Effect of glass fibre grids on the bonding strength between two asphalt layers and its Contact Dynamics method modelling

Loba Sagnol, Juan Carlos Quezada, Cyrille Chazallon & Markus Stöckner

To cite this article: Loba Sagnol, Juan Carlos Quezada, Cyrille Chazallon & Markus Stöckner (2018): Effect of glass fibre grids on the bonding strength between two asphalt layers and its Contact Dynamics method modelling, Road Materials and Pavement Design, DOI: [10.1080/14680629.2018.1439764](https://doi.org/10.1080/14680629.2018.1439764)

To link to this article: <https://doi.org/10.1080/14680629.2018.1439764>

Published online: 26 Feb 2018.

Submit your article to this journal [↗](#)

View related articles [↗](#)

View Crossmark data [↗](#)

Effect of glass fibre grids on the bonding strength between two asphalt layers and its Contact Dynamics method modelling

Loba Sagnol^{a,b,*}, Juan Carlos Quezada^a, Cyrille Chazallon^{a,c} and Markus Stöckner^b

^aICUBE, UMR 7347, CNRS, INSA de Strasbourg, Strasbourg, France; ^bInstitut Grund- und Straßenbau, Hochschule Karlsruhe Technik und Wirtschaft, Karlsruhe, Germany; ^cShandong Provincial Key Laboratory of Road and Traffic Engineering, Shandong Jianzhu University, Jinan, People's Republic of China

(Received 23 April 2017; accepted 26 January 2018)

This study evaluates the effect of glass fibre grids, used to reinforce asphalt structures, on the bonding strength between a wearing and a binder layer. For this purpose, a test surface consisting of a 6-cm thick binder (0/16 mm) and a 6-cm thick wearing layer (0/11 mm) was built. Four different grids coated with various quantities of bitumen emulsions C60B4-S and C40B5-S were used. Comparison sections were made without grid but also coated with different quantities of emulsions. Extracted cores with 150 mm diameter were tested at ambient laboratory temperature with a monotonic shear test (Leutner). Displacement, shear force and shear stress were measured. The influence of grid characteristics, the existence of a non-woven and the size of the strands as well as the effect of different emulsions on the shear bonding strength were observed, and a numerical model based on DEM simulations was developed. Also, the effect of temperatures on the shear strength with different reinforced and unreinforced specimens was studied. The numerical samples were created with the particles size distribution of the material, where a spherical shape was analysed. A viscoelastic model was implemented for the contact law. We show that the numerical model is able to reproduce the mechanical behaviour of asphalt mixture and reinforced asphalt mixture under the shear loading test. We find that the tests without a reinforcement grid reach more important values of stress at failure and that the decrease in shear stress levels at failure is more important for larger sections of the strands of the grid.

Keywords: glass fibre grids; monotonic shear test; bonding; discrete element method

1. Introduction

The increase of traffic intensity and load in the past decades has led to the development of new maintenance methods. Interlayer reinforcement products such as glass fibre grids have in recent years gained in importance in this field, and their benefits have been proved in various studies, e.g. Nguyen, Blanc, Kerzrého, and Horny (2013) who observed in a full-scale experiments that under traffic loading, the crack propagation in reinforced asphalt sections was delayed, Nejad, Noory, Toolabi, and Fallah (2015) who showed that the use of geotextiles and geocomposites of different moduli improves the pavement resistance against cracking and Arsenie, Chazallon, Duchez, and Horny (2017) who observed that the fatigue life of glass fibre grid-reinforced asphalt beams was increased during 4PB tests, compared to unreinforced beams.

However, it is also known that the insertion of grids and geocomposites at the interlayer can lead to a reduction of bonding as shown by Vismara, Molenaar, Crispino, and Poot (2012) and

*Corresponding author. Email: loba.sagnol@insa-strasbourg.fr

Sokolov (2007). The reduction of bonding resistance can be critical for the transfer of shear stresses into the pavement structure. This article describes the influence of grid and coating characteristics on the bonding between hot mix asphalt wearing and binder layer. The paper is divided into two parts:

- (1) Experimental part: monotonic shear tests on samples reinforced with different grids and coated with different emulsions as well as different emulsion application rates have been compared, especially using over- and under-dosages compared to recommended rates.
- (2) Numerical part: numerical modelling of direct shear test by Contact Dynamics (CD) Method.

2. Sample preparation

The samples required for the experimental part were double-layered cores with a diameter of 150 mm. For their construction, a hot mix asphalt double-layer outdoor test surface (5.8 m × 22 m) consisting of two 60-mm-thick layers was built on an unbound granular base layer ($E_{v2} = 108.15$ MPa). The heights of the layers were chosen to guaranty a minimal height of 40 mm per layer for the Leutner shear test.

