Advanced Pull Test to Determine Adhesion Properties of Thin Surfaces for Pavement

Y. Xiao[1], M.F.C. van de Ven[2], S.P. Wu[3], M.F. Woldekidan[4]

（1 Faculty of Civil Engineering & Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, the Netherlands, yue.xiao@tudelft.nl）
（2 Faculty of Civil Engineering & Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, the Netherlands, m.f.c.vandeven@tudelft.nl）
（2 State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Luoshi Road No. 122, Wuhan, China, wusp@whut.edu.cn）
（4 Faculty of Civil Engineering & Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, the Netherlands, M.F.Woldekidan@tudelft.nl）

ABSTRACT

Thin surfaces are specially designed to provide significant additional surface properties to pavements without affecting other qualities of the surface such as ride quality and durability. In addition to economic benefits, thin surfaces can protect pavements against deterioration caused by traffic and weather. One of the most important properties of thin surfaces is their adhesion to the substrate layer. In order to avoid bond failure and/or slippage between the thin surface and the pavement layer, a strong adhesive strength is required. Different equipment and methods, such as a Torque Bond test and the UTEP (University of Texas at El Paso) Pull-Off test, are used to determine this adhesive strength. However, these bonding tests have no loading speed control system and are not easily to be placed in a climate room for a constant temperature test.

An advanced pull test method was designed and introduced in this paper for determine the adhesive strength at the interface between a thin surface layer and the substrate layer. In a climate chamber, a displacement/force controlled test was developed, in which the load-displacement curve till failure can be measured. The possible failure paths in the thin surface, at the interface between thin surface and in the asphalt mixture layer below are discussed. A Finite Element Model (FEM) was used to simulate the boundary effect due to the different sample preparation procedures, which includes with and without cut through thin surfaces into asphalt layer. Test results indicate that this advanced pull test can be used to determine the adhesion strength at the interface between the thin surface layer and substrate layer.

Keywords: Asphalt pavement; Thin surface; Pull test; Adhesion; Finite Element Model;

1 INTRODUCTION

In the new era with sustainable construction practises, it is common use to consider the structure capacity of the pavement and typical surface fracture separately. The sustainable approach focus then on a perpetual structure, with only moving a thin surface layer in time.

Application of this concept has given rise to a new class of thin or ultra-thin surfacing. Thin surfaces are specially designed to provide significant additional surface properties to a pavement structure and bridge decks without significantly affecting other qualities of the surface such as noise, ride quality or durability.

In this paper, a thin surface is defined as a new layer of an asphalt mixture or surface dressing on the existing pavement. Thin surfaces for road pavement include thin surface layers with thickness from 25mm to 40 mm and ultrathin surface layers with a thickness less than 25 mm.

Thin surface layers can be used to increase the durability and improve the safety on road pavements. Thin surface layers protect treated surfaces against external aggressive substances spilled by traffic such as oil, gasoline, hydraulic fluid, organic solvents and compounds, most chemicals, etc. It can also protect bituminous pavements against the weather exposure, as well as protect concrete pavement from weather exposure and bridge decks from chloride attack.

The adhesion of a surface layer to the underlying pavement structure is essential, particularly when the surface layer is very thin. These thin layers are not thick enough to carry traffic induced stresses without excellent adhesion. A good bond is even more important where there is a possibility of high braking and lateral stresses. In order to avoid bond failure and/or slippage between the thin surface and the pavement layer, a strong adhesive strength is required. Structural strength is only fully developed when all the layers in the pavement are well bonded, effectively forming a single layer. [1]

Different equipment and methods, such as a Torque Bond test and the UTEP (University of Texas at El Paso) Pull-Off test, are used to determine the adhesion [2]. Van Leest has reported about some tests that were performed on antiskid layers for runways, a typical thin surface layer, in the past [3]. A simple pull test (see Figure 1, left one) was used to measure the bonding strength between the antiskid surface layer and asphalt mixture layer in the field. Other test methods like the Torque Bond test (see Figure 1, right one), which was originally developed in Sweden for the in-situ assessment of bond conditions, has been adopted in the UK as part of the approval system for thin surfacing systems. Furthermore the UTEP Pull-Off test was developed at the University of Texas at El Paso (UTEP). This test was widely used for evaluating the adhesion properties of interlayers [4, 5]. However, these bonding tests have no loading speed control system and are not easily to be placed in a climate room for constant temperature test.

