DEVELOPMENT OF AUTOMATIC TORQUE BOND TEST

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Abstract

Proper bonding between adjacent pavement layers is very important to ensure good pavement performance. Manual torque bond test is known to be one of the tests to determine mechanical properties of bond between adjacent pavement layers. However, the test has several drawbacks that may affect the accuracy of results. This paper is focused on the development a mechanically controlled automatic torque bond test in order to eradicate the drawbacks associated with the manual torque bond test. A trial test and calibration of the newly developed apparatus was performed to ensure the accuracy of results. The nominal loading rate of the manual torque bond test performed at 600Nm/min was found to be lower than the target loading rate, leading to a lower measured shear strength compared to that of the automatic torque test. It was also found that the appearance of lateral shear would not significantly affect the shear strength.

Keywords: bond test, torque, shear, loading rate.

Abstrak

Ikatan yang tepat antara lapisan perkerasan yang berdekatan sangat penting untuk memastikan kinerja perkerasan yang baik. Uji ikatan torsi secara manual dikenal sebagai satu di antara uji-uji untuk menentukan sifat mekanis ikatan antara lapis-lapisan perkerasan yang berdempetan. Namun uji ini memiliki beberapa kelemahan yang dapat mempengaruhi akurasi hasil yang diperoleh. Makalah ini membahas pengembangan uji ikatan torsi otomatik yang dikendalikan secara mekanis dengan tujuan untuk mengurangi kelemahan yang terkait dengan uji ikatan torsi secara manual. Pengujian pendahuluan dan kalibrasi terhadap alat yang baru dikembangkan dilakukan untuk memastikan akurasi hasil yang diperoleh. Laju pembebanan nominal pada uji ikatan torsi secara manual, yang dilakukan pada 600Nm/menit, memberikan hasil yang lebih rendah daripada laju pembebanan yang diinginkan, sehingga menghasilkan kekuatan geser yang lebih rendah dibandingkan dengan hasil uji torsi otomatis. Hasil penelitian ini juga menunjukkan bahwa geser lateral tidak mempengaruhi kekuatan geser secara signifikan.

Kata-kata Kunci: uji ikatan, torsi, geser, laju pembebanan.

INTRODUCTION

Most of pavement design and evaluation techniques assume that adjacent pavement layers are fully bonded together and no displacement is developed between them. The bond between layers is very important to ensure that those layers work together as a composite structure to withstand traffic and environmental (e.g. temperature induced) loadings. To achieve that condition, a thin film of bituminous bond coat (or tack coat) is usually applied at the interfaces. However, full bonding is not always achieved and a number of pavement failures linked to poor bond condition have been reported (Shaat, 1992; Lepert et al., 1992; Hachiya and Sato, 1997; Raab and Partl, 1999; Sutanto, 2004).

Theoretical research showed that poor interlayer bond condition affects stress/strain distributions within a pavement structure and reduces the capability of the pavement to support traffic and environmental loadings (Shahin et al., 1987; Al Hakim, 1997; Hachiya and Sato, 1997; Kruntcheva et al., 2000; Romanoschi and Metcalf, 2001). When horizontal loadings exist, poor bond condition at the interface beneath the surfacing could cause slippage cracking or horizontal permanent deformation at the surfacing layer. Poor load transfer from the surfacing to the layer underneath, caused by the poor bond condition, leads to a high stress concentration within the surfacing material. Slippage cracking or horizontal permanent deformation will initiate at the top of the surfacing when the surfacing material is unable to withstand the induced horizontal stresses.

The review of theoretical investigations on the effect of bond on pavement performance showed that bond between layers is an important component of the whole pavement structure and proper bonding is essential to ensure good pavement performance. Because of that, the determination of mechanical properties of bond at the interface between layers is of significant importance.

Manual torque bond test is one of the tests to determine mechanical properties of bond at the interface between layers (Sutanto, 2009). The manual torque bond test has been widely used in the UK because it is included as a compulsory test in the certification of thin surfacing course systems in the UK (British British Board of Agreement, 2000). The test is performed manually by twisting the top of a (100 ± 5) mm diameter core specimen using a handheld torque wrench at a constant rate, inducing a twisting shear failure at the interface.