The test surface was divided into 28 sections, partly reinforced by 4 grids, coated with 2 different emulsions and 3–4 different application rates. The grids were inserted between the two layers using two different emulsions. The characteristics of the four grids and the emulsions used in this study are shown in Tables 2 and 3. A sketch of the test surface is shown in Figure 1.

Figure 1. Sketch of the test surface.

Figure 2. Sketch of a grid applied on the test surface.

For the section named 600 and 650, the emulsion was applied using emulsions sprays. However, this application type turned out to be inexact, the application was therefore continued using painter rolls and brushes. To ensure a good coating of the glass fibre grids, the grids were pressed on the emulsion using brooms and brushes.

The characteristics of all sections are listed in Table 4. Figure 2 shows a sketch of a grid.

The name of each section is based on the applied emulsion (4 for C40B5-S and 6 for C60B4-S) as the first number, the grid (0 – no grid, 1, 5, W and N) as the second number and the emulsion application rate number 0 (highest) to 3 (lowest) as the third number.

3. Materials used for the test sections

The characteristics of the hot mix asphalt layers are shown in Table 1.

Four different glass fibre grids were installed on the test surface. Their characteristics are listed in Table 2. All grids were provided by one manufacturer. Specifications about the resin used to coat the glass fibres were not given. However, it is known that the resin of grid N varies from the resin of the other grids. To facilitate the application of the glass fibre grids during construction works, a non-woven is used on the grids. The grids W and 5 equal each other, except that the grid W was taken out of production before the non-woven was glued to it.

The glass fibre grids were coated with two different emulsions. Their characteristics are shown in Table 3.

Table 1. Characteristics of the hot mix asphalt layers.

Layer	Bitumen	Ring and Ball	Granular	Bulk density	Void content	Filler content
		°C	Mm	mg/m ³	%	%
Lower layer	25/55-55 RC	63	0/16	2.463	4.9	6.8
Upper layer	25/55-55 A	63	0/11	2.418	3.4	8.4

Table 2. Characteristics of the grids installed on the test surface.

Grid n	Non-woven	Resin	Tensile strength	Mesh size
			kN/m	cm ²
1	Light polyester fibre	A	100	4 × 4
5	Light polyester fibre	A	50	4 × 4
W	—	A	50	4 × 4
N	Light polyester fibre	B	50	4 × 4

Table 3. Characteristics of the emulsions applied on the test surface.

Emulsion	C40B5-S	C60B4-S
Content of residual binder (%)	40	60
Breaking value	> 180	122
Needle penetration (0.1 mm)	100	172
Softening point Ring and Ball (°C)	46.2	42.8
Fluxing agent to reduce the viscosity (%)	2 to 3	< 2

Table 4. Sections built for the study and their characteristics.

Section group	Name of the sections	Emulsions	Grids	Application rate residual binder	Recommended application rate (residual binder)
				g/m ²	g/m ²
60X	600	C60B4-S	Reference structure, no grid	816	90-150
	601			210	
	602			150	
	603			90	
61X	610	C60B4-S	1	600	600
	611			420	
	612			360	
	613			300	
65X	650	C60B4-S	5	1636	500
	651			360	
	652			300	
	653			240	
6WX	6W1	C60B4-S	W	270	350
	6W2			210	
	6W3			150	
40X	401	C40B5-S	Reference structure, no grid	140	80-120
	402			100	
	403			60	
41X	411	C40B5-S	1	280	—
	412			240	
	413			200	
45X	451	C40B5-S	5	240	—
	452			200	
	453			180	
4WX	4W1	C40B5-S	W	180	—
	4W2			140	
	4W3			100	
4N	4N	C40B5-S	N	200	500

Table 4 shows the recapitulation of each sections with the residual binder application rates for each sections.

For each section, nine cores with a diameter of 150 mm were extracted and a total of 162 specimens were tested.

4. Monotonic shear test: Leutner test

4.1. Method

The Leutner shear test is a destructive monotonic shear test with pure interlayer shearing. During the test, the binder layer of the core was fixed while the wearing layer was loaded with a constant shear displacement rate of 50 mm/min until failure occurred. The displacement, shear force and shear stress were measured during the tests. A sketch of the test is shown in Figure 3.

Figure 3. Sketch of the Leutner shear test.

The tests were performed according to the German directive TP Asphalt StB Teil 80 – Abscherversuch 2012 (TP-A 12, FGSV, 2012), except for the test temperature which was taken at ambient temperatures at $25 \pm 3^\circ\text{C}$. A temperature adjustment was made afterwards.