Figure 1 Sample pull test setups that can be used in the fields

This paper introduces a self-designed Pull test method for analysing the adhesion properties between thin surface layers and the mixture layer below. Adhesive tensile strength of the interface can be evaluated with this Pull test. FEM is employed in this paper to explain the sample preparation process in order to avoid the stress contribution from outside of test area.

2 MATERIALS

Cylindrical cores with 140 mm diameter were collected in field sections from airfield runways in the Netherlands. All the cores contained a thin surface layer on top of asphalt mixture layers. The thin surface is called antiskid layer. The top layers were constructed in different years by the contractor Possehl Spezialbau GMBH. The detail construction procedure is patent protected. Six airport runways are numbered from No.1 to No.6 in this paper. No. 1 Airport has the newest antiskid layer (constructed in 2009) while No.6 has the oldest (constructed in 1989). Aggregate used for thin surface layer is a special basalt with aggregate sizes between 1.5 - 3.5 mm from one certain place in Germany. [6]

The thickness of top layer is approximately 5 mm, and can be considered as a seal. Table 1 presents the structure characteristics of these antiskid layers.

Table 1 structure characteristics of antiskid layers

	Void content [%]	Binder content [%]	Aggregate content [%]
No. 1 Airport	18.16	28.72	53.11
No. 2 Airport	18.28	27.62	54.05
No. 3 Airport	17.25	25.17	57.67
No. 4 Airport	16.21	25.50	58.42
No. 5 Airport	17.23	27.67	55.06
No. 6 Airport	25.82	25.44	49.67

3 PULL TEST DESIGN

A wide range of test methods has been introduced to evaluate the bond properties of surface layers on pavement. Pull tests are becoming popular because they can be done fast also in the field [7]. The test can be used to quantify tensile adhesive strength and identify a failure mode, showing the weakest place in the tested system. However, the measured tensile strength is only the adhesion property at the time of testing and cannot be used to predict for other temperatures and environmental conditions. The tests are neither force nor displacement controlled, and there is no temperature control. Stress versus strain curves cannot be obtained for further analysis. Hence, it is necessary to design a suitable setup to test the adhesion between a thin surface layer and the layer below.

3.1 Pull Test Setup

Cylindrical cuts with 50 mm diameter were first cored on the samples to a depth of 10 mm to make sure that the drill passed the antiskid surface layer. A steel plate was then glued to the dried and cleaned surface with X60 glue. After the glue got its full strength, the entire sample was placed upside down on the test table in a temperature controlled chamber. The surface layer was pulled off and the tensile force was measured. [8]

Figure 2 shows the sample preparation and setup for the pull test. The tensile load is applied to the core through the steel plate glued to the top surface. Three displacement sensors were used to record the strain data during the pull test.

Figure 2 Sample preparation and test setup for pull test

3.2 FEM Simulation

A cut through the surface layer into the asphalt mixture layer below was introduced during the sample preparations. Finite Element Modelling (FEM) was used to simulation the differences between making a cut and without a cut. In the FEM modelling, the asphalt mixture layer and the surface thin layer were both simulated as elastic materials. Table 2 presents the used input parameters for the material properties.

Table 2 Input material properties for FEM

	Asphalt mixture	Surface layer	Steel plate
Stiffness [Mpa]	3000	1000	200000
Passion’s ratio	0.35	0.35	0.2

Figure 3 and Figure 4 show the stress and strain configurations when a vertical tensile force was applied. When a tensile force is applied, response stresses and strains are distributed uniformly both in the surface layer and asphalt mixture layer. Without cut, a high stress and strain contribution can be seen in the edge area surrounding the loaded area, see Figure 3. These stresses can prevent the sample from failure. Hence, this contribution has a significant influence on the final pull strength.

