1 Introduction

One of the most important problems of the actual society is the need to decrease the dependency on limited natural resources such as bitumen. Bitumen is an important material in the case of flexible road pavements, hence it's the general wish to decrease the actual dependence on that material.

The natural resources for maintenance and new construction, in general, are decreasing every year. Due to this new reality, more research is needed to achieve new economic and efficient road construction solutions, such as pavement reinforcement.

The authorities are making an effort to decrease the volume of bituminous materials used in pavements. The possibility of decreasing the volume of bituminous materials in the pavements is guaranteed by the addiction of reinforcement elements such as glass and carbon fibers, geosynthetics or geogrids, steel meshes, geotextiles, etc, that could increase the bearing capacity of pavements. The most adequate choice of these materials is one of the main objectives of the pavement rehabilitation design, which is strong dependent on the state of the old pavement and the structural and functional quality required for the new reinforced pavement.

The principal causes of flexible pavements degradation are the permanent deformation and the initiation of fatigue cracking. Steel meshes are used as reinforcement materials in some pavement distresses such as:

- increasing bearing capacity;
- increasing resistance against flow rutting;
- increasing resistance against crack appearance;
- increasing resistance against settlements at ditch side;
- minimizing the risk of reflective cracking appearance;
- Increasing resistance against distresses caused by frost heave.

The reinforcement of flexible pavements using steel meshes appeared firstly in the North of Europe, about 1970. After some experiences, it was recognized the potential of this material as a reinforcement material for flexible pavements, and other countries have also adopted this technique. The European Union has financed the REFLEX (Reinforcement of Flexible Road Pavements) project.
Structures with Steel Fabrics) project, which has provided interesting research about the improvements obtained with the introduction of steel meshes as reinforcement. These conclusions were based on some case studies located in Sweden, Finland and Italy, contributing with recommendations about the execution and steel fabrics for different proposes when using steel net as reinforcement for flexible pavements.

2 Description of the experimental pavement, modeling and results

2.1 Description of the pavement structure

The experimental pavement used in this study was initially related to another research conducted by [1]. That study consisted in the analysis and monitoring of the improvement of the bearing capacity of the pavement, reinforced with a steel mesh in the bituminous layers.

The pavement was subdivided into four experimental sections, with the same dimensions. They were composed by different binder layer thicknesses and by different rod diameters, keeping the same mesh dimensions [1].

In this study, it was used a pre-fabricated steel mesh. The rod diameters were 3,0mm, 3,8mm and 5,0mm, spaced 100mm in the two perpendicular directions [1].

Combining four different binder layer thicknesses with the three rod diameters of the steel mesh, twelve different experimental sub-sections were achieved. Other four experimental sections without steel meshes were considered in order to have a comparison to the other reinforced experimental sections, so it could be evaluated the improvement associated to the use of steel meshes. The experimental sub-sections were identified associating a letter with a number. The letter refers to the rod diameter utilized in the steel net: G to AQ-50 (5,0mm diameter rods), M to AQ-38 (3,8mm diameter rods), P to AQ-30 (3,0 diameter rods) and S to experimental sections without steel net in their constitution. The number refers to the different binder layer thicknesses in centimeters. The surface layer and the unbound granular sub-base layer have the same thickness in all experimental sub-sections [1].

Regarding the layers of the subgrade, foundation and bedrock, it was considered 50cm to the subgrade layer, 1,5m to the foundation layer and the bedrock layer forming a semi-infinite layer [2].

The identification of the experimental sections as well as its characterization are resumed in Table 1.
Table 1 – Identification and characteristics of the experimental sections [2]

<table>
<thead>
<tr>
<th>Experimental section</th>
<th>G10</th>
<th>M10</th>
<th>P10</th>
<th>S10</th>
<th>G8</th>
<th>M8</th>
<th>P8</th>
<th>S8</th>
<th>G6</th>
<th>M6</th>
<th>S6</th>
<th>P6</th>
<th>G4</th>
<th>M4</th>
<th>P4</th>
<th>S4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear layer (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel mesh (type)</td>
<td>AQ-50</td>
<td>AQ-38</td>
<td>AQ-30</td>
<td>(*)&amp;</td>
<td>AQ-50</td>
<td>AQ-38</td>
<td>AQ-30</td>
<td>(*)&amp;</td>
<td>AQ-50</td>
<td>AQ-38</td>
<td>AQ-30</td>
<td>(*)&amp;</td>
<td>AQ-50</td>
<td>AQ-38</td>
<td>AQ-30</td>
<td>(*)&amp;</td>
</tr>
<tr>
<td>Binder layer (cm)</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unbound granular layer (cm)</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Figure 1 and Figure 2 it is possible to observe the experimental sections structure.