4.1.1. Temperature adjustment

In order to enable the comparison of the shear stress results, the temperatures of the different tests were analytically adjusted to 25°C using the relation proposed by Canestrari et al. (2013) represented by the equation:

$$\tau = 10^{a \times T + b}, \quad (1)$$

where τ is the shear strength in MPa, T the temperature in $^\circ\text{C}$ during the test, and a and b are material coefficients which can be determined by regression.

To determine the parameters a and b , Leutner tests at different test temperatures varying from 4.5°C to 30°C were carried out on the specimen types 600, 610 and 650. To ensure the temperature conditioning, the cores were tempered at the test temperature for at least 12 h before the test. The number of tests done at each temperature is listed in Table 5. Figure 4 shows the different results and the regression curve for each section, based on Equation (1).

The adjustment of all results that were not obtained at 25°C was made by using the coefficient $a = -0.025$ as the correction factor for the unreinforced specimens and the coefficient $a = -0.0335$ (average value of 650 and 610) as correction factor for reinforced specimen 650

Table 5. Shear tests at different temperatures.

Section	Number of tests carried out at different temperatures			
	4.5°C	10°C	20°C	30°C
600	—	—	4	4
610	3	—	4	4
650	—	2	4	4

Figure 4. Shear stress determined at different temperature, for sections 600, 610 and 650, with regression curve.

Figure 5. Difference in average shear strength achieved under laboratory conditions and after temperature adjustment.

and 610. Results of tests performed at 25°C remained unchanged. The coefficient of determination was calculated for all specimen groups. For the reinforced groups, it is at $R^2 = 0.96$; for the unreinforced group, it is at $R^2 = 0.81$. This proves that the regression curves fit.

The difference between the results before and after the temperature adjustment is shown in Figure 5.

4.2. Results

The maximum average shear strengths achieved by each section for a given quantity of residual binder are shown in Figure 6. The grey curves represent the sections coated with C40B5-S while the black curves represent the sections coated with C60B4-S.

4.2.1. Influence of the grid

As it can be observed in Figure 6(A), every reinforced section, except the strongly overdosed section 650, reaches lower shear strengths than the unreinforced section groups 40X and 60X. These results confirm those of Vismara et al. (2012) and Sokolov (2007) about the negative influence of the insertion of grids on the bonding in an asphalt pavement structure.

Figure 6. Average shear strengths against residual binder application rates. (A) All results; (B) Zoom on unreinforced sections with standard deviation; (C) Zoom on reinforced sections with standard deviation.

For the recommended residual binder application rates (C60B4-S) of reinforced and unreinforced specimens, we find that a loss of about 60% in shear strength can be registered due to the insertion of grids (Table 6).

Table 6. Loss of shear strength due to the insertion of grids in comparison with unreinforced specimens.

Grid	Recommended application rate (residual binder, C60B4-S) g/m ²	Application rates residual binder g/m ²	Shear strength (5 & W: extrapolation) MPa	Loss in comparison to “no grid” %
No grid (0)	150	90, 150, 210, 816	1.40	—
1	600	300, 360, 420, 600	0.53	62
5	500	240, 300, 360, 1636	0.46	67
W	350	150, 210, 270	0.54	61

4.2.2. Influence of the residual binder application rate

The observations made on the influence of the application rate can be divided into three points: influence on reinforced sections with low application rates (1–3), influence on all reinforced sections (application rates 0–3) and influence on unreinforced sections.

The first observation made on reinforced section with low application rates of residual binder (from 100 g/m² to about 400 g/m²) shows no clear tendency. Only the group 6WX, without non-woven, shows a relatively linear curve representing an increase of the shear strength with more residual binder. The curve 613,-2,-1 also shows an increase, however in a far less linear way. The curves 653,-2,-1 and 4W3,-2,-1 show peaks while the curves 413,-2,-1 and 453,-2,-1 have a flat tendency.

When looking at the curves of section groups 65X and 61X, including the points 650 (strongly overdosed) and 610 (coated with recommended amount), we observe that a tendency for greater shear stress results with greater application rates. This tendency is also visible in their linear correlation coefficients, being of 0.98 for 65X and 0.92 for 61X. 6WX has also a nearly perfect linear correlation coefficient of 0.98.

