New Laboratory Testing Technique for Asphalt Concrete

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The Institute for Research in Construction, National Research Council of Canada, recently developed new laboratory equipment for testing mechanical properties of asphalt concrete. Tensile and shear (static or dynamic) loading can be applied to slab samples of asphalt pavement. The concept and the first prototype of this testing equipment are described, along with results of an experimental evaluation and testing program. The laboratory testing was carried on slab specimens extracted from the pavement of a field trial section partly reinforced by a geogrid.

Testing of the mechanical properties of asphalt concrete (AC) has been traditionally focused on compressive, tensile and bending strengths. Many tests are used to quantify these properties in static or dynamic (fatigue) modes. These testing techniques have been steadily improving in quality and sophistication, in an effort to better understand and evaluate the behavior of AC. For recent advances on asphalt laboratory testing, an interested reader is referred to the *Proceedings of the Fourth International RILEM Symposium* (*1*). Past emphasis has been on compressive, tensile, and bending strength testing. The shear strength of AC has rarely been examined, perhaps because of its simplicity. An exception is testing done using the gyratory equipment, as described by Ruth et al. (*2*). In the vast majority of laboratory testing today, a single deformation component is normally applied, resulting in a single stress component or a limited combination of stresses, for example, compressive and tension. A combination of deformation in different directions leading to a combination of stresses—for example, tensile and shear—is seldom used to evaluate the behavior of AC.

To examine the importance of combining various strains and stresses in AC testing, consider an asphalt overlay on top of a cracked AC or portland cement concrete (PCC) pavement. Furthermore, consider a moving vehicle on the overlay, which covers a crack in the old pavement underneath (Figure 1). As the wheel of the vehicle moves from one side of the crack to the other (i.e., from one independent slab to the other), the asphalt overlay is loaded with considerable shear strain and stress. This large shear stress is imposed twice in the opposite direction with every pass of the wheel. At the bottom of the overlay at the edges of the crack, a high concentration of compressive stress develops under the wheel load. Furthermore, if the crack is wide and the subgrade underneath the old asphalt deteriorated and weak, the new asphalt also becomes stressed in bending (Figure 2). There is yet another serious factor in this process: the development of tensile stress due to thermal contraction, as shown in Figure 3. All these combined actions near the crack in the old pavement contribute to the development of a "reflection" crack propagating upward to the asphalt overlay, causing premature deterioration of rehabilitated pavements (*3*).

To properly evaluate various rehabilitation measures and their ability to reduce reflection cracking and other distress phenomena in asphalt pavements (e.g., overlays and the use of geogrids as crack retardants and stress reinforcement in pavements), a combination of tensile and shear stresses must be considered. Therefore, the Institute for Research in Construction (IRC) has recently developed a testing table called Construction Material Testing System (CMTS); it can combine tensile and shear (static or dynamic) loading applied to asphalt concrete slabs. Besides general material testing (e.g., tensile, compressive, shear, and flexural strength), this equipment has also been designed to evaluate the performance of various crack rehabilitation techniques.

This paper describes the new CMTS and its functions and performance. The testing results of plain and reinforced asphalt slabs in combined tensile and dynamic shear modes are presented along with some interesting implications.

BACKGROUND

One of the major expenses incurred by transportation departments around the world is the rehabilitation of their road networks. A significant part of these funds is associated with sealing cracks, rehabilitating badly cracked locations with other techniques, and placing asphalt concrete overlays over entire road sections.

Overlays over cracked or jointed PCC, or over cracked AC, pose the problem of reflection cracking. Other locally applied rehabilitation measures—such as deep patching, milling and machine patching, crack filling and sealing, and using geogrids, geotextiles, and special rubber mixes—are all susceptible to deterioration at varying rates. This deterioration depends on climatic temperature and moisture effects, the resistance of a particular repair method of fatigue due to traffic, and the overall structural integrity of the pavement structure below. Therefore, a realistic, comprehensive, yet practical laboratory testing technique is needed to evaluate performance, life span, and economic implication of individual asphalt pavement repair methods.

Reflection cracking in a broad sense can be described as the result of stress concentration caused by horizontal and vertical movements at joints or cracks in the pavement (*4,5*). Horizontal movement and corresponding tensile stress are caused by low-temperature shrinkage; vertical movement and

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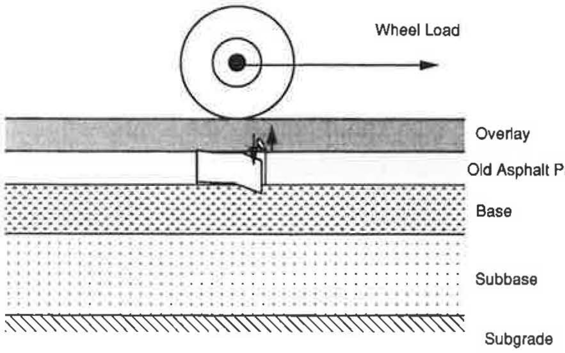

FIGURE 1 Shear stress in overlay due to crack in old asphalt.