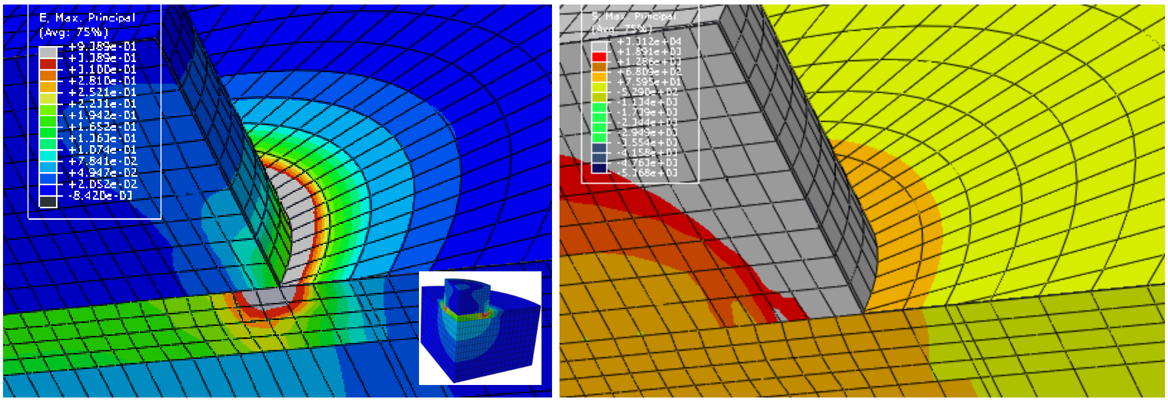

Figure 3 Pull test without cut through into the asphalt mix

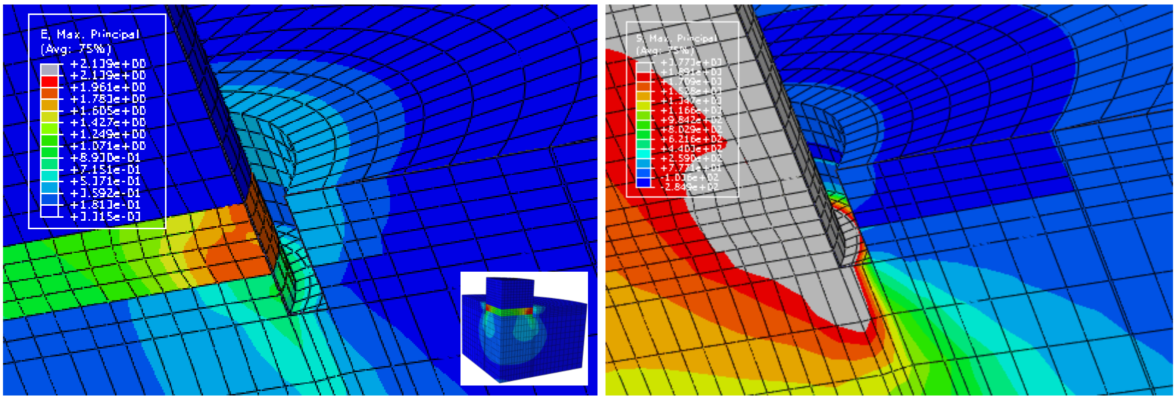

Figure 4 Pull test with cut through into the asphalt mix

With a cut through the thin surface layer, as Figure 4 shows, the applied force is applied at a certain defined area. The strain is also limited at the tested sample. With this treatment during the sample preparation, the influence from edges can be easily avoided. So it is important for the pull tests to make a cylindrical cut through the thin surface layer into the substrate layer to get reasonable results. Another point is that the load has gone through the thin surface area. If it does not fail in the thin surfacing, its strength is higher than the failure load.