For practical reasons, the manual torque bond test is generally limited to the interface between thin surfacing and the lower layer material and is typically undertaken in-situ. Choi et al. (2005) developed a laboratory-based manual torque bond test that allows the test to be undertaken in a more controlled environment (Figure 1). This laboratory-based manual torque bond test is able to test the shear strength of an interface other than the interface below the surfacing by taking a full depth core and cutting the core specimen at the positions above and below the interface of interest. Testing at various temperatures is also possible by conditioning the core specimen in a temperature controlled cabinet.

The testing procedure of the manual torque bond test in the guidelines document SG3/98/173 (British British Board of Agreement, 2000) requires the torque is applied manually at a constant torque rate so that failure occurs in (60±30) seconds. This procedure results in difficulty in controlling the torque rate, because the torque strength is unknown and the value of the torque strength is also affected by the torque rate. To avoid the aforementioned difficulty, Choi et al. (2005) used a constant torque rate of 600Nm/minute, which was achieved by synchronising the movement of the torque dial gauge with the second hand of an analogue clock. Babtie (2000) also found it difficult to keep the application of torque parallel to the interface resulting in axial bending on the specimen. Additionally, it was reported that considerably high force is needed to twist off the surfacing and that sudden failure could lead to the risk of strains and falls to the operator. It is also interesting to note that the manual torque bond test is applied without lateral support at the top part of the specimen (see Figure 1). This condition may cause the appearance of lateral shear stress acting at the interface in addition to the interface shear stress induced by the torque.

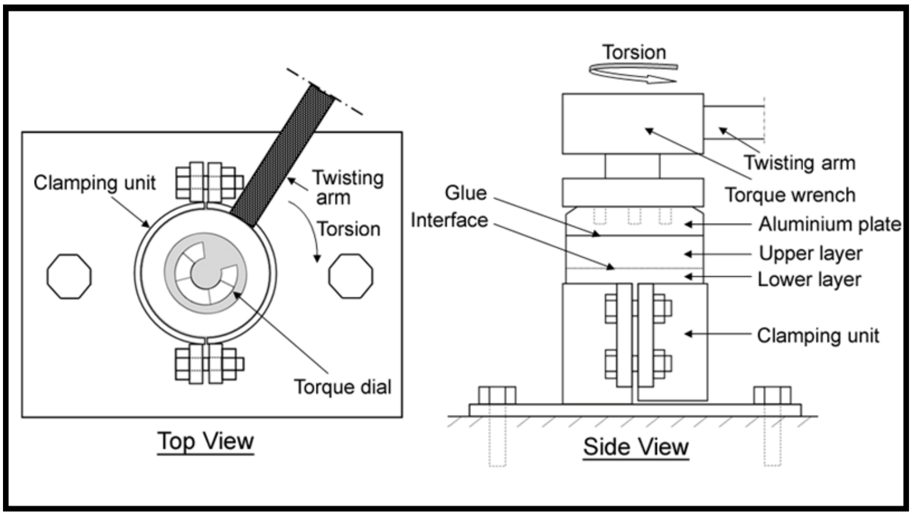

Figure 1 Schematic Diagram of the Laboratory Based Manual Torque Bond Test Developed by Choi *Et Al* (2005)

To eradicate the previously mentioned issues related to the manual torque bond test, a mechanically controlled automatic torque bond apparatus was developed in this research study. Although quite similar to the apparatus developed by Diakhaté et al. (2007), the apparatus developed in this research study uses a rack and pinion mechanism and is capable of transferring either tensile or compressive force to generate negative or positive torsional load. The automatic torque bond apparatus developed in this study was manufactured at the Civil Engineering Department, University of Nottingham.

DESIGN AND MANUFACTURE OF THE APPARATUS

The loading machine to be used in this study was an INSTRON servo-hydraulic testing machine. It comprises of a temperature controlled cabinet with a range of temperatures between -5 ˚C and 40˚C, a 100 kN servo hydraulic actuator, an axially mounted load cell and a Linear Variable Differential Transformer (LVDT). Because the testing machine is only capable to apply a vertical load or displacement, a simple rack and pinion mechanism is used in the automatic torque bond apparatus (Figure 2) to transfer the applied load or displacement and convert it into a torque or rotation respectively. Because the rack and pinion mechanism is able to transfer either tensile or compressive force to generate negative or positive torsional load, the apparatus is also able to perform a cyclic zero-mean torsional load. The force and linear displacement of the rack are measured using the load cell and LVDT incorporated in the testing machine.

