Accelerated pavement testing of thin RCC over soil cement pavements

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Abstract

Three full-scale roller compacted concrete (RCC) pavement sections built over a soil cement base were tested under accelerated pavement testing (APT). The RCC thicknesses varied from 102 mm (4 in.) to 152 mm (6 in.) and to 203 mm (8 in.), respectively. A bi-directional loading device with a dual-tire load assembly was used for this experiment. Each test section was instrumented with multiple pressure cells and strain gages. The objective was to evaluate the structural performance and load carrying capacity of thin RCC-surfaced pavements under accelerated loading. The APT results generally indicated that all three RCC pavement sections tested in this study possessed very high load carrying capacity; an estimated pavement life in terms of equivalent single axle load (ESAL) for the thinnest RCC section (i.e., RCC thickness of 102 mm) evaluated was approximately 19.2 million. It was observed that a fatigue failure would be the primary pavement distress type for a thin RCC pavement under trafficking. Specifically, the development of fatigue cracking was found to originate from a longitudinal crack at the edge or in the center of a tire print, then extended and propagated, and eventually merged with cracks of other directions. Instrumentation results were used to characterize the fatigue damage under different load magnitudes. Finally, based on the APT performance of this experiment, two fatigue models for predicting the fatigue life of thin RCC pavements were developed.

Keywords: Roller compacted concrete; APT; Pavement performance; Non-destructive testing; Fatigue analysis

1. Introduction

The Louisiana Department of Transportation and Development (LADOTD) is seeking alternate use of roller compacted concrete (RCC) for low volume roadways in the oil and gas exploration areas in the northwest region of the state. RCC is a zero-slump concrete mixture placed with modified asphalt paving equipment and compacted by vibratory rollers [1]. RCC is an economical, fast and durable candidate for many pavement applications. Properly designed RCC mixes can achieve outstanding compressive strengths similar to those of conventional concrete. Due to its relatively coarse surface, RCC has traditionally been used for pavements carrying heavy loads in low-speed areas, such as parking, storage areas, port, airport service areas, intermodal and military facilities [1]. With improved paving and compaction methods as well as surface texturing techniques, recent applications of RCC can be found for interstate highway shoulders, city streets, and rural highways [2–6]. In addition, due to low water content RCC pavements have reduced shrinkage and low maintenance costs [7].

Thickness design for RCC pavements may follow the same design strategy as for conventional concrete pavements, i.e., keeping the pavement’s flexural stress and fatigue damage caused by wheel loads within an allowable limit [1]. By flexural stress is meant the tensile stress at the bottom of a RCC slab under traffic loading. The critical (maximum) flexural stress under wheel load divided by

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flexural strength of the concrete slab is defined as Stress Ratio (SR). A fatigue curve (so called fatigue model) between different allowable load limits and SRs is needed in the thickness design, which can be determined from laboratory beam fatigue tests. The design thickness is then estimated based on the allowable loads to failure at a certain design SR. Both the Portland Cement Association (PCA) and the U.S. Army of Corps Engineering (USACE) developed the thickness design procedures for RCC industrial pavements, and the PCA procedure was later incorporated into a computer program called RCC-PAVE [1]. However, both the USACE and PCA design procedures were developed for the thickness design of RCC pavements for heavy industrial applications (such as ports and multimodal terminals) with a minimum design RCC thickness of 203 mm (8 in.) [1]. The following fatigue model is used in RCC-PAVE [8]:

$$\log N_f = 10.25476 - 11.1872 \ (SR) \quad \text{for} \ SR > 0.38$$  

(1)

where $N_f$ is the allowable number of load repetitions.

Meanwhile, Eq. (2) shows the fatigue model used for PCC pavement thickness design developed by American Concrete Institute (ACI) [9]:

$$N_f = \frac{4.2577}{(SR - 0.4325)}^{3.268} \quad \text{for} \ 0.45 < SR < 0.55$$

$$\log N_f = 11.737 - 12.077 \ (SR) \quad \text{for} \ SR \geq 0.55$$

(2)

The main objective of this study was to evaluate the structural performance and load carrying capacity of thin RCC pavements constructed over typical Louisiana base materials through the accelerated pavement testing (APT). The ultimate goal is to come up with a design alternative (a thin RCC surfaced pavement structure) suitable to be used for low volume roads under heavy truck traffic in Louisiana.