The comparison of the reinforced sections with low application rates with the complete reinforced sections leads to the assumption that low quantities of residual binder applied on sections with grids with non-woven have no improvement effect on the bonding. The quantity for which the bonding is improved seems not to be reached for the C40B5-S-coated sections. It can be assumed that the required minimum quantity is depending on the thickness and the absorbability of the non-woven. We can also observe in section 650 that, for a great amount of emulsion (here 1636 g/m²), a reinforced section can achieve shear strengths comparable to the best results of the unreinforced sections.

The addition of residual binder on unreinforced specimens causes at first an increase in bonding until the second application rate. From this peak, the shear stresses decrease again. This effect is mostly explained through the creation of a slip plane caused by a surplus of residual binder, as described by Canestrari et al. (2013). However, the shear stress of section 600, having an application rate of 816 g/m², reaches an average value comparable to the value of 602.

4.2.3. Influence of the emulsion type

We observe that the curves 40X and 60X, having the same emulsion application rate but different residual binder quantities, reach similar shear strengths and show similar curve progressions from application rate 3 to application rate 1, although emulsion C40B5-S has a lower residual binder content, but harder bitumen and more fluxing agent (see Table 3). When looking on the reinforced sections, we can see that the results of the C40B5-S-coated sections are lower than the results of C60B4-S-coated sections. Here, the firmer bitumen and fluxing agent of C40B5-S are not enough to overcome the lower residual binder content.

Figure 7. Influencing components on the bonding: comparison of the grids 5 (with non-woven) and W.

Figure 8. Influencing components on the bonding: comparison of grids with resin A (grids 1 and 5) and B (grid N).

4.2.4. Influence of the non-woven

The grids W and 5 differ from each other only by the existence of a light non-woven between the strands of grid 5, while grid W has none. Figure 7 shows that for the same quantity of residual binder, the results of the grid W are higher than of grid 5. It can, therefore, be assumed that the existence of a light non-woven between the strands has a low negative effect on the bonding.

4.2.5. Influence of the resin

Grids 5 and N differ only in the resin used to coat and protect the glass fibre of the grid. For grid N, only the emulsion C40B5-S with an application rate of 200 g/m² of residual binder was tested. This section can directly be compared with section 452, also coated with 200 g/m² of residual binder of C40B5-S. As showed in Figure 8, we can observe that the shear stress results of section 4N are largely higher than those of section 452. Furthermore, on Figure 6(C) (zoom on reinforced sections), we can observe that the grid N reaches the highest shear stresses of all reinforced C40B5-S-coated sections and achieves better results than C60B4-S-coated section for the same amount of residual binder.

Figure 9. Influencing components on the bonding: comparison of the shape of the strands of the grids 1, 5 and N. Left: strands md, Right: strands cmd.

4.2.6. Influence of the shape of the strands

3D-scans of the strands of the grids were made in order to analyse their shapes. For this examination, nine strands of each grid direction (machine direction “md” or warp yarn and cross machine direction “cmd” or filling yarn) of the grids N, 5 (same as W) and 1 were scanned with a 3D microscope. The average shapes can be seen in Figure 9.

We observe that the strands of the grid 1, having a tensile strength twice as high as 5 and N, are nearly twice as wide as the grids 5 and N, without being noticeably higher than the two other grids.

The comparison of the strands of the grids 5 and N shows that the strands of the grid N are slightly taller but also slightly thinner than the strands of the grid 5, which can lead to a better interlocking with the granular of the upper layer, explaining partly the better results of 4N comparing to 452 as discussed before.

5. Microscopic examination

The pictures in Figure 10 were made with a $20\times$ magnification and show about 1 cm of the interface width of 6 observed cores. The upper part of the picture shows the wearing layer, and the lower part is the binder layer. The cores were cut perpendicular to the interlayer in the direction of rolling; the strands coming out of the cores are therefore filling yarns (cmd). As

Figure 10. Results of the microscopic examination of the interfaces of cores from the sections 600, 602, 610, 611, 650 and 651 with a $20\times$ magnification.

only a few specimen scans were taken, the following pictures can only give an impression of the interlayer.

On the picture of the unreinforced specimens (600 and 602), we can see that the interface is not clearly visible between the wearing layer and the binder layer. This similarity in appearance is also visible in their test results, as both achieve more than 1.1 MPa average shear strengths. No voids are visible on both samples.

The pictures of 610, 611 and 650 show an md-strand running along the interface, and picture 651 shows cmd-strands coming out of the core

The existence of voids is visible under the strands of picture 611 and 651; however, no voids can be seen on picture 610 and 650. This may lay on the more important amount of residual binder present on the specimens 650 and 610 in comparison with 611 and 651 (611: 420 g/m² and 651: 360 g/m² against 610: 600 g/m² and 650: 1636 g/m²). This residual binder is also visible in the pictures 650 and 610 as shining black points under the strands.

