spalling distress in CRCP, including crushed gravel and optimized aggregate gradation. Major findings from these TxDOT-funded research projects and future challenges are summarized.

Key words: coarse aggregate—cracking—CRCP—spalling
INTRODUCTION

Texas is a big state with a lot of concrete pavement. In the year of 2006, Texas had about 9,400 lane miles of continuously reinforced concrete pavement (CRCP) and about 4,100 lane miles of jointed concrete pavement (JCP). With the population booming in Texas, urban areas are expanding quickly. More and more Texas Department of Transportation (TxDOT) districts are specifying the building of concrete pavements, mostly CRCP, to encounter the public’s demand for a safe, economic, and smooth transportation system in urban areas. CRCP is known for its long service life and relatively low maintenance. In Texas, CRC pavement is expected to serve the public for about 30 to 50 years with minimum maintenance interruptions. To meet this goal, it is important for TxDOT to construct good concrete pavement that will last the expected service life.

Many factors are known to influence the behavior of CRC pavement, including pavement thickness, concrete properties, construction practice, environmental variables, and traffic loads. Among these factors, pavement thickness is normally governed by established thickness design procedures. Environmental variables, e.g., humidity and temperature fluctuations, and traffic loads are not controllable. As such, it is perceived that better concrete pavement can be produced if we understand the effects of concrete properties and construction practice on the short-term and long-term behaviors of CRC pavement. Over the years, TxDOT has funded research projects to obtain knowledge of concrete materials and to put the knowledge into practice. It is necessary to review the research performed for TxDOT to determine the future research needs. This paper is the natural product of the need to periodically review and assess current conditions.

Aggregates, occupying 70% to 80% volume of concrete material, is the focus of this paper. The importance of aggregate to the properties of concrete has long been recognized by university researchers and the state highway agency in Texas. As early as 1921, the State Highway Department of Texas (now TxDOT) was involved in concrete aggregate research by furnishing a truck to researchers and paying the freight on samples shipped to the laboratory (Thomas and Parkinson 1928). At that time, concrete technology was still in its infancy. It is not surprising to learn that concrete was mixed by hand and the water-cement ratio was changed to make workable concrete. The researchers found that wear was not correlated to compressive strength of concrete. In addition, they learned that using a larger aggregate size resulted in less wear. Although these conclusions may be quite obvious to us today, the efforts of early research laid a solid foundation of the path, on which we are still traveling, to long-lasting concrete pavements.

RESEARCH EVOLUTION

Like any human effort to understand a natural phenomenon or myth, research supported by TxDOT struggles but yet pushes forward with unyielding endeavors to provide a better concrete pavement system to the public. Although mistakes are unavoidable, researchers are slowly but surely unveiling the ways that concrete properties and construction practices affect CRC pavement performance. During the past 30 years, TxDOT provided full support to concrete aggregate researchers at Texas public universities, as clearly shown in Figure 1. Please note that not all related research projects are listed. For instance, research projects addressing the durability issue of aggregates, e.g., alkali-silica reaction, are not included because this paper concentrates on aggregate specifically in paving concrete. The research embraced laboratory studies and field tests. The importance of test sections for concrete pavement was emphasized throughout all the research projects, and more than ten field test locations around Houston area were included. The total funding for research activities on aggregate in paving concrete is well over five million dollars.
Figure 1. Historical development of research projects related to aggregate in paving concrete

CRC pavement was first placed on Texas highways in the 1950s, primarily in conjunction with the interstate highway program (Hankins, Suh, and McCullough 1991). The Center for Transportation Research (CTR) of the University of Texas at Austin (UT Austin) performed field surveys on ten districts in 1974 and four urban districts in 1976 for TxDOT. Again in 1978, a follow-up survey was performed. The survey was conducted by two persons in one vehicle, traveling on the shoulder at approximately five mph. The distresses recorded were transverse and localized cracks, spalling, pumping, punchouts, and repair patches. One important conclusion was that the use of 8 in. CRCP in Texas for $1 \times 10^6$ to $6 \times 10^6$ equivalent 18 kip single-axle application was not adequate (de Velasco and McCullough 1981). Another important finding was that limestone concrete pavement outperformed gravel concrete pavement by showing larger crack spacing (i.e., fewer cracks per unit length) and less spalling. Texas highway engineers started comparing the performance of CRC pavement made with river gravel or crushed limestone aggregate in the 1970s. The surveys and subsequent analysis by CTR affirmed the conjecture that CRC pavement performs differently with various coarse aggregate type. Mainly, CRC pavement with limestone coarse aggregate performs better than those with siliceous river gravel with regard to crack spacings and failures.