The torque, torque rate, angular rotation and rotation rate are calculated using the following equations:

$$T = FR, \quad \dot{T} = \dot{F} R \qquad (1)$$

$$\theta = \frac{\delta}{R}, \quad \dot{\theta} = \frac{\dot{\delta}}{R} \qquad (2)$$

with T is the torque, F is the force applied through the rack, R is the pitch circle radius of the pinion gear, $\dot{T}$ is the torque rate, $\dot{F}$ is the loading rate of the rack, θ is the angular rotation of the pinion gear, δ is the linear displacement of the rack, $\dot{\theta}$ is the rotation rate of the pinion gear, and $\dot{\delta}$ is the displacement rate of the rack.

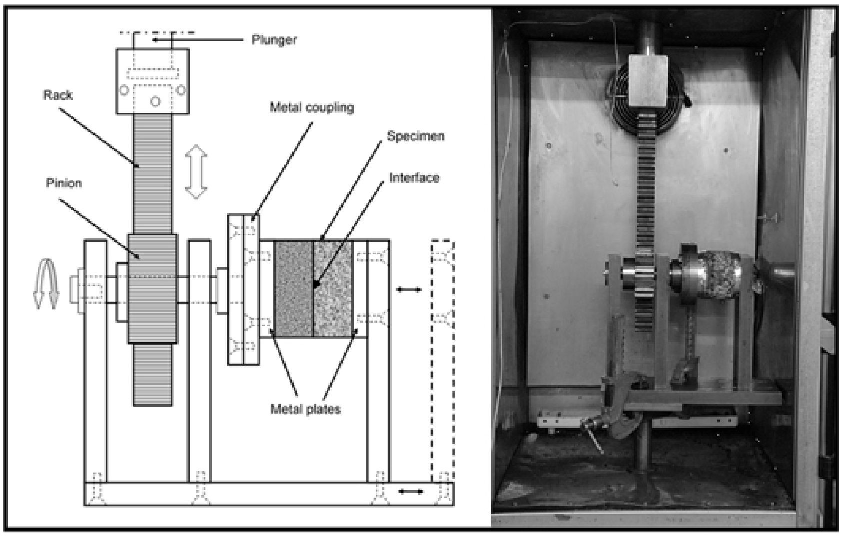

Figure 2 Schematic and Photograph of the Automatic Torque Bond Apparatus.

The dimension of the specimen to be tested dictated the dimension of the apparatus. Because the apparatus was intended to eradicate the issues in the manual torque bond test, it was decided to use a core specimen of 100 mm nominal diameter. Choi *et al.* (2005) showed that the interface torque strength obtained from a manual torque bond test on a 100 mm diameter core specimen at a constant torque rate of 600 Nm/min and a temperature of 10˚C could be up to 400 Nm. Therefore, the automatic torque bond apparatus was designed with a maximum capacity of 600 Nm to allow testing of a stronger interface or at a lower temperature. The designed maximum capacity dictated the dimension of the weakest point in the apparatus and it was found that the minimum diameter of a steel pin that locks the pinion gear into its shaft should be 5 mm. To allow quick and easy test setup, 100 mm diameter and 10 mm thick cylindrical metal platens were to be glued on top and bottom of the specimen so that the specimen can be easily placed into the test frame by bolting the metal platens.

The test requires a double-layered cylindrical specimen of 100 mm nominal diameter. A trial test (to be discussed later) revealed that the specimen needs to be trimmed at 20 mm below the interface in order to prevent failure at the bottom part of the specimen as well as to better simulate the position of the interface in the manual torque bond test. Prior to testing, the diameter of the cylindrical specimen is carefully measured using a vernier calliper. Metal loading platens are glued to the top and bottom surfaces of the specimen. The specimen is left until the glue hardens and gains sufficient strength. After the glue has gained sufficient strength, it is conditioned in a temperature-controlled cabinet for at least 5 hours prior to testing.