6. Interpretation of the results

The results of the sections coated with C40B5-S will not be further discussed due to their very low shear stress results.

As observed before, the unreinforced section group 60X shows a peak for an amount of 150 g/m² (application rate 2) of residual binder. The negative slope starting after this point is the expected result of the creation of a slip plane as mentioned before, due to the excess of residual binder. This new plane created between the upper and the lower layers of the structure appears to prevent a good interlocking between the granular of the upper and lower layers.

Knowing this, we can assume that the positive slope starting again from section 601 (210 g/m² of residual binder) and leading to section 600 (816 g/m² of residual binder) cannot be due to the interlocking between the aggregates, as it is disturbed through the excess of residual binder. The remaining influencing factor can then only be the adhesion due to the residual binder between the two layers.

The difference between the factor “interlocking” and the factor “adhesion” is visible in the slope between 603 and 602, and 601 and 600, respectively. While the first ascension, due to interlocking and adhesion, is relatively steep with an average slope of 6.01E-3, the second ascension, where the interlocking is lost and only the adhesion is working, is significantly flatter with an average slope of 9.04E-4.

Based on this result, a comparison was made between the average slopes of the different groups 61X, 65X and 6WX, 603-602 (positive slope before the slip plane appears) and 601-600 (positive slope after the slip plane appears).

The average slopes of each group were calculated using the method of least squares and can be seen in Figure 11.

The tendency described before can be observed again on this graph. The group 6WX using the grid W, without non-woven, shows the second steepest slope. Here, the steep slope can be explained by not using a non-woven, which enables a direct interlocking of the granular. However, as it was observed on the microscope picture, the grid strands are still disturbing the bonding by creating voids under the strands, explaining the difference of slope between the 6WX and 603-602.

Because of this possible interlocking, we can assume that with more residual binder, a slip plane would appear and cause a fall of the curve as happens on the unreinforced specimen curves.

The groups 61X and 65X show both flatter slopes, having both a non-woven between the strands of their grids. We assume that the interlocking of the aggregates is lightly disturbed through the non-woven, so that the main bonding agent is the adhesion through the residual

Figure 11. Average slope of each section group.

binder. Here, the residual binder fills the voids under the strands of the grids, leading to better shear strength results. We observe that a great amount of residual binder as used for section 650 leads to the shear strength values equalling the best results of the unreinforced sections.

The representation of the curve as linear to infinity is most likely not correct, it should be assumed that the curves would more likely have a sigmoid form. However, the linearity of the curves is a good approximation for the middle part as represented.

7. Numerical modelling of direct shear test by CD method

In this section, we have reproduced numerically the shear tests, for sample configurations with a similar quantity of residual binder with the aim to identify the influence of the glass fibre grid sections on shear strength levels using the CD Method.

7.1. Numerical procedures

7.1.1. CD method

The simulations were carried out by means of the CD method with spherical particles (Dubois & Jean, 2003; Jean & Moreau, 1992; Radjai & Richefeu, 2009). The CD method is a particle-based approach which simulates the interaction of a collection of rigid or deformable bodies in contact. This approach allows to model the behaviour and to obtain a micromechanical insight of granular materials such as filling materials in construction foundations, earthworks and transport infrastructure (railway ballast, asphalt). Over the past two decades, the discrete element approach has been used by many researchers to simulate the microstructure of asphalt mixtures (Adhikari & You, 2008; Cai, McDowell, & Airey, 2014; Collop, McDowell, & Lee, 2006; Liu & You, 2009). In the CD method, the equations of motion for each particle are formulated as differential inclusions in which velocity jumps replace accelerations. The unilateral contact interactions and Coulomb friction law are treated as complementarity relations or set-valued contact laws. For our simulations, we used the LMGC90 software, which is capable of modelling a collection of particles of various shapes by different algorithms (Dubois & Jean, 2003).

7.1.2. Sample preparation

The numerical samples were composed of rigid spherical particles with two size distributions which correspond to those used for the experimental samples. Each particle had a diameter

Table 7. Particle size distribution for each layer of the sample.

Diameter (mm)	2	5.6	8	11.2	16
Bottom layer (%)	16.4	14.4	17.2	21.3	2.3
Upper layer (%)	15.6	17.8	20.1	1.5	0

Figure 12. Snapshot of a sample with a reinforced grid 1 after the preparation stage.

ranging from 2 to 10 mm for the upper layer and from 2 to 16 mm for the bottom layer (see Table 7). Here, the graded curve was cut at 2 mm to avoid modelling all the fines in the mastic, to reduce the total number of particles and then the simulation time for the contact detection process.