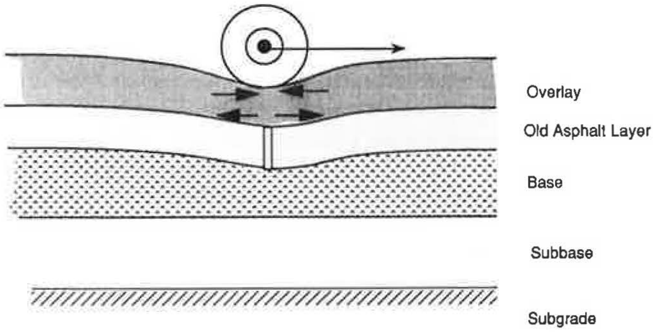

FIGURE 2 Bending stress in overlay.

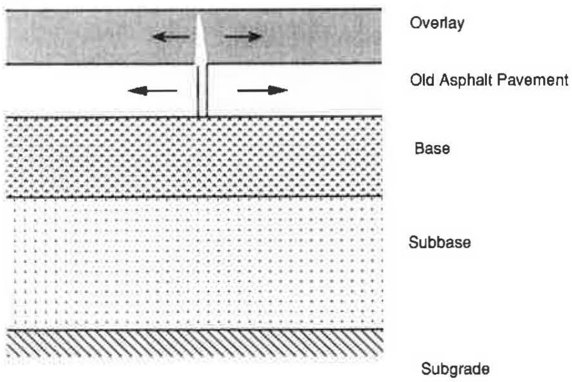

FIGURE 3 Crack formation in overlay due to thermal shrinkage.

corresponding shear stress are caused by the traffic load. A contributing factor to the development of tensile stresses is the high thermal conductivity of subgrade; contributing to the development of shear stresses is a weak pavement structure. Furthermore, a contact stress concentration develops under the crack edges between the old asphalt pavement and the granular base, causing the granular base to settle in that area. As a result (and dependent on the extent of the settlement), bending of the overlay occurs. Consequently, the overlay above the crack in the old pavement is stressed by shear, tensile, and bending stresses simultaneously.

It is clear that to fully understand the process of reflection cracking and to propose effective measures for arresting this type of cracking, laboratory testing using dynamic shear and tensile stress loading simultaneously must be carried out. Similarly, to evaluate properly various rehabilitation measures applied to cracked PCC or AC, such combined loading must be used.

The objective of the presented research work was to develop CMTS and to carry out its initial evaluation. The testing program was focused on resistance of AC to the combined effect of tensile stress and dynamic shear loading. In addition, to further illustrate the importance of this type of testing in evaluating the use of geogrids in improving the material resistance to failure under these loading conditions, plain AC was compared with AC reinforced by a geogrid. This program has been carried out using asphalt concrete slab specimens extracted from an experimental overlay that was constructed on the campus of the National Research Council of Canada.

TENSILE AND SHEAR TESTING TABLE (CMTS)

The concept of CMTS is rather simple; it is shown schematically in Figure 4. The system resembles a table consisting of two halves: one half of the table can move horizontally, and the other half can move vertically. When an asphalt specimen is fixed to the top of this table (i.e., to both halves, Figure 4), the horizontal movement of one half will generate tensile stress in the specimen, and the vertical movement of the other half will generate shear stress. Depending on the AC slab fixation to the table and on other boundary conditions, the vertical movement may also translate to a bending movement.

The main components of this new testing table are two thick sheets of steel 60.0 × 60.0 × 2.5 cm (24 × 24 × 1 in.), as shown in the overall photograph of CMTS (Figure 5). As described, one half of this table moves in the horizontal direction (referred to as the "horizontal plate"), and the other moves in the vertical direction ("vertical plate"). Horizontal movement is facilitated by the use of four linear bearings mounted on the bottom of the horizontal plate, moving along two heavy horizontal rods. Vertical movement is arranged by using two large commercially available tool-making die plates. The vertical dynamic (cycling) movement is provided by a hydraulically driven loading jack, as seen in Figure 5. The horizontal movement of the horizontal plate (i.e., the strain rate) is controlled through a variable-speed electric motor and set of gears.