2.1.1 Instrumentation

Strain gauges were positioned, approximately, in the middle of the unbound granular layer and at the bottom of the bituminous layers, during the construction. The details and procedures used during the instrumentation are described by [1].
2.1.2 In situ tests

Regarding the in situ tests carried on the experimental sub-sections, it was used the FWD (Falling Weight Deflectometer). The equipment used in the tests is shown in Figure 3 and Figure 4.

During the FWD tests, a load pulse is applied on the pavement surface which intends to simulate the load produced by a wheel in movement. The load is produced by the impact of a mass on a circular plate. The plate diameter in these tests is 300mm and the load is 65 kN.

Taking into account the symmetry of the load system and in order to simplify the modeling, only a quarter of the plate will be considered, which corresponds to a load of 16.25kN. Also a quarter-circle to a square with 0.15m side was assumed. Calculations were done after taking into account the change of the load value from circular geometry to a square one.

2.2 Modeling

The numerical modeling has been performed with the commercial code ADINA using a bisymmetric simplification, which has the advantage of minimizing the required amount of memory.

The model is based from the experimental sections described before. These experimental sections have measuring probes until 2.1m. In the experimental sections modeling, a “slice” from the original section with the appropriated dimensions was used to validate the models. In the Figure 5 it could be seen a schematic structure of the pavement with the symmetric axis. The simplification carried out is shown in Figure 6.
Sliding supports, allowing for vertical displacements, are adopted in all four borders. In the lower boundary, representing the end of the bedrock layer, a full clamped edge is assumed, as the height is big enough to ensure that the displacements can be considered to vanish at that boundary.

After some calculations carried out by the program, it was concluded to consider 4mx4m dimensions to the model in Figure 6.

The load considered in the modeling, produced by the FWD tests, was already described previously.

2.2.1 Steel mesh characteristics

Three dimensional and rectangular finite elements were used, with eight nodes by element in every layer except the transition layer. The transition layer makes the transition between the three bottom layers and the first two layers. In the transition layer, tetrahedrons finite elements with four nodes were considered. An X translation, Y translation and Z translation were adopted as degrees of freedom.

2.2.2 Materials properties

The bituminous mixtures are better characterized by the viscoelastic behavior and thermoplastic behavior, since this material has a high deformation module and it is sensitive to temperature changes [3].

With the objective of simplifying the material properties, a linear elastic behavior was assumed. The characteristics of the pavement layers, based on the experimental study conducted by [1], were initially used. These values are shown in Table 2.
Table 2 – Young modulus and Poisson’s ratio for pavement layers [1]

<table>
<thead>
<tr>
<th></th>
<th>Elastic module (MPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear layer</td>
<td>4275</td>
<td>0.40</td>
</tr>
<tr>
<td>Binder layer</td>
<td>6500</td>
<td>0.40</td>
</tr>
<tr>
<td>Unbound granular layer</td>
<td>483</td>
<td>0.35</td>
</tr>
<tr>
<td>Subgrade</td>
<td>171</td>
<td>0.35</td>
</tr>
<tr>
<td>Foundation</td>
<td>246</td>
<td>0.35</td>
</tr>
<tr>
<td>Bedrock</td>
<td>613</td>
<td>0.35</td>
</tr>
</tbody>
</table>

The steel Young modulus and Poisson’s ratio are given in Table 3.

Table 3 – Steel Young modulus and Poisson’s ratio

<table>
<thead>
<tr>
<th></th>
<th>Elastic module (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>A500 steel</td>
<td>200</td>
<td>0.30</td>
</tr>
</tbody>
</table>

2.2.3 Steel mesh

The steel mesh was located in the interface between bituminous layers (wear and binder layers).

In the calculations, linear finite elements were used.

2.3 Calibration of the model

The experimental sections without steel meshes were used to calibrate the model.

Since the results were not the expected ones, elastic properties were changed until the results from ADINA were similar to the experimental results provided by the FWD test, for the case of sub-sections S4, S6, S8, S10. The final values achieved are shown in Table 4. The quality of this modeling can be observed in Figure 7 for section S4.