The cylindrical metal platens glued at both ends of the specimen are bolted to the automatic torque bond apparatus and a thread sealant is used to ensure that the bolts do not loosen during testing. The specimen and the apparatus are then placed inside a temperature-controlled cabinet and attached into an axial testing machine. To perform testing at a constant torque rate, a constant vertical force is applied into the rack of which the rate can be calculated using equation (1). For testing at a constant rotation rate, the rack is subjected to a constant vertical displacement rate calculated using equation (2). The vertical force and its corresponding displacement are measured using a load cell and an LVDT incorporated into an axial testing machine respectively. The applied torque is calculated from the measured vertical force using equation (1), while the corresponding rotation is calculated from the measured vertical displacement using equation (2).

After the automatic torque bond apparatus (Figure 2) had been manufactured, it was attached to the testing machine to calibrate the torque and its corresponding rotation and to check whether any play and/or friction existed within the system that may affect the accuracy of the results. The applied torque was calibrated by attaching a torque meter into the apparatus. A number of vertical forces were applied and the resultant torque readings from the torque meter were recorded. The applied torques were calculated from the applied vertical forces using equation (1) and then calibrated with the readings from the torque meter. The rotation of the pinion gear was calibrated by applying vertical displacements into the rack and the corresponding rotations of the metal coupling (shown in Figure 2), connected by a shaft into the pinion gear, were measured using an angle meter. The applied rotations were calculated from the applied vertical displacements using equation (2) and then calibrated with the rotations of the metal coupling.

The presence of any play within the system was checked by performing trial tests on a number of 14 mm Stone Mastic Asphalt over 20 mm Dense Bituminous Macadam (SMA/20DBM) specimens of 100 mm nominal diameter using two different loading rates (600 Nm/min and 180˚/min) at a temperature of 20˚C. Six identical tests were carried out for each test condition. Following the trial tests, a slip was found in the attachment of the rack to the actuator and a small modification to the attachment was carried out. A slight play was also found between the rack and the pinion gear and a support was then added at the back of the rack in order to eliminate the play. The presence of any friction within the bearing system was checked by applying a set of displacements into the rack without any specimen placed in the apparatus and monitoring the resistant forces. It was found that the resistant forces were less than 0.04 % of the of the maximum design load, which was considered very small and not significant.

It is interesting to discuss that for the trial testing at 180˚/min, some of the specimens failed at the bottom part of the 20DBM binder course. A visual observation on the 20 DBM layer revealed that its bottom part appeared to be highly voided. The air void content of the 20DBM was then measured by slicing a number of 20DMB cores (60 mm thick) into 3 parts (bottom, middle, and top) and it was found that the air void content at the bottom part was higher than that at the middle and upper parts. The relatively high air void content at the bottom part of the 20DBM appeared to weaken the torque strength of the material. Trimming the specimen at 20 mm below the interface of interest to discard the relatively high voided bottom part was found to successfully prevent failure within the asphalt layer. Besides preventing failure within the relatively high voided bottom part of the specimen, the trimming at 20mm below the interface was chosen in order to better the simulate the manual torque bond test because the guidelines document SG3/98/173 (British Board of Agreement, 2000) require the specimen to be held at 20 mm below the interface. The finding regarding the relatively low structural integrity of the relatively high voided bottom part of the specimen also indicates that the torque bond test appears to be not suitable for a double layered specimen containing a highly voided asphalt layer (e.g. porous asphalt) because the specimen may fail within the asphalt layer rather than at the interface between the adjacent layers.

COMPARISON BETWEEN MANUAL AND AUTOMATIC TORQUE BOND TESTS

After the automatic torque bond apparatus had been developed, it was necessary to compare the results obtained from the automatic torque bond test to those of the manual torque bond test. A series of manual and automatic torque bond tests were performed on SMA/20DBM and 10 mm proprietary Thin Surfacing over 20 mm Dense Bituminous Macadam (TS/20DBM) specimens of 100 mm nominal diameter. The tests were performed at a target torque rate of 600 Nm/min and temperature of 20°C. Five identical tests were undertaken for each material combination and test equipment.