Undesirable horizontal movement of the vertical plate, caused by large horizontal forces transmitted through the AC slab during testing, is restricted by two ball bearings mounted on consoles and acting on the vertical plate. Similarly, undesirable vertical movement of the horizontal plate, caused by vertical force transmitted to this plate through the AC specimen, is restricted by a similar arrangement. Furthermore, the weight of the vertical plate is counter-balanced by a dead load, so stresses caused by the weight of this plate are not transmitted to the tested specimen.

To facilitate testing, slab specimens are glued onto two steel plates (away from the testing table). These plates are held together by two aluminum handles attached to the side of the plates by a set of screws. After the glue is set, this assembly is placed on the testing table and firmly bolted to the horizontal and vertical plates of the CMTS. The handles are then removed, and the sample is ready for testing. In this way,

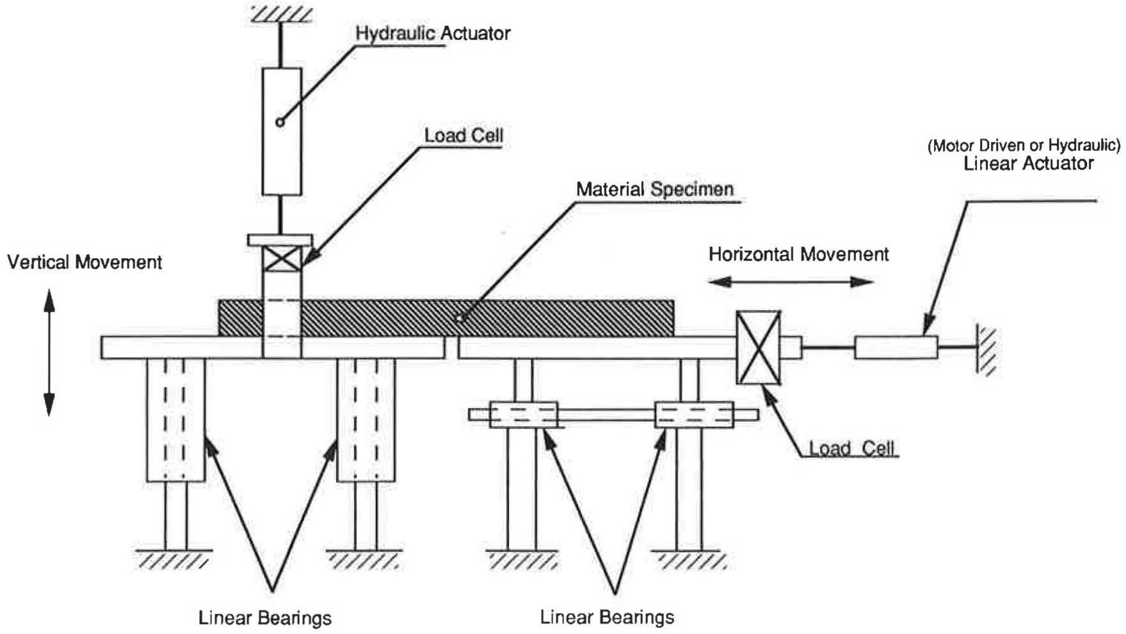

FIGURE 4 Concept of CMTS.

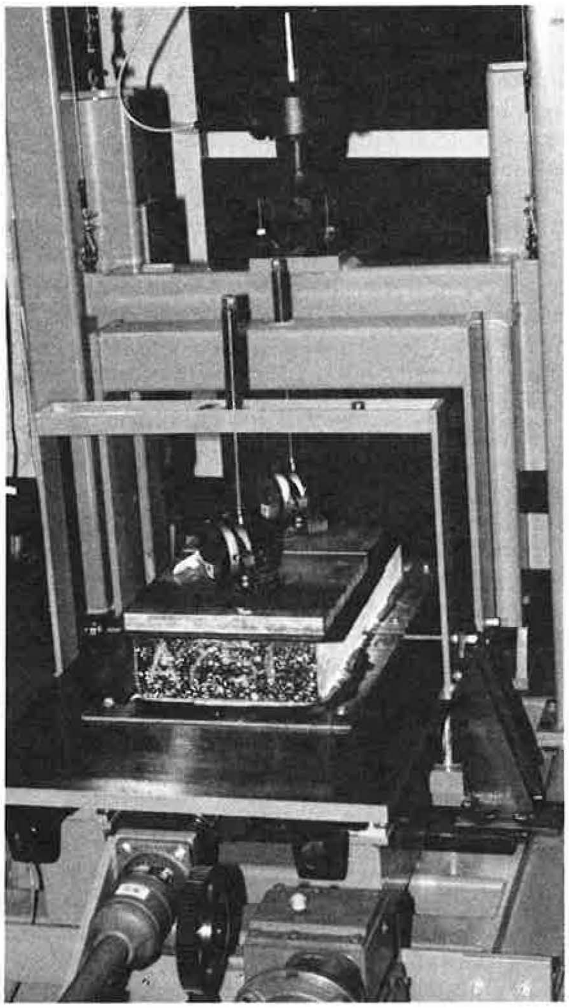

FIGURE 5 CMTS: thick AC slab ready for testing.

any number of samples can be prepared before the testing without tying up the CMTS.