To further pursue the coarse aggregate type issue, a pilot research project 422 was sponsored by the Texas State Department of Highways and Public Transportation, now TxDOT. This project mainly focused on the laboratory evaluation of concrete materials made with siliceous river gravel (SRG) and crushed limestone (LS). The measured properties were elastic modulus, thermal expansion coefficient, drying shrinkage, and tensile strength (Green et al. 1987). It was confirmed that mix containing LS aggregates exhibited higher tensile strength (indirect tension test), a higher modulus of elasticity (flexural test), higher flexural strengths, and lower shrinkage values than the mix containing SRG aggregates.

Recognition of the vast challenges to evaluate the effects of various coarse aggregate types on CRC pavement performance led to the joint study of two flagship universities, UT Austin and Texas A&M University for the Project 1244 in the year of 1989. The project spanned over seven years and a total of 13 reports were generated. With a total of eight testing projects, it was conclusively established that concrete
material properties (mostly aggregate related), construction practices (e.g., placement temperature and
time, curing method), and environmental conditions (humidity and temperature variations) can determine
CRC pavement performance.

With the most important factors identified, TxDOT provided more research funds for improving CRC
pavement performance. The five-year Project 1700 was purposed to better predict the behavior of
concrete in the field and to better evaluate relevant concrete properties in the laboratory. Research
included predicting concrete hydration temperature, in situ concrete strength, moisture-related cracking in
concrete, and measuring of thermal expansion coefficient of aggregates for concrete. The research results
from the study were further evaluated in the field, and it was expected that all the efforts would help
TxDOT and the industry manufacture better CRC pavement for Texas highway travelers.

At the same time, TxDOT was willing to experiment with potential approaches that may improve the
performance of CRC pavement made with siliceous river gravel aggregate. These examined methods
included the use of synthetic and steel fibers in concrete (Folliard et al. 2006) and crushed river gravel
(Research Project 4826). Recently, an implementation project was launched to evaluate the potential
benefit of optimized aggregate gradation for paving concrete (Project 9026).

The historical development of research projects clearly demonstrates our sharpening understanding of the
influences of concrete constituents on concrete materials and the effects of concrete properties on
pavement performance. In general, interested properties were first studied in the laboratory and then their
effects on CRC pavement performance were evaluated in the field by the use of test sections. Field studies
led to more findings, and thus another round of lab testing. TxDOT personnel strove hard to make this
process as smooth as possible. The CRC pavement testing locations around the state of Texas are
evidence of the endeavor of TxDOT for a better transportation system for the public.

Because there are so many reported results over the span of 30 years, it is impossible to detail every
aspect related to aggregate in paving concrete. Thus, the authors decided to present the major findings in
four separate parts: laboratory tests, pavement performance, model development, and aggregate
classification. The focus will be on the influence of coarse aggregate type, especially LS vs. SRG.

LABORATORY TESTS

Mechanical Properties

Strength

It is generally accepted that pavement cracks occur when the tensile stress developed in the course of time
exceed the concrete strength. Although this premise oversimplifies the complicated cracking initiation
phenomenon, it is still applied in current research for pavement.

In one laboratory study, at the curing condition of 75°F temperature and 40% relative humidity
(simulating field condition), it was found that with a similar mix design, concrete with limestone coarse
aggregate had slightly lower compressive strength up to seven days than that of siliceous river gravel
(Dossey and McCullough 1992). At 28 days, the two concrete mixtures had comparable compressive
strength.

Splitting tensile test (ASTM C 496) was used to compare concrete mixtures in several projects. This test
method measures the indirect tensile strength of concrete. Laboratory tests indicated that the use of LS in
Concrete was comparable to the use of SRG in respect of tensile strength at early ages (Dossey and McCullough 1992; Dossey, McCullough, and Dumas 1994). For instance, an average splitting tensile strength of 180 psi for SRG mixture and 187 psi for LS mixture at the age of one day. As such, the splitting tensile strength cannot be used to explain the difference of the use of LS and SRG in CRC pavement. As one of the recommendations of Project 1244, this indirect tensile strength was proposed as the quality control parameter in the place of compressive strength (McCullough, Zollinger, and Dossey 1995).

Tensile flexural strength measured following ASTM C 78 is often viewed by researchers as similar to the loading condition of concrete pavement under loading. The evaluation of this property of concrete mixture is often preferred by engineers. A recent study focused on the flexural fatigue strength of concrete mixtures made with LS and SRG aggregate (Suh 2005). It was found that except for very high stress levels ($S > 0.9$), the LS mixtures generally had a higher fatigue resistance than SRG mixtures for a given stress level. However, the specimen size (6 in. × 6 in. × 20 in.) required in the test procedure prevents its popularity among inspectors. A study by Green et al. (1987) revealed the significant effects of curing humidity and temperature on the flexural strength development of concrete mixtures made with LS and SRG aggregates. The results are plotted in Figure 2 below. For 100% relative humidity, only at low temperature (50 °F) the flexural strength of concrete made with LS aggregate was higher than those made with SRG aggregate at all ages, i.e., 1, 3, 7, 28 and 90 days. For high temperature (100°F) the flexural strength of LS concrete was lower than that of SRG concrete after 7 days. However, for the 40% RH curing condition, which was used to simulate the field condition, LS concrete obviously outperformed SRG concrete, especially at low and high temperatures.