2. Description of APT experiment

2.1. RCC test sections

Three RCC pavement test sections were constructed for this study. Fig. 1 presents the pavement structures of the test sections. Each section is about 4 m (13 ft.) wide and 21.8 m (71.5 ft.) long. As shown in Fig. 1, each section has a similar 216-mm (8.5-in.) soil cement base and a 254-mm (10-in.) cement treated subgrade layer built over an existing embankment subgrade. The only difference among these sections is the thickness of RCC layers. The RCC thicknesses for Section 1, 2 and 3 are 102 mm (4 in.), 152 mm (6 in.) and 203 mm (8 in.), respectively, Fig. 1. Normal highway construction procedures were followed in construction of the subgrade and base layers. A modified asphalt paver was used in the RCC placement and a special-designed pug mill was used in the production and mixing of RCC mixtures [10].

2.2. Materials

The RCC mixtures used in this experiment include a type I Portland cement, a #67 crushed limestone, and a No. 89 crushed limestone manufactured sand. The designed RCC mix contains a well-graded aggregate blend of 57 percent coarse and 43 percent fine aggregate by weight and 11.4 percent cement with an optimum moisture content of 6.5 percent. More details of RCC mix design may be found elsewhere [10].

Silty-clay embankment soil (A-6) was used for both soil cement and cement treated soil layers. To meet the Louisiana roadway design specification, a 8 percent cement by volume was applied to the 216 mm (8.5-in.) soil cement base, and a 4 percent cement by volume was used in the 254 mm (10-in.) treated subgrade layer.

Cylindrical samples of RCC were prepared on site during the construction. RCC cores and saw-cut beams were prepared after the construction for the laboratory strength tests. Test results indicated that, for the RCC mixtures used in the test sections, the average compressive strength at 28 days and average flexural strength were 37,232 kPa (5400 psi) and 4558 kPa (661 psi), respectively. More details on the laboratory test results may be referred to elsewhere [10].

2.3. Instrumentation

Fig. 2 shows the instrumentation layout of this experiment. Each test section was instrumented with three earth gages (Tokyo Sokki KM-100HAS), and two concrete pressure cells (Geokon 3500), two H-type asphalt strain gauges (Tokyo Sokki KM-100HAS), and two concrete
strain gages (Tokyo Sokki PML-60), which were placed at various locations and at layer interfaces, Fig. 2. Several moisture sensors (TDR CS-616) and thermocouples (T108-L) from Campbell Scientific were also installed. National Instruments DAQ hardware was utilized to collect the dynamic responses from pressure cells and strain gages, and a Campbell Scientific data logger for collecting data from thermocouples and TDR. LabVIEW ver. 12 and Campbell Scientific PC400 software were used to convert the electronic signal and to store the data for this experiment.

2.4. Accelerated pavement testing

As shown in Fig. 3, a heavy vehicle load simulation device – ATLaS30 was used for the accelerated pavement testing in this experiment. The ATLaS 30 is approximately 20 m (65 ft.) long, 3.1 m (10 ft.) wide, and 2.1 m (7 ft.) high, constructed around two parallel steel I-beams. The ATLaS wheel assembly models one half of a single axle and is designed to apply a dual-tire load up to 135 kN (30,000 lbf) by hydraulic cylinders. With a computer-controlled loading system, the weight and movement of traffic is simulated repetitively over a 12.2 m (40-ft.) long loading area in a bi-directional mode with a top speed of 9.7 kilometer per hour (6 mph). Within 24 h approximately 3900 bi-directional loading cycles (each cycle = two loading passes) can be applied over the 12.2 m (40-ft.) long loading area.

In this experiment, each test section was loaded by an incremental loading sequence of 40, 72, 89, 98 and 112 kN (9, 16, 20, 22 and 25 kips), each of 78,000 loading passes. If a section was not failed by the first round of loading, continuous loading of second round was made until the pavement failed. The accelerated loading test was conducted under a natural southern Louisiana climatic
condition in Port Allen, LA. No environmental or temperature control was utilized. The testing period for the three RCC test sections was about 12 months. The total precipitation received during this period was approximately 1600 mm (63 in.), with a year-around average air temperature of 19.5 °C (67 °F). The average humidity ranged from 49.2% to 92.4%. Such high annual temperatures, humidity and precipitation may be considered as a typical pavement environment for many U.S. coastal states. In addition, the moisture sensor data were collected periodically during the experiment. The moisture data will be analyzed and incorporated into an on-going finite element simulation study to determine the variation of subgrade strength due to the change of moisture.