A high-speed PC data acquisition system monitors the load cells, displacement transducers, and temperature sensors. Data processing computer programs are then used for data analysis and graphical output of the test results.

The CMTS will soon be relocated into a large cold room so that the effect of temperature changes (to −40°C) can be included in future research programs. The intellectual property of the CMTS has been protected. Interested companies or other agencies, however, can contact the authors for a licensing agreement.

LAYOUT OF FIELD TRIAL

As mentioned, the main objective of this project was to test the CMTS, using plain and geogrid-reinforced AC slabs. To obtain realistic samples, the AC slabs were extracted from a road test section constructed with standard paving equipment. The field preparation was carried out on the campus of the National Research Council of Canada in Ottawa, Ontario, on May 3, 1991. The selected site was a very lightly trafficked service road, thus allowing total closure of the site (half of the road) to traffic and eliminating operational disruption. The size of the test section was 15 m (50 ft) long and 3 m (10 ft) wide.

Before the asphalt was placed, the site was cleaned and then the old asphalt spread with a thin layer of sand. The purpose was to seal small existing cracks and to even out some irregularities. At the same time, the thin layer of sand prevented the new asphalt from adhering to the old, thus allowing easy removal of the asphalt slab samples from the site. A standard hot asphalt mix known as HL4 designed by the Ministry of Transportation of Ontario was used.

Once preliminary preparations were completed, the asphalt spreader was then backed over the sand in order to lay down a lift of HL-4 asphalt mix approximately 37 mm (1.5 in.) thick over the first half of the total length [i.e., first 7.5 m (25 ft)]. The thickness of the lift in the second half (i.e., the next 7.5 m) was increased to 50 mm (2 in.). One meter at the beginning of the first layer was used as a ramp for the compactor, resulting in the total area of 14 × 3 m available for testing. A portion of this uncompacted first lift was then covered with a 3-ton polyester geogrid. The second lift was laid over the entire test section, consisting of 37 mm over the first 7.5 m and 50 mm over the second 7.5 m. The entire area was then compacted by a standard Dynapac compactor and then by a rubber tire roller using an appropriate number of passes. The final compacted section measured approximately 7.5 m × 3.0 m × 75 mm (25 ft × 10 ft × 3 in.) and 7.5 m × 3.0 m × 10 mm (25 ft × 10 ft × 4 in.). More than 200 cores were extracted from this section in order to characterize its various parts—thin, thick, plain, and reinforced subsections—according to density and indirect tensile strength. In addition, many slabs 30 × 60 cm (12 × 24 in.) were cut and transported to the laboratory for testing. Great care was exercised in lifting slabs from the pavement to avoid any damage. This was accomplished by supporting the slabs at all times with thick plywood sheets.

LABORATORY TESTING

As discussed, many times a combination of the tensile stress and the shear stress can be critical to the integrity of the asphalt layer. In addition to the plain AC, this loading condition also poses another very important question: How will AC reinforced by a geogrid respond to such a stress combination? To understand fully the effect of the combined tensile and shear loading on AC, plain and reinforced, an entire range of the stress combination was applied to the test specimens. Because AC is a viscoelastic-plastic material that creeps in time with load, there are three possibilities for applying the tensile stress: constant strain, constant stress, and stress relaxation. The constant strain test (i.e., horizontal movement only) does not pose a problem, except that the resulting tensile stress is a function of the strain rate. Therefore, it is important to consider the rate of applied strain. Such direct tensile stress tests on slab specimens are used in many laboratories, usually under uninterrupted constant strain rate control. A stress relaxation test is also easy to perform: rapidly apply a tensile stress and allow the stress to relax. Once movement of the horizontal plate is stopped, the tensile stress in the AC slab will drop rather quickly. For a constant stress test, the horizontal movement of the table must continue, but its speed (i.e., the strain rate) must be controlled to compensate for stress relaxation of AC and failure progression (cracks propagation) during testing. Considering these possibilities, a range of the tensile and shear stress combinations was determined as follows:

- Tensile stress only (i.e., direct tensile test based on constant strain);
- Initial tensile stress with relaxation (i.e., constant displacement) combined with a dynamic shear;
- Constant tensile stress without relaxation and combined with a dynamic shear; and
- Dynamic shear only.