![Figure 2. Tensile flexural strength development with age (plotted with data in Green et al. 1987). Example of label: LS-50F-40% -concrete made with LS aggregate, cured at 50°F and 40% RH.](image)

Aggregate type was also found to affect the correlation between compressive and tensile strengths (McCullough, Zollinger, and Dossey 2000). The tensile-flexural strength ratio of concrete was also influenced by the coarse aggregate used (de Velasco and McCullough 1981). Clearly, the prediction of one strength parameter from another should be cautioned.
However, the sole use of strength parameters to predict the performance of CRC pavement is questionable. This opinion is backed up by a 24-year performance review of concrete pavement made with SRG and lightweight coarse aggregate (Won, Hankins, and McCullough 1989). The 28-day concrete properties of the two concretes are summarized in Table 1. The lightweight coarse aggregate was prepared by heating shale at high temperatures and the maximum size was approximately ¾ inch. In comparison, the conventional SRG aggregate used had a maximum size of approximately 1½ inches. The test slabs consisted of a 6 in. thick concrete on a subbase of 6 in. of cement-stabilized oyster shell. Lightweight concrete performed better by having no failures, relatively large crack spacings, and a good appearance after 24 years even though the compressive, tensile, and flexural strengths of the lightweight concrete were all lower than the SRG counterpart. Clearly, a stronger concrete does not necessarily provide a better concrete pavement.

Table 1. 28 day mechanical properties of concrete made with different coarse aggregate (Won et al. 1989)

<table>
<thead>
<tr>
<th>Mechanical property</th>
<th>Concrete with lightweight</th>
<th>Concrete with SRG aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength, psi</td>
<td>3828</td>
<td>4313</td>
</tr>
<tr>
<td>Tensile strength, psi</td>
<td>312</td>
<td>488</td>
</tr>
<tr>
<td>Modulus of elasticity, psi</td>
<td>$3.05 \times 10^6$</td>
<td>$7.8 \times 10^6$</td>
</tr>
<tr>
<td>Flexural strength, psi</td>
<td>607</td>
<td>643</td>
</tr>
</tbody>
</table>

Elastic Modulus

Elastic modulus is expected to affect early-age cracking pattern by influencing the stress due to drying shrinkage and thermal fluctuations (Suh, Hankins, and McCullough 1992). The relatively larger crack spacing reported for lightweight concrete pavement (Won, Hankins, and McCullough 1989) might be partially attributed to the lower elastic modulus of lightweight concrete ($3.05 \times 10^6$ psi), in addition to the low thermal expansion coefficient.

However, the measurement of elastic modulus itself is an interesting evolution process. For Project 422, the concrete elastic modulus values were obtained by the use of a beam tested under third point loading, following ASTM C 78 (Green, Carrasquillo, and McCullough 1987). The slope of the cord connecting the two points on the deflection-stress curve at 20% and 50% of ultimate stress values was used to calculate the modulus. For Project 1244, the modulus was measured in compression testing (Dossey and McCullough 1992) according to ASTM C 469. Because different procedures were followed, the observations were contradicting. In flexural testing, the elastic modulus of LS concrete was found to be higher than SRG concrete at early ages, up to 7 days. On the contrary, the compressive elastic modulus of LS concrete was found lower than SRG concrete for all tested ages, up to 28 days.

It is felt that the measurement of elastic modulus of concrete under direct tensile would be more meaningful when concrete pavement cracking is concerned. However, unless some breakthrough occurs, the testing procedure of direct tension is too complicated for practical application.

Toughness

With the increase of pavement thickness (larger than 8 in.), tying pavement with its shoulder and the requirement of 1 in. asphalt bond breaker and better base (4 in. hot mix base or 6 in. cement-treated base) in Texas, the spalling of concrete became the major distress of CRC pavement, taking the place of
punchout. Two-year monitoring of 32 CRCP test sections with four construction projects built in 1989 in Houston area raised the issue of spalling with concrete made with SRG aggregate (Otero Jimenez, McCullough, and Hankins 1992). Subsequently, TxDOT has been sponsoring research projects focusing on reducing spalling in CRC pavement. Implementation projects on spalling repair were also funded.