Figure 3 shows a comparison of the nominal shear strength from the manual and automatic torque bond tests. The nominal shear strength is calculated from the measured peak torque using the following equation:

$$\tau = \frac{2T}{\pi R^3} \qquad (3)$$

with τ is the shear strength, T is the torque and R is the radius of the specimen. Because the torque rate is considered to be less accurate, the results from the manual torque bond test, as expected show higher Coefficients of Variation (COVs) than that shown by the results from the automatic torque bond test of the corresponding material combination. It is interesting to note that the results of the automatic torque bond test are (20-30) % higher than the results of the manual torque bond test. The difference was thought to be due to several drawbacks associated with the manual torque bond test, namely inaccurate torque rate, the appearance of lateral shear due to the absence of a lateral support at the top part of the specimen, and axial bending on the specimen due to the application of a torque that is not parallel to the interface.

To investigate the accuracy of the applied torque rate in the manual torque bond test, nominal torque rate is plotted against nominal shear strength from the manual torque bond test and the plot is presented in Figure 4. The nominal torque rate of the manual torque bond test is defined as the measured peak torque divided by the recorded time to failure. Figure 4 shows that most of the nominal torque rates from the manual torque bond test are below the target torque rate of 600 Nm/min. The figure also demonstrates that the nominal shear strength increases as the nominal torque rate increases. The trends of the data demonstrate that applying a nominal torque rate of 600 Nm/min would give nominal shear strength values of approximately 1.262 MPa for the TS1/20DBM specimen and approximately 1.296 MPa for the SMA/20DBM specimen. It should be noted that the actual torque rate could fluctuate during the test because there is a possibility that the operator would apply a high torque rate at the beginning of the loading and that the torque rate would gradually decrease as the force needed to induce the torque gradually increased.