In situ tests including sand patching, Dynamic Friction Tester (DFT), walking profiler and falling weight deflectometer (FWD) were performed after construction of RCC surfaces. During the APT loading, the walking profiler was used to monitor the changes of surface profile in terms of International Roughness Index (IRI) and the crack mapping survey was continuously performed.

3. Discussion of APT results

3.1. Pavement responses under wheel loading

The survivability of embedded sensors in this study was roughly 50 percent. A number of sensors were found damaged or wire-cut during the construction. How to protect an embedded sensor below an RCC layer during a paver’s operation remains as a challenge. However, for all of those survived sensors the responses under the wheel loading seemed to be as expected. Typical responses of pressure cells and strain gages under the ATLAs dual-tire’s loading are presented in Fig. 4. For example, under the bidirectional loading, when the wheel is approaching from right to left, the longitudinal strain first shows compression, then tension; and when the wheel is approaching from left to right, it first shows tension, then compression. This phenomenon may be partially due to the orientation of the embedded strain gage and partially due to the bidirectional loading. As a matter of fact, the measured longitudinal tensile strains under two consequential load repetitions (i.e., bidirectional loading) are slightly different from each other but quite repeatable, in which both measured from the peak to a reference zero-strain line (i.e., roughly 538 micro-strain as shown in the Fig. 4(b)). On the other hand, the transverse strain gage only shows pure tension under the dual tire loading in both directions, Fig. 4. A small difference between the two peaks in a bi-directional loading could be due to a slightly inclined slope of RCC pavement surfaces built for the drainage purpose.

Fig. 5 presents the measured maximum stresses and strains under different loads at the bottom of RCC slabs during an initial (undamaged and pre-loading) pavement condition for the three RCC sections in this study. As shown in Fig. 5, the measured stresses and strains are all increased with the increasing load intensities and decreased with the increase of RCC thickness.

To validate the measured pavement responses, each RCC test section was modeled as a two-layer pavement structure, i.e., RCC over a solid foundation, using a finite
For simplification, the base and subgrade layers in the FE analysis were combined into one single solid foundation layer. First, based on the backcalculation of FWD deflections a modulus value of 27.6 GPa (4000 ksi) was chosen for the RCC representing an average elastic modulus of this material in field pavement conditions. Second, based on the elastic analysis using KENSLABS a modulus value of 262 MPa (38 ksi) was backcalculated for the solid foundation layer representing the combined stiffness of the base and subgrade layers considered. As presented in Table 1, the predicted surface deflections matched well with those measured deflections under different FWD loads, except the FWD load of 40 kN (9000 lb.) under which the measured deflections were technically negligible. When plotting the predicted surface deflections verse the load intensity, a generally linear trend can be observed for all three RCC pavement sections, Fig. 6. However, the slope of the linear trend is generally steeper for a thinner RCC pavement indicating a thin RCC slab would have more relative damage than a thick RCC slab under a heavy load.

As mentioned earlier, the critical tensile (flexural) stress at the bottom of RCC slab is the only load-induced pavement response required in a RCC pavement thickness design. The KENSLABS FE model was used in predicting the critical tensile stresses on RCC test sections. The prediction results are presented in Table 1 as compared to the estimated field tensile stresses. Note that the field tensile stresses were estimated from the obtained instrumentation responses plotted in Fig. 5. By assuming the measured vertical stress, longitudinal strain and transverse strain all representing a single point at the bottom of a RCC slab and the slab as a homogeneous elastic layer with a modulus value of 27.6 GPa (4000 ksi) with a Poisson’s ratio of 0.15, the field critical tensile stresses under different ATLAS dual tire loads may be estimated by solving three simultaneous equations based on the Hooke’s law. As seen in Table 1, the FE predicted and the field tensile stresses are generally matched to each other fairly well with an average ratio of 1.12 between the predicted and field tensile stresses. This may indicate that those measured pavement responses in this study are generally reasonable and validated at least in the beginning of wheel loading. Part of the discrepancies may result from the simplified elastic assumptions used in the FE model, variation of in situ pavement thicknesses and the sensitivity of the gages.

3.2. Performance of RCC sections

The overall APT results indicate that all RCC test sections tested in this experiment had very high load carrying capacity. In the end, two sections (Sections 1 and 2) were considered to have reached their pavement lives due to the extensive fatigue cracking and significant surface roughness as shown in Fig. 7. The following sections discuss the detailed performance of each RCC section tested.