Severe spalling of CRC pavement is currently considered by researchers as being the development of delaminations in concrete pavement before the traffic load (Senadheera and Zollinger 1996). Delamination is often found passing through the interface between SRG aggregate and mortar in spalled pavement. Two remedy methods were proposed based on the above observation and two separate research projects were sponsored by TxDOT. One method is to increase bond strength between coarse aggregate (e.g. SRG) and mortar. It is hoped by doing so the delamination will be reduced. The method was thoroughly studied in Project 0-4826. The fracture toughness test was used in this project. The other method is to prevent the crack propagation by the use of steel fibers, recognizing cracking/delamination is not totally avoidable. This approach was evaluated in research project 0-4392 (Folliard et al. 2006). Flexural toughness of concrete mixtures was evaluated following ASTM C 1018.

Texas Transportation Institute (TTI) researchers used two approaches to evaluate the fracture toughness of concrete mixture made with different coarse aggregate. The RILEM procedure of size-effect fracture test on notched concrete beams was originally used (Senadheera and Zollinger 1996). The results indicated that concrete with SRG aggregate had higher fracture toughness (0.41 MPa m) than that with LS aggregate (0.37 MPa m) at 24 hours. However, the brittleness of siliceous gravel concrete was found to be more than twice that of limestone concrete, and the effective length of the fracture process zone for limestone concrete was more than twice that for siliceous gravel concrete. In Project 4826, TTI researchers turned to the test procedure proposed by Tang et al. (1999) on notched Brazilian splitting tensile specimens. However, for concrete with limestone aggregate at 24 hours, the fracture toughness was found to be about 0.45 MPa√m, while for SRG concrete the value was 0.23 MPa√m. Again, as for the case of elastic modulus, the use of different test procedures generated different values and trend. More research is needed to clarify the discrepancy.

CTR researchers found that the use of steel and synthetic fibers with different dosages increased the flexural toughness for concrete mixtures, especially for those with SRG aggregate (Folliard et al. 2006). However, in the study, concrete with SRG aggregate demonstrated higher flexural toughness indices than LS counterpart in all categories. It is also interesting to note that ASTM C 1018-97 is now withdrawn as an ASTM standard test.

**Physical Properties**

*Coefficient of Thermal Expansion*

The importance of the coefficient of thermal expansion (CoTE) of concrete to CRC pavement has long been recognized. The coarse aggregate is the major part of concrete volume and thus is the major factor of concrete CoTE. However, the lack of an accurate and repeatable test method on aggregate CoTE prevented its wide application in the construction industry. Currently, the evaluation of CoTE value on a concrete mixture can be regularly performed by TxDOT, using modified AASHTO TP 60 (Won 2005). In a recent study, TxDOT tested a total of 94 coarse aggregate using the same mix design (Du and Lukefahr 2007). All concrete mixtures with LS aggregate had a CoTE value less than 5.5 in/in/°F and only 20% of test SRG concrete mixtures had such low thermal expansion. Noticeably, about 50% of tested SRG concrete mixtures had a CoTE smaller than 6.0 in/in/°F. Lightweight aggregate concrete tested in this study showed a low CoTE value of 4.8 in/in/°F.
The prototype CoTE measurement was quite rudimentary about 20 years ago. Two strain gages were placed on each specimen, and deformations were recorded for every 30°F curing temperature change from 45°F to 135°F and backward to 45°F (Green et al. 1987). However, even with current technology, these tests may still generate contradicting results. For instance, it was found in Project 7-3925 that gap-graded concrete mixtures generally had lower CoTE values (McCullough, Zollinger, and Dossey 2000). A recent research publication found that optimized gradation reduced the CoTE value of concrete by 0.81 in/in/°F (Kim and Won 2007). TTI researchers attempted to directly measure CoTE of coarse aggregate using dilatometer in a recent project (Mukhopadhyay, Neekhra, and Zollinger 2007). However, TxDOT is still in the stage of evaluating the device and procedure.

Drying Shrinkage

The importance of drying shrinkage to CRC pavement has long been recognized by researchers. As early as 1981, the effect of aggregate type on concrete drying shrinkage was clearly pointed out (de Velasco and McCullough 1981). It was believed that the increase in crack width of CRC pavement is a function of the residual shrinkage (drying shrinkage after formation of the crack) and an early-age crack would have higher residual shrinkage than a later crack, a fact that results in the greater width (Suh et al. 1992). At low (50°F) or high (100°F) temperatures and a relative humidity of 40%, Green et al. (1987) found that LS concrete shrank, measured on 6 x 12 in. cylinders, significantly slower than SRG concrete, probably due to the higher bond strength between coarse aggregate and mortar in LS concrete. However, for the condition of 75°F, the differences were negligible. On the contrary, a later study found limestone concrete had a higher drying shrinkage at 256 days than SRG concrete (Dossey and McCullough 1992). It is not easy to explain these observations. This actually raised a very interesting concern. Is the standard curing temperature around 73°F a valid approach for evaluating drying shrinkage for paving concrete with different coarse aggregate? In addition, can coarse aggregate be adequately characterized by its type? Or do we have to evaluate important properties of a specific aggregate source even though the aggregate type is known?