During these tests the forces and displacements are monitored by high-speed data acquisition equipment. In addition, the crack initiation, development, and propagation is continuously being observed and recorded using photo and video cameras. The video recording is particularly effective during the cycling of the vertical plate because the progressive nature of failure of the AC can be easily followed.

RESULTS

The testing program reported in this paper has been carried out at a room temperature of 22°C using the following types of test:

1. Direct tensile stress, in which only the horizontal plate is moving in a constant strain rate mode; and
2. Constant tensile stress combined with dynamic shear, in which the movement of the horizontal plate is load-controlled and the cyclic movement of the vertical plate is displacement-controlled (±1.27 mm/±0.05 in.).

An aspect of stress relaxation was also included in the direct tensile stress test in order to investigate the characteristic creep behavior of AC: soon after peak load was observed, the movement of the horizontal plate was arrested for a short period of time, until the load decreased by 50 percent (usually 30 sec), and then horizontal displacement recommenced. As Figures 6 and 7 indicate, the load rapidly increased to another peak, reaching the envelope of a continuous test. After this secondary peak, the load continued along a load displacement curve similar to that expected for a test without stress relaxation.

Figure 6 depicts typical load-versus-displacement relationships of thin AC slabs, plain and geogrid-reinforced; Figure 7 shows the same relationships for thick AC slabs. One might argue that instead of load, tensile stress should be used for comparison purposes as in Table 1, because cross sections of samples are not identical. This comparison would be realistic only up to the load displacement peak, at which massive cracking failure occurs. After this failure, the area of the cross section cannot be determined because of the propagation of cracks. Moreover, in the case of reinforced samples, the load, after the failure of AC, is transmitted only by the geogrid and the stress definition becomes meaningless. It is clear from Figure 6 that the plain AC slabs lost their entire strength at about 20 mm (0.8 in.) of total displacement, at which point the slabs failed and were practically pulled apart. On the other hand, the AC slabs reinforced by a geogrid behaved quite differently. In Figure 6 the first part of the R143 load deformation curve—that is, up to about 12 mm (0.4 in.) of displacement—is similar to that of plain AC. Following this, however, the "strength" of the slab increased and continued to resist horizontal deformation up to a total displacement of about 35 mm (1.4 in.). This observation indicates that during the first part of the test, load is activated by the strength of the AC alone. After a partial failure of the AC and a sufficient

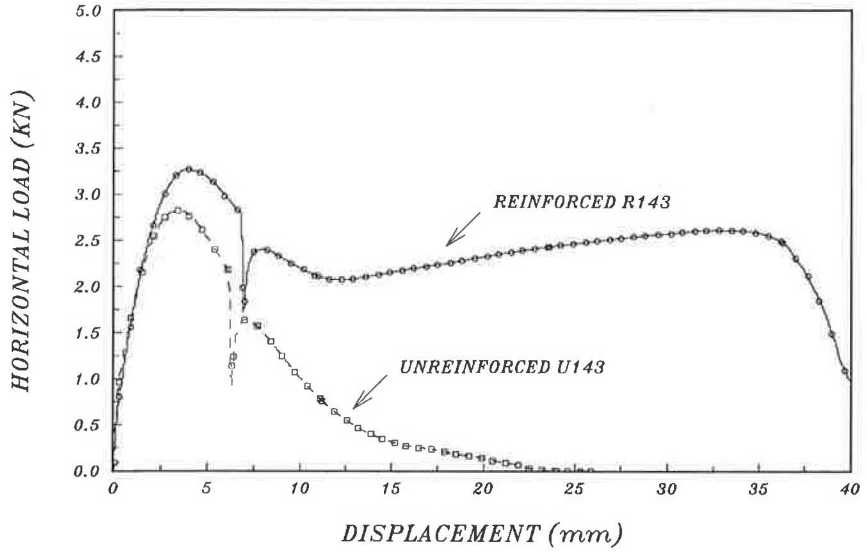

FIGURE 6 Interrupted constant strain rate tensile test, thin AC slabs (approximately 60 mm).