3.2.1. Section 1

Fig. 8 presents the loading sequence and the corresponding predicted ESAL numbers for Section 1. This section began the wheel loading by the loading sequence of 40, 72, 89, 98 and 112 kN (9, 16, 20 and 22 and 25 kips), then...
tested under the 72 kN (16-kip) wheel load till its fatigue failure. The total estimated ESALs for section 1 are approximately 19.2 million.

In this study, the predicted ESAL numbers were computed using an equivalent axle load factor (EALF) multiplied by the corresponding number of load repetitions under a certain ATLaS30 axle load. The EALFs for different ATLaS30 axle loads were estimated based on the AASHTO’s rigid pavement equations as follows [11]:

\[
\log(\text{EALF}) = 4.62\log(18 + 1) - 4.62\log(L_x + L_2) + 3.28\log L_2 + \frac{G_t}{\beta_s} - \frac{G_t}{\beta_{18}}
\]

(3)

\[
G_t = \log \left( \frac{4.5 - p_t}{4.5 - 1.5} \right)
\]

(4)

\[
\beta_s = 1.00 + \frac{3.63(L_x + L_2)^{0.52}}{(D + 1)^{0.46}L_2^{0.32}}
\]

(5)

where

- \(L_x\) is the load in kip on different axles;
- \(L_2\) is the axle code, 1 for single axle, 2 for tandem axles and 3 for tridem axles;
- \(p_t\) is the terminal serviceability, which indicates the pavement conditions to be considered as failures;
- \(D\) is the slab thickness in inches.

Fig. 9 shows the cracking development under different load repetitions observed on this section. FWD backcalculated subgrade moduli (Mr) at different stations were also plotted on a vertical axis to the left side in Fig. 9. Neither visible nor measurable distresses could be obtained on this section at the ends of 40 kN, 72 kN and 89 kN (9-kip, 16-kip and 20-kip) of ATLaS dual-tire loading. However, at the beginning of the 92 kN (22-kip) loading, a hairline longitudinal crack around Station + 10 was noticed, which was in the middle of one tire print, Fig. 9. With additional load repetitions, the longitudinal crack propagated and expanded continuously, and resulted in some pumping fine materials through the cracks and saw-cut joints on this section. After 480,000 load repetitions, longitudinal cracks from outside the wheel path started to initiate. Finally, the inside and outside longitudinal cracks connected to each other and a punchout type failure occurred around Station+15 after a total of 706,500 passes of ATLaS dual tire loading. Interestingly, the observed cracking failure was confined only in the first half of the loading area on Section 1, Fig. 8.

The following observations may be drawn from Fig. 9: (1) the initial longitudinal crack observed in the middle of one tire print seems to be a bottom-up crack due to high tensile stresses at the bottom of the 102 mm (4-in.) RCC slab; (2) The weaker subgrade portion under the loading area caused a higher tensile stress under the slab than did the stronger subgrade portion; (3) with continuous load repetitions and more pumping of fine materials, voids would be formed underneath the slab, which generated more deflections and cracks of the slab under loading; (4) due to only a very thin RCC slab thickness (102 mm), the final cracking pattern was kept in a relatively narrow area, quite different from the cracking pattern observed on the 152 mm (6 in.) RCC section to be described below.

### 3.2.2. Section 2

It took much more loading repetitions to fail this section than Section 1. A total of 1,750,850 load repetitions of various load magnitudes were applied on this section and the cumulative ESALs to pavement failure was estimated to be 87.4 million. Fig. 10 shows the cracking development under different load repetitions observed on Section 2. Similar to the Section 1, the crack was also first originated in the longitudinal direction in Section 2. However, at this time the longitudinal cracking was initiated along the edge of a tire print. Another major difference observed is that the cracking pattern was much wider in Section 2 than that of Section 1.
The following observations may be obtained from Fig. 10: (1) the initial longitudinal crack observed at the edge of a tire print seems to be a top-down fatigue cracking, presumably caused by a high shear stress cut vertically along a tire wall; (2) The more uniform subgrade moduli resulted in a final cracking failure covering the entire loading area; (3) with continuous load repetitions and pumping, voids must be formed underneath the RCC slab, which generated more deflections and cracks under loading; (4) due to the combination factors of the thicker slab thickness, more uniform subgrade support and possibly high shear stresses under tire walls, the final cracking pattern of Section 2 was found much wider than that of Section 1; (5) with only a 51 mm (2-in.) increase in RCC thickness, the load carrying capacity of a RCC pavement has been increased significantly from 19.2 million ESALs to 87.4 million ESALs.