Table 3 presents the FEM results of principal stresses and strains at the interface. Results of one node at the edge of planned test area and one node inside the test area were plotted. The applied tensile loading is 1963N (equal to 1 MPa) in this simulation. It is obviously to see that the principal stresses and strains is much lower in the simulation without a cut, which indicate higher applied loading is needed before failure accrued.

Table 3 Simulation results on generated stresses and strains

Inside the edge		Maximum Principal Stress [MPa]	Maximum Principal Strain
	Without cut	0.092	0.067
	With cut	0.9684	0.628
At the edge		Maximum Principal Stress	Maximum Principal Strain
	Without cut	0.076	0.059
	With cut	1.376	0.867

4 RESULTS ANALYSIS

The tensile adhesion strength is defined as the tensile force divided by the area of fractured surface :

Where P is the tensile adhesion strength, Mpa; F is tensile force at failure, N; A is the area of failure surface, mm^2.

Four different modes of failure can be defined when applying a load with this setup. These different failure modes provide valuable information about the thin surface layer and the asphalt mixture layer below. First, if the failure occurs at the bond surface, which is the interface, the pull-off strength is in fact the tensile adhesive strength. In this case, the ultimate load is real value of the adhesion between the surface layer and the substrate asphalt layer. Second, when the failure occurs between the steel plate and the thin surface, there is an adhesive failure. In this case, the tensile strength of the overlay system is higher than the failure load, and a stronger glue is needed. Third, if the failure occurs in the surface layer material, the surface layer is the weakest point of the system, while the adhesion strength at the interface exceeds the applied stress. Fourth, if the failure occurs in the substrate, or underlying concrete, the surface layer and the interface are stronger than the layer below. In this case, the failure stress is the tensile stress of the substrate concrete. In some cases the failure occurs partially along the bond surface and partially in either the overlay or substrate concrete, and the failure mode is a combination of two or more of the failures discussed above.

Figure 5 Failure surfaces at the interface

The illustration in Figure 5 is an example of a failure mode at the interface. In this research, most of the tests failed at the interface, only 3 out of 50 of them show a combined failure. Test results of combined failure is then not included in the data analysis.

4.1 Comparison

Pull tests were performed on cores both with cut through and without cut through into the substrate asphalt mixture layer. The difference between these two different sample preparation methods are compared and analysed. The test condition used was 20 ºC for the temperature and load controlled speed is 0.025 $N/mm^2 \cdot s$. The test results are showing in Table 4 and Figure 6.

Table 4 The differences between with cut and without cut

	Applied failure force [kN]		Increased percentage
	With cut	Without cut	
Sample 1	1.684	2.578	53.0 %
Sample 2	1.428	1.868	30.8 %

From left graph in Figure 6, it can be see clearly that the applied failure force is much higher when there is no cut compared to the result after cut. In Table 4, a maximum failure force increase of 30.8% and 53% is shown when there is no cut during the sample preparations. This means that the test results from tests without cut through are much higher. This is because when there is no cut through, the failure area is larger than the glued area, which means that the failure surface used to calculate the adhesive strength is smaller than the failure area that occurred during the tests. The right graph in Figure 6 shows the displacement-force curves. It can be concluded that more failure energy is need when there is no cut introduced during the pull test. The stiffness of test sample is higher with a cut compared to without a cut. This may result from the influence of glue that around the test area. Further research is needed to check this influence.