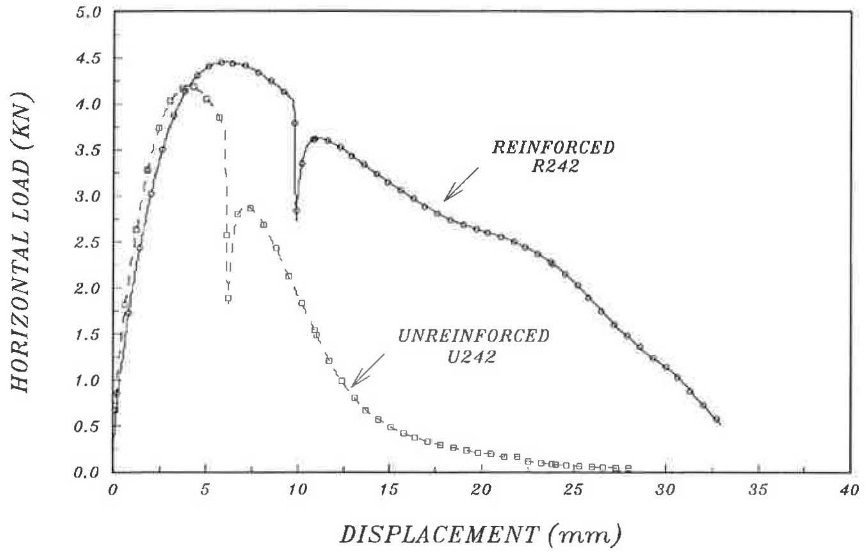

FIGURE 7 Interrupted constant strain rate tensile test, thick AC slabs (approximately 90 mm).

TABLE 1 Direct Tensile Stress, Strain Rate: 4 mm/min (0.15 in./min)

Sample		Plain				Sample	Reinforced			
		Depth (mm)	Peak Load (kN)	Peak Stress (MPa)	Peak Displ. (mm)		Depth (mm)	Peak Load (kn)	Peak Stress (MPa)	Peak Displ. (mm)
Thin	U143	60.4	2.81	0.153	3.7	R142	58.6	3.31	0.185	4.2
	U142	61.2	3.08	0.167	3.2	R143	71.4	3.27	0.185	4.0
		60.8	2.94	0.160	3.5	-	65.0	3.29	0.186	4.1
Thick	U243	92.2	3.18	0.122	4.5	R242	96.0	4.46	0.149	6.2
	U242	85.8	4.19	0.150	4.0	R243	96.7	4.97	0.172	5.5
Average		89.0	3.68	0.136	4.3		96.3	4.72	0.160	5.9

deformation, load is transferred to the geogrid and it becomes the only stress-resisting structural element. In other words, the second part of Curve R143 in Figure 6 represents the tensile strength of the geogrid and its interlock within the AC. The behavior of thick samples shown in Figure 7 is similar to that of thin samples shown in Figure 6, except that the load does not increase after being transferred to the geogrid. In this case, the interlock between the geogrid and the AC was not as effective as in the case of the thin samples.

The results of all the direct tensile strength tests carried out using four plain AC slabs and four reinforced AC slabs are also summarized in Table 1. It can be seen not only that is the peak stress higher for reinforced AC, but also that the peak displacement is considerably larger. These data indicate that a reinforced AC at room temperature (22°C) does not fail in tension in an abrupt manner (i.e., deforming as an elastic body up to a breaking point). Instead, the failure is initiated through small cracks and, at the same time, the geogrid begins to activate.

The second part of the testing program was carried out, combining horizontal tensile stress with vertical shear stress. For these tests, small loading frames were attached to both horizontal and vertical plates (i.e., across and above the plates) so that a vertical static load could be applied to the top of both sample halves (Figure 5). Relatively uniform stress distribution was accomplished by using thick (25 mm) aluminum 300 × 300 mm plates resting on thin (0.6 cm) sheets of rubber. The load was applied through a large screw and a loading cell. The main reason for this arrangement was to eliminate vertical tensile stress on the glued bottom of the slabs during the vertical cyclic movement of the vertical plate. The overall procedure for these tests followed these steps:

1. Horizontal load was applied at the rate of 4 mm/min (0.15 in./min) up to 1.11 kN (250 lbf) for thin samples and 1.78 kN (400 lbf) for thick samples. At this stage the movement of the horizontal plate was stopped.
2. Immediately after, the plates on top of the sample were loaded through the screw–load cell arrangements by 4.45 kN (1,000 lbf) resulting in 47.9 kPa pressure between the loading plates and the surface of the AC slabs.
3. As soon as the sample was loaded by the top plates, the vertical plate started to cycle in vertical movement with a frequency of 2.5 Hz and ± 1.25 mm (0.05 in.) from the zero position. At the same time movement of the horizontal plate resumed in order to maintain a constant tensile load of 0.67 kN (150 lbf) for thin samples and 1.11 kN (250 lbf) for thick samples.
4. After failure, defined as a single continuous crack from top to bottom and across the sample, the cycling of the vertical plate was stopped.
5. The movement of the horizontal plate continued at the top constant strain rate (only for reinforced slabs) in order to evaluate the geogrid-AC interlock. This determination can be seen as large peaks at the end of the graphs (Figures 8 and 9).