The bulk density of the particles was 2700 kg/m^3 . The coefficient of friction between the particles was set to $\mu = 0.7$ which is a typical value used for rock-crushed aggregates (Cai et al., 2014). For the contact between the glass grid and the particles, this value was equal to zero.

The preparation protocol consisted of first pouring the particles of the bottom layer by gravity into a cylindrical box with 150 mm diameter with zero particle–wall friction. The layer obtained by this procedure was subjected to vibrations of small amplitude (6 mm) by applying a vertical sinusoidal displacement on the top wall during 1 s with a frequency of 30 Hz, obtaining a layer of 60 mm height. For the samples with the reinforcement glass grid, the grid was put over the first layer. The average dimensions of the reinforcement grid were of 150 mm length, 0.7 mm height, and 4 mm and 8 mm width for the grids 5 and 1, respectively (as shown in Figure 6(C)), so that the average sections (filling yarns and warp yarns) were conserved. This procedure was repeated for the second layer. Finally, the resulting sample was confined between two plates inside the cylinder box.

Following this entire process, we prepared five samples for each configuration (without reinforced grid, with grid 5 and grid 1). The cylindrical samples had the same geometrical properties: radius 75 mm and 120 mm of total height. The number of particles was about 5200 for all samples, with a packing fraction ranging from 0.584 to 0.59. Figure 12 shows a snapshot of the resulting numerical sample with the glass grid.

7.1.3. Viscoelastic contact law

To model an asphalt mixture under a shear loading, a viscoelastic contact law is implemented during the shear test. The chosen contact law was the Burgers model which is a more accurate model of viscoelastic behaviour for hot mix asphalt materials. It describes finely the creep,

relaxation and dynamic properties of asphalt mixtures and has become a commonly used contact model in the discrete element modelling simulation of asphalt mixtures. This model consists of the Maxwell model combined in series with the Kelvin–Voigt model. The time-dependent normal contact stiffness K_n is given by:

$$K_n = \left[\frac{1}{K_m} + \frac{t}{\eta_m} + \frac{1}{K_k} (1 - e^{-\frac{t}{\tau}}) \right], \quad (2)$$

where K_m is Maxwell normal stiffness, η_m is Maxwell normal viscosity, K_k is Kelvin–Voigt normal stiffness, η_k is the Kelvin–Voigt normal viscosity; t is the loading time and $\tau = \eta_k/K_k$ is the relaxation time. The values used in our simulation were 2×10^6 N/m for K_m , 2×10^6 N/m for K_k , and 2×10^7 N.s/m and 2×10^7 N.s/m for η_m and η_k , respectively. This set of parameters generated the best fit regarding the shear stress and displacement curve obtained for the sample without reinforcement grid. To model the brittle behaviour of this material, a yield stress criterion was imposed to identify when cohesive contacts were lost. When shear or tension stress reached the yield value of 2.7×10^6 Pa, the bond between particles was broken and a frictional contact law was applied instead. Assuming a perfectly isotropic behaviour, tangential stiffness K_t is estimated as a function of normal stiffness as: $K_t = K_n/(2(1 + \nu))$ where ν is the Poisson's ratio. For the sake of simplicity, this ratio was set to 0.3. This contact law was adapted to the CD formulation implemented in the LMGC90 software.

7.1.4. Direct shear test modelling

To perform the shear tests, the cylindrical box was replaced by two cylinders, having 60 mm height and separated by 2 mm. The shear tests were performed by imposing a velocity of 50 mm/min of the upper cylinder until a displacement of 2.5 mm was reached. The shear stress was obtained by measuring the total reaction of contacts between particles and the upper cylinder normalised by the cross-section of the sample. The time step was 2×10^{-4} s in all simulations, and at most 15,000 time steps were required to obtain a displacement of 2.5 mm. The CPU time was 2×10^{-2} s per particle and per time step on a Dell computer with speed 3.3 GHz.

7.2. Validation of the numerical modelling

7.2.1. Influence of grid section

We give in Figure 13 the results of the evolution of the shear stress τ as a function of the measured displacement for each sample configuration. The simulated behaviours were those which have been obtained with a residual binder of 300 g/m². With such a residual binder rate, the interlocking between aggregates remains the main factor influencing the shear strength. 601-e is the sample without glass grid whose shear strength can be estimated to 0.85 MPa, 652-e is the sample with grid 5 whose shear strength can be estimated to 0.35 MPa and 613 is the sample with the grid 1 whose shear strength is 0.11 MPa (see Figure 11).