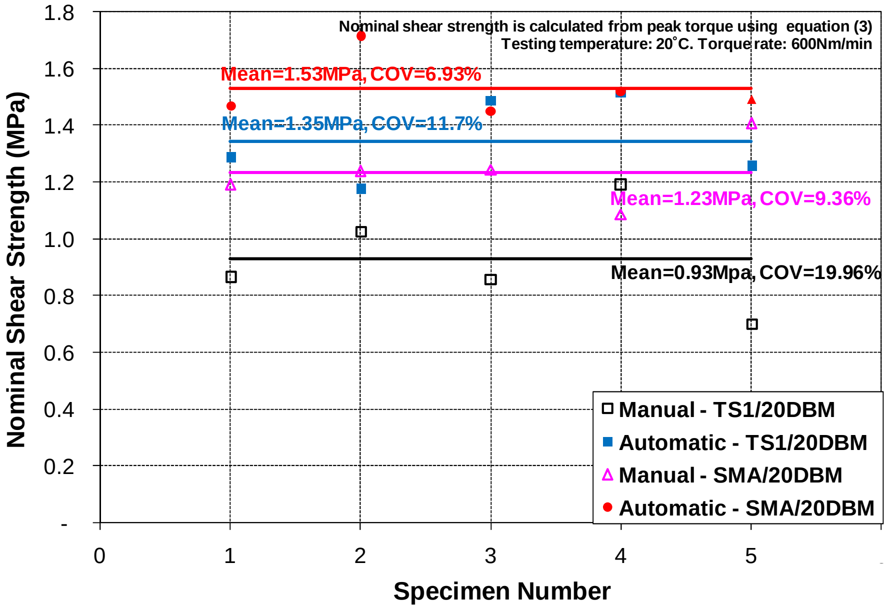

Figure 3 Comparison between Manual and Automatic Torque Bond Tests

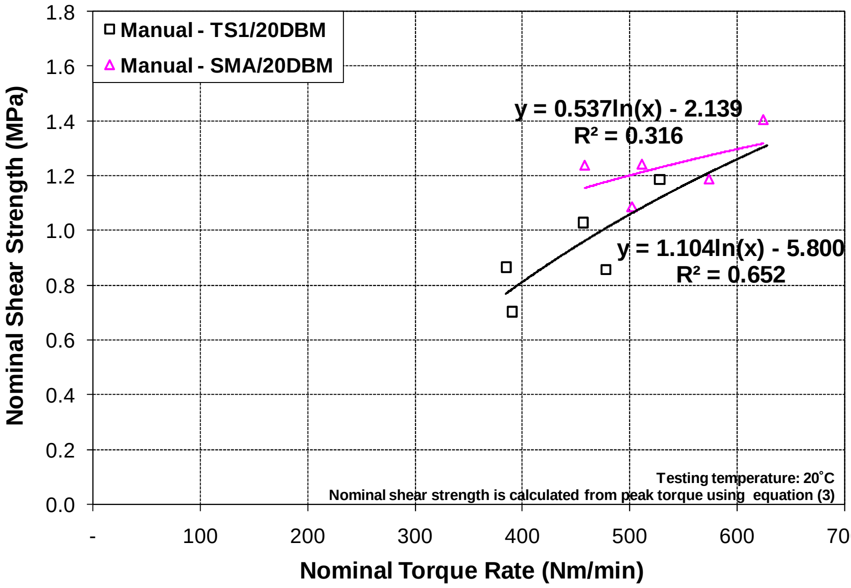

Figure 4 Nominal Torque Rate Versus Nominal Shear Strength Plot from the Manual Torque Bond Test

Because there is no lateral support at the top part of the specimen in the manual torque bond test (see Figure 1), lateral shear would appear at the interface (Figure 5), in addition to the measured torque. To investigate the significance of the lateral shear in the manual torque bond test, nominal lateral shear was calculated from the measured peak torque using the equation presented Figure 5. The length of the twisting arm of 0.8 m was used in the calculation. The results presented in Table 1 demonstrate that the values of the nominal lateral shear are very small compared to the nominal shear strengths presented in

Figure 3. Considering the variability of nominal shear strengths shown in Figure 3, the appearance of lateral shear would not significantly affect the shear strength.

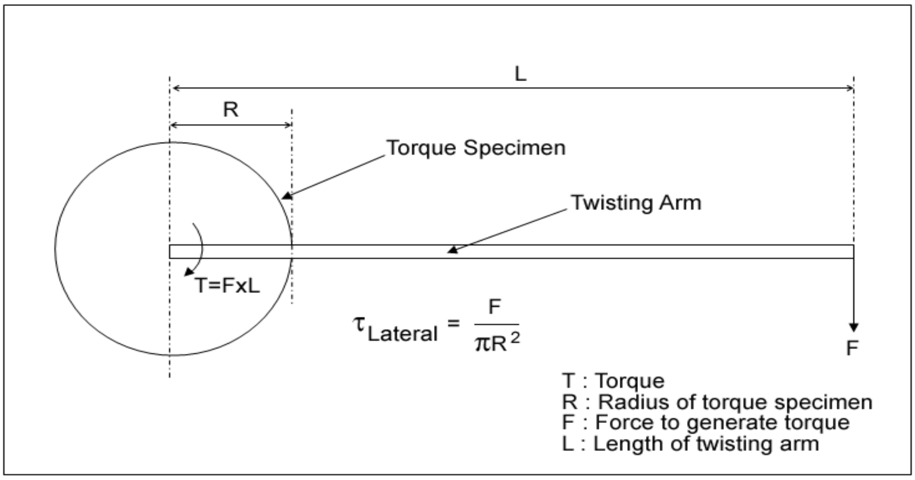

Figure 5 Lateral Shear Acting at the Interface

Table 1 Nominal Lateral Shear in the Manual Torque Bond Test

Specimen	Peak Torque (Nm)	Nominal Lateral Shear (MPa)
TS1/20DBM-1	160	0.0066
TS1/20DBM-2	190	0.0079
TS1/20DBM-3	159	0.0066
TS1/20DBM-4	220	0.0091
TS1/20DBM-5	130	0.0054
SMA/20DBM-1	220	0.0091
SMA/20DBM-2	229	0.0095
SMA/20DBM-3	230	0.0095
SMA/20DBM-4	201	0.0083
SMA/20DBM-5	260	0.0108

CONCLUSIONS

The following key points can be derived from the study:

1. At a constant torque rate of 600 Nm/min, the shear strength measured using the automatic torque test is higher than the shear strength measured using the manual torque bond test.
2. The nominal loading rate of the manual torque test performed at 600Nm/min has been found to be lower than the target loading rate, hence leading to the lower measured shear strength compared to the automatic torque test.
3. The results of the manual torque test on SMA/20DBM and TS1/20DBM specimens performed at 600 Nm/min and using a twisting arm of 0.8m in length show that the

values of nominal lateral shear are very small and not significant compared to that of the nominal shear strength.

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