Table 4 - Elastic module and Poisson’s ratio from experimental sections S4, S6, S8 and S10

<table>
<thead>
<tr>
<th></th>
<th>Elastic module (MPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear layer</td>
<td>4275</td>
<td>0.40</td>
</tr>
<tr>
<td>Binder layer</td>
<td>6500</td>
<td>0.40</td>
</tr>
<tr>
<td>Unbound granular layer</td>
<td>483</td>
<td>0.35</td>
</tr>
<tr>
<td>Subgrade</td>
<td>153</td>
<td>0.35</td>
</tr>
<tr>
<td>Foundation</td>
<td>120</td>
<td>0.35</td>
</tr>
<tr>
<td>Bedrock</td>
<td>450</td>
<td>0.35</td>
</tr>
</tbody>
</table>
In different subsections, different values were assigned to the elastic properties for the subgrade, foundation and bedrock. This is due to the fact that these properties depend on the earthworks quality.

Observing Figure 7, it’s noted that an adequate modeling was achieved.

2.4 Discussion of results

After the calibration, the remaining experimental sections with steel net reinforcement were analyzed. The results are described below.

2.4.1 Experimental section 4

Figure 8, Figure 9 and Figure 10 show the experimental results and ADINA results comparison, for the case of subsections 4.
In spite of some slight differences, especially near the plate, the results can be considered as satisfactory.

3 Study of the variation of the position and type of the steel mesh

3.1 Description of the sections

The study of the variation of the steel mesh position and type was based on the experimental section S10.

In that section, it was used an AQ-38 steel mesh, with a 3.8 mm rod diameter. The steel mesh was placed between the binder layer and the wear layer, as it was considered in the experimental section S10.

For the study of the position of the steel mesh, three positions were considered: between the binder layer and the wear layer; 3mm above the binder layer in macadam; and 6 mm above the
wear layer in asphalt concrete. It was considered always a mesh with 10 cm in all the three models.

3.2 Modelling

The modeling criteria adopted is the same one as described before for the experimental sections.

The same dimensions for the model and the same boundary conditions are used in the analysis.

3.2.1 Load definitions

The considered load represents a truck characterized by a single 130kN axis. The load representative for the truck is shown in Figure 11.

![Figure 11 - Representative load of the truck axes](image)

To avoid incompatibilities, it was considered only one load, instead of the two represented in Figure 11. The simplification has consisted in the transformation of the 0.25m circular load into a 0.50 square load.

3.2.2 Modelling

The criteria used are the same as described before in 2.2.1.
3.2.3 Material characteristics

The material characteristics used were the ones used before in experimental sections P10, M10 and G10 after calibration. The material characteristics are shown in Table 5.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Elastic module (Mpa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear layer</td>
<td>4275</td>
<td>0.40</td>
</tr>
<tr>
<td>Binder layer</td>
<td>6500</td>
<td>0.40</td>
</tr>
<tr>
<td>Unbound granular layer</td>
<td>483</td>
<td>0.35</td>
</tr>
<tr>
<td>Subgrade</td>
<td>130</td>
<td>0.35</td>
</tr>
<tr>
<td>Foundation</td>
<td>120</td>
<td>0.35</td>
</tr>
<tr>
<td>Bedrock</td>
<td>430</td>
<td>0.35</td>
</tr>
</tbody>
</table>

3.2.4 Steel meshes

The steel meshes were modeled by the same procedure adopted in the experimental sections. Linear elements with two nodes were considered.

3.3 Discussion of results

Figure 12, Figure 13 and Figure 14 present the vertical displacements and the horizontal extensions between the wear and binder layers and vertical displacements between the binder and unbound granular layers.

Figure 12 - Vertical displacements between the wear and binder layers
Figure 13 - Horizontal strains between the wear and binder layers

Figure 14 - Vertical displacements between the binder and unbound granular layers

Figure 15 - Vertical displacements between the wear and binder layers
From the analysis of the figures above, referring to the variation of the steel mesh opening, it is possible to conclude that the increase of the displacement and the strain was achieved when the steel mesh opening has increased. The less satisfactory results were observed when the steel mesh increases the opening from 5cm to 10cm, so it could be concluded that a more efficient reinforcement is obtained when it is used 5cm.

Concerning the steel mesh position, the less satisfactory results were observed when the position change from the base of wear layer to an inferior position. The steel mesh is more efficient when positioned between the wear layer and binder layer.

4 Conclusions

From the research study developed in this dissertation, the main following conclusions could be pointed out:

- The experimental work has validated the theoretical model.
- It was confirmed the increase of bearing capacity on pavements reinforced with steel mesh.
- It was not possible to confirm the variation of bearing capacity when using different diameters, due to the heterogeneity of the subgrade, foundation and bedrock layers.
- The displacements did not decrease when using different thickness of the binder layer.
- The steel mesh is more efficient when a 5 cm opening is used and when it is placed between the binder and wear layers.

References