Figure 13(A) displays these results for the five samples without reinforcement grid. Herein, we can identify a slope at the beginning of the measured displacement until the failure of the sample is reached (peak shear stress value), showing a post-peak relaxation. The peak in the shear stress is obtained for a displacement between 2 and 2.3 mm, where this range of values is similar to the identified one during the laboratory tests. For the other configurations, the evolution is similar to measured values at failure and with a final displacement quite close to experimental data.

The results show the influence of the reinforced glass grid in the evolution of shear stress curve. Using a reinforcement glass grid with 300 g/m² of residual binder reduces by 68% the value of the shear stress for the 652-e and by 87% for the 613. This is the effect of the creation

Figure 13. Shear stress evolution as a function of imposed displacement for different configurations. (A) Without the reinforcement grid (configuration 601-e); (B) With grid configuration 652-e; (C) With grid configuration 613.

of discontinuities on the interface between the two layers of aggregates: the quantity of bonds created between the two layers is smaller with larger grid sections. For the samples without a grid, the bonded aggregates take the entire section of the sample, while using the reinforcement grid reduces by 80% and 60% for the grids 5 and 1, respectively. This effect induces strain localisation in preferential shear bands created on the interface by the reinforcement grid. During the shear tests, the glass grid was pushed by the surrounding particles within the upper layer, cutting the sample by the concentrated shear stress.

7.2.2. Influence of the residual binder application rate

To highlight the influence of the residual binder application rate, two supplementary configurations were simulated numerically: the configuration 600 (without the reinforcement glass grid and a residual binder of 816 g/m^2) and the configuration 610 (with the grid 100 SB and a residual binder of 600 g/m^2). To take into account an application rate bigger than the initial value of 300 g/m^2 used in Section 6.2.1, the yield stress value $\sigma_{\max}$ was modified for these configurations. The yield stress value $\sigma_{\max}$ for the 600 configuration was increased to 4.2 MPa to fit the shear stress τ value obtained experimentally. Following the linear evolution of shear stress τ as a function of the residual binder rate showed in Figure 11, a linear relation between the residual binder rates and the yield stress values for the 601-e and 600 configurations was calculated. Finally, the yield stress values can be estimated as a function of the residual binder rate as follows:

$$\sigma_{\max} = 1.8 + 0.003 \times RB, \quad (3)$$

Figure 14. Shear stress evolution as a function of imposed displacement for different residual binder values. (A) Without the reinforcement grid and 816 g/m² (configuration 600); (B) With grid 100 SB and 600 g/m² (configuration 610).

Figure 15. Comparison between the values of shear stress and peak displacement at failure for the experimental tests and numerical simulations for each sample configuration. (A) Samples with RB = 300 g/m²; (B) Samples with larger values of RB. (C) Position of the chosen points in comparison with all study results.

where RB is the residual binder rate (g/m²) and $\sigma_{\max}$ is the modified yield stress value in MPa. Figure 14 displays the evolution of shear stress τ for the configurations with large residual binder application rates estimated from Equation 3. As expected, the peak values for shear stress are larger than those obtained for numerical tests with a residual binder of 300 g/m². Larger application rates improve the bond of the interface for the configurations with or without the reinforced

grid, where the peak shear stress values increase linearly. Nevertheless, one can note a difference between the τ peak values between both configurations. For both configurations, the τ peak values increase at the same rate, but the presence of the reinforced glass grid creates a gap between them. Even if the yield stress value is larger for the 610 configuration (Figure 14(B)), creating a stronger bond on the interface, the presence of the reinforced glass grid reduces the quantity of bonds between the two layers.

7.2.3. Comparison with experimental results

To validate the numerical modelling, Figure 15 displays the values of experimental and numerical shear tests for the configurations analysed during the numerical study. For each configuration, the average numerical values show a good agreement with experimental data for both shear stress and displacement at failure. One can note that these results are within the incertitude inherent to the experiments where error bars are overlapping for each sample configuration.

8. Conclusion

This article studied the influence of glass fibre grids on interlayer bonding with experimental and numerical modelling.

For the experimental part, 28 different sections were built, with varying types of grids (with and without non-woven, different resins), types of emulsions and emulsion application rates. The 228 cylindrical cores extracted from the surface were tested with a monotonic shear test. The results were:

- The insertion of glass fibre grids has a negative influence on the bonding, as for the recommended application rates, the shear strength of reinforced specimens reach only about 60% of the shear strength of unreinforced specimens
- The application rate on reinforced samples has a great effect on the bonding. For low application rates, no positive influence on the shear stress is visible. However high application rates can lead to shear stresses similar to the ones of unreinforced samples.
- Important variations can be observed for the different emulsions.
- The use of a non-woven between the strands leads to a loss of interlocking between the layers and so to lower shear stress results. For grids with non-woven, a high application rate is greatly important.
- The resin with which the glass fibre is coated can have a positive influence on the bonding.
- The form of the strands can lead to a better interlocking between the grid and the upper layer.