Durability Properties

The aggregate-related durability issue was drawn to the attention of TxDOT more than 20 years ago (Carrasquillo and Farbiarz, 1989). In the 1990s, alkali-silica reaction (ASR) was identified with Texas concrete pavement and structures. A five-year research project, 0-4085, “Preventing ASR/DEF in New Concrete,” was initiated in 2000, and many important findings were generated and have been used in TxDOT specifications. The research evaluated several ASTM standard tests methods on assessing ASR. The accelerated mortar bar test (AMBT) ASTM C 1260, is deemed as a reasonable indicator of aggregate reactivity or a reasonable means of assessing various mitigation measures. However, its severity and sometimes false passing of reactive aggregates cast doubt on its effectiveness (Folliard et al. 2006). One-year testing of ASTM C 1293 is preferred, but in many cases we cannot afford the waiting time. As for delayed ettringite formation (DEF), researchers proposed a maximum internal concrete temperature of 158°F to effectively prevent the occurrence of DEF. Alkali-carbonate reaction was not emphasized because the potentially susceptible rocks are not common in Texas.

PAVEMENT PERFORMANCE

Introduction

In Texas, test sections have been used to validate laboratory research findings and new technologies to better understand pavement behaviors with proposed changes of mix design, steel placement, and
construction practices. Cracking spacing, crack width, concrete and steel stress, punchout, and spalling are generally recognized as pavement performance indicators (McCullough, Zollinger, and Dossey 2000). Stresses in concrete and steel are important, but they are difficult to evaluate in situ. In the passing years, very little research had focused on this topic. Punchouts are no longer a major distress for CRC pavement in Texas, and this paper will not discuss it here. The remaining section emphasizes cracking pattern of CRC pavement and its spalling hazard.

Cracking Patterns

Crack Control

In order for CRC pavement to perform satisfactorily, it is generally agreed that crack spacings should fall between 3.5 and 8 ft. (Otero Jimenez, McCullough and Hankins 1992). Before the 1990s, the steel reinforcing ratio in CRCP was thought to be the main factor controlling cracking spacing because steel has a lower CoTE value than concrete. While SRG concrete has a higher CoTE, it was thought by researchers and engineers that a lower steel reinforcing ratio in SRG pavement may generate similar cracking spacings and thus similar crack widths as those in LS pavement. Based on this methodology and using software model CRCP-4, a design standard, TxDOT CRCP-89B, was originated but lasted only for one month (McCullough, Zollinger and Dossey 2000). This standard put unfair penalty to LS aggregate by requiring more reinforcing steel, and test sections did not support the premise of similar cracking spacing and crack width. Instead, SRG sections had shorter cracking spacing and wider crack width than LS sections did two years after construction (Otero Jimenez, McCullough and Hankins 1992). This highlights the importance of carefully examining the results predicted by computer models before putting them into practice.

Further research found that a variety of factors could affect the cracking pattern of CRC pavement including placement temperature (setting temperature), construction season, curing techniques, crack inducers, saw cutting, and aggregate blend (McCullough, Zollinger and Dossey 2000). For instance, substantially more failures occurred when the concrete placement temperature was in the range of 90°F to 99°F. Because there are many factors affecting cracking pattern of CRC pavement, the control of crack spacing and width is still an art to be mastered.

Crack Initiation and Stabilization

Before opening to traffic, cracks are normally observed in CRC pavement at early ages due to volume change. This emphasizes the importance of strength and stress developments of concrete during the first several days for CRC pavement. Incidentally, many factors are influencing the strength and stress of concrete at the same time. Loss of moisture and temperature fluctuations of fresh and hardened concrete are identified as the most important controllable parameters for early-age cracking. Tensile stresses are developed due to drying shrinkage and temperature drops. When the strength is exceeded by the stress (or certain crack initiation criterion is met), cracks form, subsequently propagate, and finally stabilize. They are determined by environmental loads (temperature and moisture changes), traffic loads, and physical restraints (external and internal).

Researchers found that almost without exception, cracks occurred when the slab temperature dropped significantly (Suh, Hankins, and McCullough 1992). The first concrete crack of the winter construction occurred much later than in summer construction, as a result of a smaller temperature drop. LS concrete sections had fewer and delayed cracks than corresponding SRG sections, possibly due to lower CoTE value, lower temperature rise, larger strain capacity, and lower elastic modulus of LS concrete. The
differences were not as significant for winter construction as for summer construction. In addition, it was believed that the steel did not have as much influence on cracking during the early ages because the bond between concrete and steel may not have been fully developed. Many of the transverse cracks occurred over the transverse steel bars, a phenomenon that was more significant in the sections having double-layered steel (Suh, Hankins, and McCullough 1992).