Figures 8 and 9 represent time versus horizontal force for plain and reinforced AC under conditions of combined constant tensile stress and dynamic shear stress for thin (approximately 60 mm) and thick (approximately 90 mm) AC slabs, respectively. It should be noted that measured force is used in this paper, i.e., not converted into stress. The reason is that as cracks initiate and later propagate, the area of the slab cross section is essentially indeterminate.

The first three test steps usually take 30 to 50 sec. After that, the vertical plate starts to cycle, not only imposing large shear stress in the central cross section of the slab, but also generating a horizontal force. The total horizontal force in these figures consists, therefore, of two components: one is caused by the movement of the horizontal plate and the second is generated by movement of the vertical plate. This can easily be seen on all four graphs in Figures 8 and 9. The fluctuation of horizontal force due to the cycling of the vertical

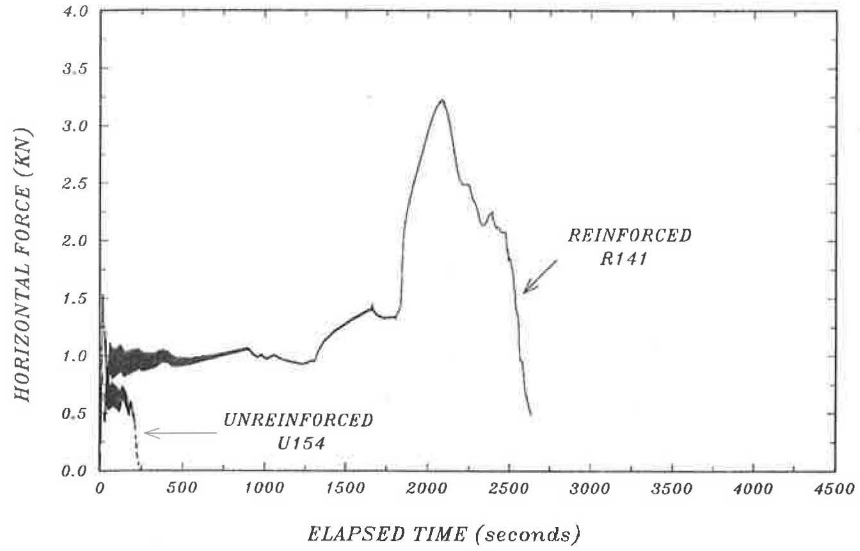

FIGURE 8 Combined tensile and shear stress test, thin AC samples (approximately 60 mm).

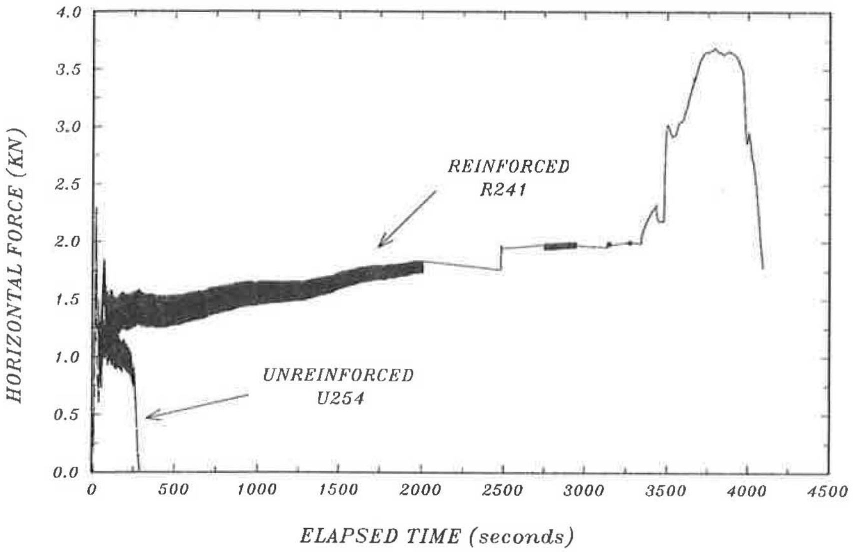

FIGURE 9 Combined tensile and shear stress test, thick AC samples (approximately 90 mm).

plate is quite large at the beginning of the test, but slowly diminishes with cycling as the slab loses its strength.

FAILURE MODES

The close observation of crack initiation and propagation, including an overall mode of failure, revealed several interesting facts.