The results of the numerical analyse show that the implementation of viscoelastic contact law is able to reproduce experimental data from the shear test, regarding shear stress and maximum displacement at failure. The numerical model shows the influence of using a reinforcement glass grid on shear stress, where these values are reduced by 70% in comparison with non-reinforced samples when underrated tack coat. This is the result of strain localisation in preferential shear bands created by the reinforcement grid. The general results of these simulations for each configuration are in a good agreement with the average values of experiments despite the intrinsic variability within “samples”. These results allow to validate the numerical model in a preliminary instance regarding the effect of glass fibre grids in asphalt layers. These findings are encouraging to use the numerical simulation to study at the particle-scale and go towards a better understanding of the mechanical behaviour of asphalt mixtures in complex phenomena as pavement rutting, crack propagation and aggregates pull-out.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

- Adhikari, S., & You, Z. P. (2008). 3D microstructural models for asphalt mixtures using X-ray computed tomography images. *International Journal of Pavement Research and Technology*, 1(3), 94–99.
- Arsenie, I. M., Chazallon, C., Duchez, J. L., & Hornych, P. (2017). Laboratory characterisation of the fatigue behaviour of a glass fibre grid-reinforced asphalt concrete using 4PB tests. *Road Materials and Pavement Design*, 18(1), 168–180.
- Cai, W., McDowell, G. R., & Airey, G. D. (2014). Discrete element visco-elastic modelling of a realistic graded asphalt mixture. *Soils and Foundations*, 54(1), 12–22.
- Canestrari, F., Ferrotti, G., Lu, X., Millien, A., Partl, M. N., Petit, C., . . . Raab, C. (2013). Mechanical testing of interlayer bonding in asphalt pavements. *RILEM State-of-the-Art Reports*, 9, 303–360.
- Collop, A. C., McDowell, G. R., & Lee, Y. W. (2006). Modelling dilation in an idealised asphalt mixture using discrete element modelling. *Granular Matter*, 8(3), 175–184.
- Dubois, F., & Jean, M. (2003). LMGC90 une plateforme de développement dédiée à la modélisation des problèmes d'interaction [LMGC90, a development platform dedicated to the modelisation of interaction problems]. In *Actes du sixième colloque national en calcul des structures* (Vol. 1, pp. 111–118).
- Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV). (2012). Arbeitsgruppe “Asphaltbauweisen”, TP Asphalt StB, Teil 80: Abscherversuch [Technical testing regulation for asphalt: Shear test]. *FGSV 756/80*, FGSV Verlag.
- Jean, M., & Moreau, J. J. (1992). Unilaterality and dry friction in the dynamics of rigid body collections. *Proceedings of Contact Mechanics International Symposium* (pp. 31–48). Lausanne, Switzerland.
- Liu, Y., & You, Z. (2009). Visualization and simulation of asphalt concrete with randomly generated three-dimensional models. *Journal of Computing in Civil Engineering*, 23(6), 340–347.
- Nejad, F. M., Noory, A., Toolabi, S., & Fallah, S. (2015). Effect of using geosynthetics on reflective crack prevention. *International Journal of Pavement Engineering*, 16(6), 477–487.
- Nguyen, M.-L., Blanc, J., Kerzrého, J.-P., & Hornych, P. (2013). Review of glass fibre grid use for pavement reinforcement and APT experiments at IFSTTAR. *Road Materials and Pavement Design*, 14(1), 287–308.
- Radjai, F., & Richefeu, V. (2009). Contact dynamics as a nonsmooth discrete element method. *Mechanics of Materials*, 41(6), 715–728.
- Sokolov, K. (2007). *Laboruntersuchungen an unterschiedlich verstärkten Asphaltsschichten* [Laboratory investigations on differently reinforced asphalt layers]. Paper presented at Tagung Asphaltverstärkungen mit Einlagen. Erfahrungen und Perspektiven, 15 May 2007, Dübendorf, CH. EMPA-Akademie.
- Vismara, S., Molenaar, A. A. A., Crispino, M., & Poot, M. R. (2012). Characterizing the effects of geosynthetics in asphalt pavements. *7th RILEM International Conference on Cracking Pavements* (pp. 1199–1207).