Another interesting observation in one research project was that all of the surface cracks could be traced to cracks observed on the pavement edge, though many cracks observed on the pavement edge did not reach the pavement top surface (McCullough, Zollinger, and Allison 1993). This calls for the evaluation of the effect of applying curing compound on exposed edge concrete.

Suh et al. (1992) identified the location pattern of new cracks in a slab segment, defined by existing cracks. They found that for a slab segment longer than about eight ft., the occurrence of new cracks is quite random. However, some trend was observed if the segment length was less than eight ft. The new crack, if any, would be almost at the middle length if the segment and was about three ft. or shorter. For a segment with a length between about three and eight ft., the cracks would be closer to the ends as the length increased. Several research projects revealed that the crack pattern evolved quickly in the first month and 80% to 90% of the stable pattern developed between 28 and 90 days after construction. The final surface cracking patterns typically took three years to stabilize (McCullough, Zollinger, and Allison 1993). Note that the crack distribution of SRG test sections at five days for the summer placement is poorer than that at 2,600 days for the winter placement (McCullough, Zollinger, and Dossey 2000).

**Crack Spacing**

Crack spacing of CRC pavement is probably the most important parameter affecting its long-term performance. AASHTO has recommended a desirable spacing between three and a half (or three by some researchers) and eight ft. The lower limit is to avoid the high tensile stress of concrete at the transverse cracks, which may cause punchouts and spallings. The upper length is to prevent the high stress and yielding in longitudinal steel. Crack spacings are of bimodal distribution and average spacing is discussed here for convenience.

Various factors have been identified to affect crack spacings, including concrete material properties and environmental conditions. Concrete tends to contract due to drying shrinkage and temperature drops, but the internal (longitudinal and transverse steel) and external restraints (underlying base) through the interface resist this contraction. If the resulted complex stress conditions exceed certain criteria, cracks form. The following discussions are qualitative because of the nature of this paper.

Since stress is proportional to strain (due to drying and temperature drop from setting temperature) and elastic modulus, the crack spacing is expected to be larger if the concrete mixture has a lower CoTE, a lower modulus, a slower drying process, smaller temperature drops, and fewer contraction restraints. A high-strength concrete is not necessarily beneficial because the elastic modulus will also be higher, and the setting temperature may also be higher, which means a larger temperature drop at later ages. Researchers have found that in colder areas, crack spacings appear to be smaller for both LS and SRG aggregates (de Velasco and McCullough 1981).

The type of coarse aggregate in concrete is well known as the important factor affecting crack spacing. Researchers have found that in areas with similar temperatures, limestone pavements have larger crack spacing than gravel concrete pavement (de Velasco and McCullough 1981). LS pavements tend to stabilize at a crack spacing of around six ft and there is a much lower spacing of two to three ft. for SRG
pavements (McCullough, Zollinger, and Dossey 2000). After 24 years, the lightweight aggregate test sections had an average crack spacing larger than seven feet (Won, Hankins, and McCullough 1989). The differences in elastic modulus, CoTE value, and brittleness of the concrete with different coarse aggregates are often resorted to for the explanation. However, this approach is challenged by the tests using blended aggregate of LS and SRG. Although it is conclusively demonstrated in the laboratory that the properties of blended aggregate concrete vary with blending ratio, the test sections could not confirm its benefit in crack spacing because one test project showed that there was little difference at 640 days between using SRG and a blend (50/50 by mass) of SRG and LS, as shown in Figure 3 (McCullough, Zollinger, and Dossey 2000).

![Figure 3. Comparison of crack spacing distributions for LS, SRG, and blended coarse aggregate at 640 days (McCullough, Zollinger, and Dossey 2000)](image)

To understand the effect of temperature drops on crack spacing, we need to follow the concrete setting and hardening process. During this process, the heat of cement hydration is generated, and concrete will usually have a temperature rise above the ambient. The temperature peak normally occurs six to eight hours after concrete placement. In addition, there is little volume expansion of concrete from plastic to solid state, and thus concrete is under slight compression initially. As such, after passing the peak temperature, concrete will contract due to cooling and drying. At a certain temperature, concrete should be at a zero-stress condition, ideally. This temperature is called the zero-stress temperature, and it is used to calculate the stress due to temperature drops. Apparently, for the same low annual temperature, the temperature drop will be lower if the zero-stress temperature is decreased. This highlights the importance of controlling concrete placement temperature and paving time. Furthermore, there is a decrease of crack spacing when placed in the morning than in the afternoon for blended aggregate (Fig 3.9, McCullough, Zollinger, and Dossey 2000). For sections placed at the same time and cured the same way, LS concrete had temperatures about 10°F lower than SRG concrete. The probable explanation lies in the fact that the heat capacity of calcium carbonate is about 12% higher than that of silicon dioxide.