3.2.3. Section 3

Only 392,500 load repetitions (approximately 11.3 million ESALs) were applied on Section 3. No significant damage was observed on this section. Due to the known, very high load repetitions received on Section 2, the APT test on this section was discontinued after the 392,500 ATLaS loading repetitions.

4. Preliminary fatigue analysis of thin RCC pavements

A preliminary fatigue analysis of RCC test sections was conducted based on the cracking performance obtained on Sections 1 and 2 and the field critical tensile stresses estimated from the obtained instrumentation responses. With the estimated critical tensile stress under a specific ATLaS dual tire load, the stress ratio, SR, can be obtained. For each fatigue failure section in this study, different SRs versus numbers of load repetitions of various ATLaS dual tire loads were accumulated all together to develop a 100 percent fatigue damage for the section considered. Such information were grouped together in an Excel spreadsheet and using the Solver function in Excel, the following two fatigue equations were able to obtained in this study:

For Section 1: \[ \log N_f = 9.071 - 12.729 \times SR \] (6)
For Section 2: \[ \log N_f = 9.507 - 12.597 \times SR \] (7)

Fig. 11 shows a comparison between the developed fatigue equations in this study and those of RCC-PAVE and ACI fatigue models as listed in Eqs. (1) and (2). It can be observed that the developed fatigue equations for thin RCC pavements generally shift to the left of the RCC-PAVE model developed for thick industrial pavements.
and the ACI fatigue model for regular PCC pavements. Such results confirm the necessity of developing a fatigue model for thin RCC pavement design.

Table 2 lists the estimated fatigue damage predicted using three fatigue models: RCC-PAVE, Eqs. (6) and (7). As can be seen in Table 2, when the Eq. (6) model (the fatigue model developed from Section 1) is used on Section 2, the predicted fatigue damage would be 190 percent and 300 percent, respectively, at the first visual crack and end of testing, as compared to 65% and 100% percent, predicted from its own model. Similarly, when predicting fatigue damage using the fatigue model of Eq. (7), the cumulative fatigue damage of the first visual crack and end of testing would be 14.5% and 34%, respectively, as compared to

![Loading Sequence](image1)

![Cracks vs. load repetitions](image2)

Fig. 8. Loading sequence and corresponding ESALs for Section 1.

Fig. 9. Cracks vs. load repetitions for Section 1.
43% and 100% percent, predicted from its own model. This confirms that Section 2 should perform much better than Section 1 in term of fatigue performance. When using the developed fatigue models – Eqs. (6) and (7) to predict the fatigue damage on Section 3, somewhat reasonable prediction results were obtained for the section. On the contrary, the RCC-PAVE model fails to predict any fatigue damage for thin RCC pavements tested in this study. Even at the end of fatigue failure, the RCC-PAVE model only predicts the cumulative fatigue damage of 2.5% and 6.9%, respectively, for Sections 1 and Section 2. It is expected in the end of this research a unified fatigue equation by considering various RCC thicknesses can be developed for the fatigue analysis of thin RCC pavements under the climatic conditions for many U.S. coastal states.

5. Summary and conclusions

Three full-scale RCC over soil cement pavement sections including three RCC slab thicknesses (102, 152 and 203 mm, respectively) were tested under an APT experiment. A heavy vehicle load simulation device – ATLaS30 was used in the APT testing and each section was instrumented with different pressure cell and strain gages. The following observations and conclusions may be drawn from this study:

- All RCC sections performed better than expected under various heavy truck loads indicating that a thin RCC pavement would have outstanding load carrying capacity to be used for low-volume roadways with significantly heavy truck traffics when properly constructed.
Two RCC sections were able to sustain load until a fatigue cracking failure. The fatigue cracks were found to initiate originally in the longitudinal direction at a location at the edge or in the center of a tire print.

With continuous load repetitions and the crack pumping actions, voids would be formed underneath a RCC slab, which generated more deflections and propagate cracks into a fatigue cracking failure.

Due to the combination effects of slab thickness and base/subgrade support, the final fatigue cracking pattern was found much wider in a thicker RCC section than that in a thinner RCC section.

Based on the APT performance of RCC sections in this study, a set of fatigue prediction equations were developed. The developed models were found to better suit in predicting the fatigue damage of a thin RCC pavement.

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### References


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