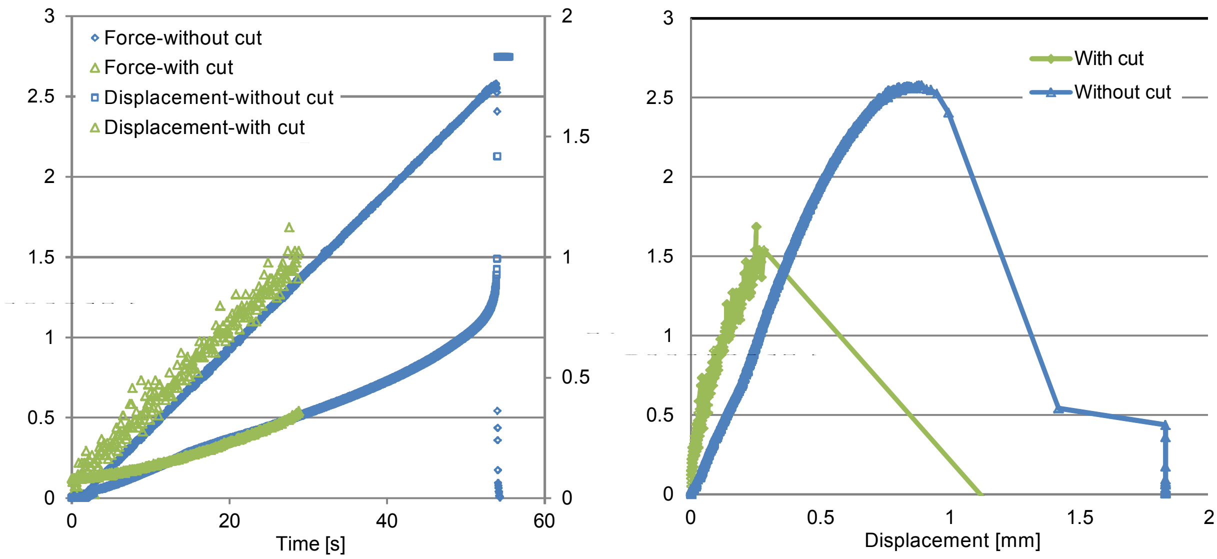

Figure 6 Test results on cores both with cut through and without cut

Figure 5 shows the failure area during the pull tests. The picture at the right side shows the failure surface without cut. Lot of glue can be seen at the surrounding area, while the failure area is much larger than what it should be. These are the main reasons for the higher tensile strength results.

4.2 Direct Tensile Strength

All tests that discussed below were carried on with the method has a cut through the thin surfacing.

Figure 7 illustrates the Direct Tensile Strength (DTS) results at 0 °C, 10 °C and 20 °C, with the same loading speed of 0.025 N/mm2·s. Three test temperatures were performed on one core and three parallels tests were performed, as the left on in Figure 7 shows.

Figure 7 DTS at different temperatures on the same cores

The graph at the right in Figure 7 illustrates that the DTS decreases with increasing test temperature. This shows the same temperature influence on the strength as observed for bitumen binder and asphalt mixture. When the environmental temperature is higher, the binder that bond aggregates together will become softer and result in lower strength of the asphalt mixture. Figure 7 also shows that at same test temperature, the variation between the three test results is acceptable which indicates that the repeatability of the DTS is quite good. This indicates that this advanced pull test works quite well for determining the adhesive strength of the interface between a thin surface layer and substrate asphalt mixture layer.