The use of skewed transverse steel or steel fibers only had limited effects on crack spacing.

**Crack Width**

When CRC pavement cracks, the monolithic concrete slab is divided into discontinuous segments, if the top surface is considered. The cracked surfaces, once formed, separate with time due to releasing of
tension stress, drying shrinkage, loading deformation, creep, temperature drops, substrate concrete restraints, and other factors, with certain randomness. One researcher found that the coefficient of variation for crack widths in the same crack was about 30% (Otero Jimenez, McCullough, and Hankins 1992). It is critical that the crack width is small enough to provide full load transfer and prevent water flow through the cracks. AASHTO has a maximum limit of 0.04 in., and researchers pointed out a crack width less than 0.025 in. at 32°F is desirable (McCullough, Zollinger, and Dossey 2000). Fortunately, no test sections in Texas had cracks wider than the limit of 0.04 in.

Thermal contraction, residual drying shrinkage after cracking, creep and relaxation, and possibly longitudinal steel reinforcement are significant factors affecting the crack width of CRC pavement. Lightweight and LS aggregate concrete pavements were found having smaller crack widths than SRG pavements, even though the former two had longer crack spacing. The explanations included smaller deviations from zero-stress temperature, lower CoTE values, and delayed initial cracking for lightweight and LS concrete. The later the cracking happens in CRC pavement, the more creep compensates for thermal contraction and moisture drying. Crack width is not necessarily proportional to crack spacing because beyond some certain length, the contraction of the upper concrete should be totally restrained by the substrate, including longitudinal steel. The above observations also explain why summer construction produces wider cracks than winter construction. Winter construction is featured with smaller temperature rise, slowing drying, late cracking, and longer crack spacing.

One interesting observation in one project was that the thicker the CRC pavement, the smaller the crack width (McCullough, Zollinger, and Dossey 2000). This is contrary to the observation on reinforced beams where the thicker the cover, the wider the crack. It is possible that the thicker the pavement, the slower the drying of surface concrete due to moisture supplied from substrate, yielding more creeping of concrete into the equation. It is known that poor curing causes wider cracks. Another explanation lies in the fact that if we keep the reinforcing ratio the same, the increase of pavement thickness actually reduces the ratio of steel bond surface area to surrounding concrete volume.

**Crack Meandering**

Crack meandering in CRC pavement is associated with the crack propagation in concrete. Early-age (one or two days) crack patterns have a tendency to be meandering, with relatively wide crack widths. Cracks in lightweight and LS aggregate concrete pavements were found to be straight with little meandering. To explain the above phenomena, it is believed by the authors of this paper that the coarse aggregate has a determining effect. Lightweight and LS aggregate concrete mixtures have weaker aggregate and stronger bond strength between more aggregate particles, as clearly shown in splitting tensile test, than those of SRG concrete. As a result, existing cracks can propagate usually through lightweight and LS aggregate particles but seldom through SRG particles. To circumvent the SRG particles, cracks may deviate from their straightness and meandering results. When cracks happen at an early age (most often for SRG), the bond strength is weaker and, subsequently, the chances for the crack to go through aggregate particles are lower, which means more potential for meandering.

**Spalling of CRCP**

Spalling is currently the major distress of CRC pavement in Texas. Several research projects were launched to study spalling mechanisms and potential measures to prevent or minimize its happening. In addition, an implementation project on spall repair of CRC pavement was sponsored. Despite the above endeavors, our understanding on spalling is still limited, and the following discussions are preliminary. To have a brief taste of the complexity of the spalling issue, consider that limestone and lightweight coarse aggregate concrete were found to have much less spalling distress in field surveys. For instance,
SRG concrete pavement could have 14 times more spalled cracks than LS concrete pavement for the same length. Also consider that spalling can happen as early as 12 months, or as late as 10 years, or never.

The research on spalling dates back to the 1960’s. In the 1970’s, the survey by CTR on Texas CRC pavements found that warmer districts had the lowest percentages of spalling in most of the cases (de Velasco and McCullough 1981). There was also a trend for more spalling with larger crack spacings. In addition, LS concrete had less spalling compared to SRG concrete for similar crack spacing. Another project found no spalling in lightweight aggregate test sections after 24 years (Won, Hankins, and McCullough 1989). Lower elastic modulus, stronger aggregate-mortar bond, and possibly higher strength of LS concrete were proposed to explain the differences.