Unreinforced AC

Cracks begin in the central region and at the bottom of the AC slabs, where tensile stress is the highest. These cracks are at the end of the mounting plates and the glue, where the highest stress concentration exists. The bottom cracks propagate upward very quickly and soon are joined by surface cracks propagating downward, as seen in Figure 10. Both thin and thick slabs fail between 400 and 500 cycles.

FIGURE 10 Failure mode-cracking pattern for unreinforced AC slab during combined tensile and shear stress test.

Geogrid-Reinforced AC

The first cracks appear at the bottom of the slabs. Besides the vertical cracking, the slabs also crack horizontally at the bottom just above the glue. This is not a failure of the AC; instead, the slabs are being lifted from the mounting plates because of the vertical movement of the vertical plate. As a result, the slabs lose bond 5 to 6 cm from the edge of the mounting plates.

The vertical cracks propagate upward with continued cycling to the level of the geogrid, where they are arrested. A simplified finite element modeling of this test was carried out to explain some aspects of the failure mechanism. This analysis showed that in the middle of the slab height, for these types of boundary conditions and loading, the shear stress is the highest. This fact coincides with observations of these tests, revealing horizontal cracking at the level of the geogrid. Sometimes this cracking occurs as a change in the direction of cracking from vertical to horizontal, yet sometimes these horizontal cracks are self-initiated before they are joined by the bottom vertical cracks. This type of failure progresses slowly and usually takes about 5,000 cycles and large horizontal deformation before further vertical cracking occurs at the top of the samples (Figure 11, thin sample). Horizontal cracking or delamination at the level of the geogrid indicates poor interlock between the geogrid and asphalt concrete; it also indicates poor asphalt mix and geogrid design. Such delamination could be a serious problem leading to pavement failure, that is, to the disintegration of the asphalt concrete

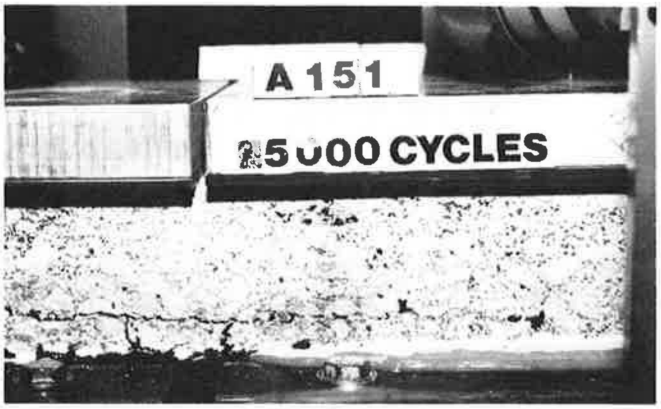

FIGURE 11 Horizontal cracking at level of geogrid due to shear load, thin AC slab.

layer above the geogrid. It is clear that there is a need to develop an "integrated" design encompassing the design of the geogrid with the mix. For a geogrid applied to an overlay, the presented testing technique will be useful in developing an optimum overlay thickness.

CONCLUSIONS

This paper describes the development of a new piece of laboratory equipment: CMTS. The first application has been for testing the mechanical properties of asphalt concrete. The main advantage of the CMTS is its ability to combine tensile and dynamic shear stresses in a single test. The results of the first testing program presented here demonstrate the importance of considering the combination of tensile shear loading, which very often occurs in real pavement. The main conclusions can be summarized as follows:

1. The failure mechanism of unreinforced asphalt concrete due to the tensile loading begins at the bottom of the layer. This is caused by the fact (confirmed by finite element stress analysis) that shear stress is highest at the bottom due to fixation (i.e., gluing in the experiment or, in a real situation, the bond between an overlay and the surface of the old pavement). In pavement, cracks may also be initiated at the surface, if construction cracking caused by steel drum compactors (known as checking) is present.
2. Dynamic shear stress greatly accelerates tensile cracking, leading to a fast progressive failure of unreinforced asphalt concrete.
3. The presence of a geogrid can arrest bottom vertical cracks and considerably slow failure. This is true only if a good interlock between the geogrids and asphalt concrete is achieved during construction. Because dynamic shear stress can generate horizontal cracking on the geogrid level, the development of a proper construction technique for reinforced asphalt pavement is of paramount importance.
4. It is expected that the type of testing developed here will assist in evaluating the interlock characteristic of a reinforced asphalt concrete.

This paper represents only the first phase of the research program carried out on the new testing equipment combining shear and tensile stresses. The second phase is already on its way to confirm findings presented in this paper and to evaluate new testing procedures (including effects of loading types, loading rates and different boundary-fixation conditions) on large numbers of lab experiments.

ACKNOWLEDGMENTS

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