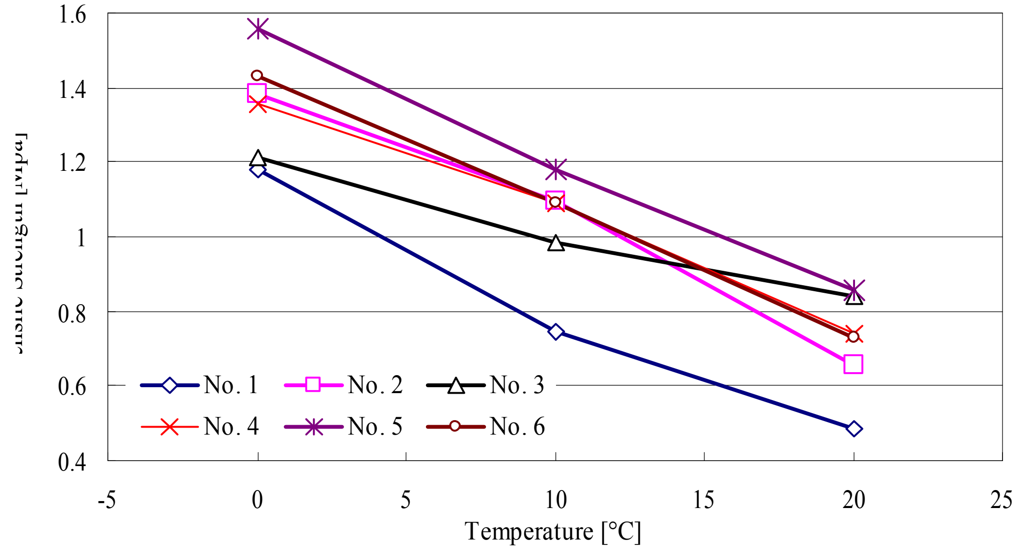

Figure 8 Average DTS at three evaluated temperatures [8]

Figure 8 presents the average DTS at the interface between the antiskid layer and substrate asphalt mixture layer at three evaluated temperatures, 0 °C, 10 °C and 20 °C. Samples from six airports of different age were tested.

From figure 8 it can be seen that the newest antiskid layer, antiskid layer in No. 1 Airport, has the lowest tensile strength. No. 5 and No. 6 Airports, the two oldest airports, have the highest tensile strength. The other three have nearly the same DTS. It is believed this is due to the influence of ageing. The binder in thin surface layer got harder and generates higher tensile strength with ageing. The surface characteristics of asphalt mixture layer may also have a significant influence on the interface tensile strength.

5 CONCLUSIONS

In this paper, a new pull test setup was introduced to test the adhesion properties between thin surface layer and asphalt mixture below. FEM simulation was employed to develop sample preparation process. Pull tests were first performed to compare the differences between two different methods of sample preparation, with or without circle cut into the layer below. Several pull tests were then used to determine the adhesive strength on a specific thin surface layer. The following can be concluded from this research:

1. FEM simulation indicates that there is a huge influence from surrounding area when no circle cut into the layer below is used. With a circle cut, the test area can be clearly defined and the test results are comparable.
2. Pull tests without circle cut result in a failure surface with glues at the edge. The pull-off failure surface is obviously larger than the planned test area. This has a huge influence on the result of the adhesion strength test.
3. Test results show that this new pull test setup can be easily and successfully used to determine the adhesion strength between a thin surface layer and the layer below.
4. The adhesive strength at the interface between an antiskid layer and asphalt mixture layer is the weakest point in this research. It is smaller than the strength of the antiskid layer and of the asphalt mixture layer.
5. In this research, the adhesive strength increased when the test temperature decreased. It was concluded from the results that the adhesive strength during service life, probably due to ageing.

6 REFERENCES

[1] London, D.f.T., Design manual for roads and bridges-Vol. 7 Pavement Design and Maitanance. 1999.

[2] Tashman, L., et al., Evaluation of Construction Practices That Influence the Bond Strength at the Interface between Pavement Layers. Journal of Performance of Constructed Facilities, 2008. **22**(3).

[3] Leest, A.J.v. and G. Gaarkeuken, Resistance of surface layers on airfields in the Netherlands-in situ and laboratory testing, in 2005 European Airport Pavement Workshop. 2005.

[4] Tashman, L., K. Nam, and T. Papagiannakis, Evaluation of the Influence of Tack Coat Construction Factors on the Bond Strength between Pavement Layers. 2006, Washington State University: Washington, D.C.

[5] Deysarkar, I., Test set-up to determine quality of tack coat, in Department of Civil Engineering. 2004, University of Texas at El Paso.

[6] Xiao, Y., et al., Surface Texture of Antiskid Surface Layers Used on Runways, in TRB 90th Annual Meeting. 2011: Washington DC, USA. p. 11.

[7] Al-Qadi, I.L., et al., Tack coat optimization for HMA overlayers-Laboratory Testing. 2008, Illinois Department of Transportation: Report No. FHWA-ICT-08-02.

[8] Xiao, Y., et al., Adhesion Properties of Tar-Containing Antiskid Surface Layers on Runways in Airfield, in T&DI Congress 2011: Integrated Transportation and Development for a Better Tomorrow. 2011: USA. p. 10.