Spalling is often rated as minor and severe. A minor spall is defined as edge cracking where the loss of material has formed a spall of one-half in. width or less, the cause of which could be local deformation or debris clogging. Before the 1990s, severe spalling, which are so wide that a smooth ride is affected, was attributed to poor construction operations, for instance, over vibration of concrete. The occurrence of severe spalling was found to be less variable with age, traffic, location (de Velasco and McCullough 1981). From the early 1990s, TxDOT has been funding a number of research projects related to spalling in CRC pavements. Researchers further classified spalling as “deflecting spalling” and “delamination spalling” (McCullough, Zollinger, and Dossey 2000). Deflection spalling occurs at the cracks due to repeated traffic load and temperature variations. With existing delaminations in depths of one to three in. from the surface, delamination spalling generally starts at the crack and progresses away from cracks for some distance. Delamination spalling will be the focus of the following discussions.

Placement season and aggregate type are found to be the two most important variables in spalling development. Delamination of concrete can occur in the early ages before opening the pavement to traffic. Shear and vertical stresses caused by moisture gradient due to drying and, to a lesser degree, temperature gradient in the vertical direction are used to explain the observation that CRC pavements placed in summer showed more spalling than those placed in winter. The importance of timely and adequate curing is highlighted. Because delaminations start from cracks between coarse aggregate particles and mortar, the integrity of interfacial transition zone is essential to minimize delamination development. Limestone aggregates are usually thought to have a better bonding with the mortar phase than SRG aggregate, especially at early ages. Stronger bond strength and lower CoTE are used to account for the outstanding performance of LS concrete. TxDOT Project 4826, “Use of Crushed Gravel in Concrete Paving,” attempted to improve the spalling resistance of SRG concrete by generating rougher aggregate surface (crushing) and producing stronger interface (holding back mixing water). Unfortunately, field tests are still inconclusive at this time, and a longer evaluation will be necessary.

The use of fiber-reinforced concrete in CRC pavement is still under evaluation with test sections.

**MODEL DEVELOPMENT**

Several models for use in CRC pavement have been developed and are still under development through the course of time. Accompanying our more and deeper understanding of material properties and pavement behaviors, models are changing from purely empirical to empirical-mechanistic. More and more relevant factors, including aggregate type and temperature variations are put into the models. The development of the software CRCP series is the perfect example. The first version CRCP-1 was introduced in 1975 and is now evolved to CRCP-10. The modeling of pavement deformation under traffic load was expanded from one dimension to three dimensions, using the finite element method.
Researchers also attempted to predict the concrete properties, including CoTE, when different aggregates are used. The prediction was purely based on the oxide contents of coarse aggregate, using programs CHEM or CHEM2 (Dossey, McCullough, and Dumas 1994). However, this accuracy of this approach still requires validation.

AGGREGATE CLASSIFICATION

Fully recognizing the importance of coarse aggregate for paving concrete, TTI researchers proposed a classification system to TxDOT (Peapully, Zollinger, and McCullough 1994). Physical, chemical, mechanical, and thermal properties of coarse aggregates were discussed, and their importance for concrete pavement was evaluated. With the goal of being simple and easy to use, visual examinations in the field and laboratory evaluation were proposed. Visual examination is to provide preliminary information on coarse aggregate, including nominal size, origin, surface type (crushed or not), color, and presence of any obvious impurities. Laboratory evaluation requires detailed investigation of aggregate properties.

Unfortunately, a lot of aggregate information is needed to establish a usable classification system for coarse aggregates, and the proposed system is not applicable now.

SUMMARY AND SUGGESTIONS

The effects of coarse aggregate on the short-term and long-term performance of CRC pavements, especially limestone and siliceous river gravel, have long been known to engineers and researchers. However, how the coarse aggregate influences concrete properties and thus pavement performance is more complicated than it appears. Although in the past 30 years, intensive and comprehensive research was performed in Texas to understand pavement performance with respect to coarse aggregate and to further mitigate the adverse influence of SRG coarse aggregate, we are not yet in a comfortable position to specify coarse aggregate simply based on its physical, mechanical, and chemical properties.

There are several complex phenomena in CRC pavements that we are still trying to comprehend. For instance, the spalling issue was thought to be related to stresses due to moisture loss. However, the better performance of LS concrete could not be explained. In addition, TxDOT is currently sponsoring research on mid-depth cracking issue, which appears similar to punchout at the surface but the detachment of concrete blocks happen at the mid-depth of pavement. Another case is the evaluation of bond strength between coarse aggregate and mortar. Concrete should be treated as a composite mixture rather than a homogeneous material. It is felt that research should be focusing on this direction.

With the development of electronic devices, more and more fundamental properties of aggregate and concrete can be easily evaluated in the laboratory. One outstanding case is the thermal properties of aggregate. The heat capacity and thermal conductivity of the aggregate are important for CRC pavement because they influence the temperature rise and zero-stress temperature. It is anticipated that more fundamental properties of aggregate will be used to determine its acceptance for a specific construction project.
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REFERENCES


