Development of a semi-flexible heavy duty pavement surfacing incorporating recycled and waste aggregates – Preliminary study

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HIGHLIGHTS

- The cold mixtures are used in grouted macadam replacing the traditional mixtures.
- The RAP and altered granites use is an alternative to natural aggregates.
- The cementitious grouts are incorporated with milled glass and waste mud.
- The cold mixture with altered granite and S30MG presents the best characteristics.

ABSTRACT

This paper analyses the possibility of using altered aggregates and Reclaimed Asphalt Pavement (RAP) in cold mix asphalt used to produce grouted macadam pavements in comparison with the conventional hot mix porous asphalt skeleton. It also investigates the cementitious grouts performance when incorporated with milled glass and Panasqueira Waste Mud and geopolymeric grouts. This paper aims mainly at studying the introduction of mineral waste materials in grouted macadam pavements. The results indicate that the cold mixture 8/12.5 with altered granite and cementitious grout with 30% milled glass presents the best mechanical performance.

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1. Introduction

The recycling of asphalt pavements is nowadays used worldwide as a major road and airport pavements rehabilitation technique due to the increasing cost of asphalt, the scarcity of quality aggregates, the pressing need to protect the environment and the increasing disposal costs of old asphalt pavements [1–5].

Road rehabilitation and rehabilitation operations can be classified into two main classes dependent on pavement material types: flexible (asphaltic, bituminous composites) and rigid (cementitious, concrete, pozzolanic composites). In this investigation, an innovative semi-flexible hybrid composite pavement type, where the surface course comprises a semi-flexible material, has been developed with the objective of combining some of the best qualities from both flexible and rigid pavements surfaces. This type of composite road surfaces are commonly named grouted macadams.

In grouted macadams, the flexible, jointless, water proofing properties that characterize asphalt are accompanied by a high static bearing capacity, rutting and wear resistance, as well as resistance to oil and fuel spillage that are characteristic to conventional concrete surfaces [6–9]. The mechanical properties of grouted macadams lend themselves ideally to scenarios where a combination of slow and heavy traffic is prevalent, including industrial areas, airports, ports, bus terminals, cargo centres, etc.

The first development of the semi-flexible pavements was carried out in the 50’s, in France, as a surface course protection against the oils and fuels spillage [10]. Between 1988 and 2000, 165,000 m² of grouted macadams were constructed in Copenhagen Airport [11], which is a practical example of the application of these pavements. Since then, several studies have been conducted to investigate the performance characteristics of this pavement surfaces type [12–15].

The process of constructing a grouted macadam layer is composed of two stages. In the first stage, a hot mix porous asphalt with high voids content (25–35%) is laid with a traditional asphalt...
paver and lightly compacted. In the second stage, the porous asphalt layer is impregnated with a highly flowable self-compacting cementitious grout [16,17].

This paper includes results of a laboratory investigation into the properties of a grouted macadam range impregnated with a number of grouts that incorporate innovative formulations capable of replacing conventional materials of natural origin. In particular, milled glass and a selected waste mud were utilized in formulating highly workable cementitious grouts. Marsh Cone flow time measurements were supplemented with additional rheometric measurements in order to more fully characterize the grouts (e.g. yield stress and relative plastic viscosity).

Additionally in this investigation, conventional aggregates normally used in porous asphalt production were replaced with Reclaimed Asphalt Pavement (RAP) or altered aggregate, and were incorporated into a cold mix porous asphalt skeleton. The advantages of using a cold mix asphalt include ease of mixing and handling; eliminating the requirement for large sized production plants and allowing rapid installation even in remote areas; energy savings; reducing emissions; and health and safety benefits [9]. The performance of these cold mix asphalt skeletons were compared with a conventional hot mix asphalt produced with natural aggregates. The resultant grouted macadam composites characterization was carried out by using the following tests: indirect tensile strength; compressive strength and an activation principle, in order to achieve low viscosities. Superplasticisers play an important action in the production of more durable grouts with improved rheological characteristics [18]. Taking into account the various water/cement ratios proposed by Anderton and Setyawan, Table 2 presents the water/cement ratios adopted in this investigation to produce a Weaker grout (W) and a Stronger grout (S).

2.2. Grouts formulations

In this investigation, 12 cementitious grout formulations in addition to 4 geopolymeric grout formulations were developed and tested. The cementitious grout designs utilized specific combinations of water/cement ratios, superplasticiser type and content, and cement replacement type and content. On the other hand, the geopolymeric grouts were manufactured using a waste mud activated with various concentrations of alkali solution.

An overview of the various cementitious and geopolymeric compositions are presented in Tables 4 and 5, respectively. The following sections present additional details of the various grout components.

2.2.1. Superplasticisers

Two types of superplasticisers were used in formulating the cementitious grouts, each having a different activation principle, based on the studies of Anderton [12] and Setyawan [15]. Anderton utilized a styrene–butadiene based admixture to improve particle adhesion and ultimately grant flexural strength. Setyawan, on the other hand, used a water/cement ratio lower than Anderton's mixtures, with the aid of third generation superplasticisers (Polycarboxylate-based admixture), in order to achieve low viscosities. Superplasticisers play an important action in the production of more durable grouts with improved rheological characteristics [18]. Taking into account the various water/cement ratios proposed by Anderton and Setyawan, Table 2 presents the water/cement ratios adopted in this investigation to produce a Weaker grout (W) and a Stronger grout (S).

2.2.2. Cement replacement materials

The milled Glass (MC) used in this investigation was processed from recycled bottles. The glass used was soda-lime type, composed essentially of silica, as well of sodium and calcium oxides. A tubular ball mill device coated with neoprene was used for the milling process. For an average final particle size of 125 µm the milling time was determined by using a ratio mass/time of

<table>
<thead>
<tr>
<th>Table 2</th>
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<tbody>
<tr>
<td>Weaker and stronger grouts design (wt % of cement mass).</td>
</tr>
<tr>
<td>Water/cement</td>
</tr>
<tr>
<td>Styrene–butadiene</td>
</tr>
<tr>
<td>admixture (%)</td>
</tr>
<tr>
<td>Polycarboxylate-based</td>
</tr>
<tr>
<td>admixture (%)</td>
</tr>
</tbody>
</table>

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**2. Materials**

2.1. Asphalt skeleton

2.1.1. Aggregates

The aggregates used in this study were natural granites (5/15), altered granites (8/12.5) and RAP. All mixtures incorporated limestone filler. In Table 1 the selected mechanical and volumetric properties, including bulk density, water absorption and percent crushed aggregates are presented. The RAP bitumen content, as well as its bulk density, are indicated in Table 1.

2.1.2. Binders

In the case of the conventional hot mixture asphalt, a 100/150 pen grade bitumen was used. For the cold mixture asphalt, a Polymer Modified Emulsion (PME) manufactured by CEPSA, with the commercial product name of Styemul was used. The binders characterization was based on the penetration test, with measured penetration values of 128 dmm for the 100/150 pen grade bitumen and 220 dmm for the PME residue. As far as the softening point test is concerned, the 100/150 pen grade bitumen had a softening point temperature of 43.0°C whilst the PME had a softening point of 42.2°C.

2.1.3. Open-graded asphalt design

Knowledge gained from the literature proved essential for producing the standard porous asphalt mixture. Anderton [12] and Oliveira [14] were the main references used for the mixture design and production processes.

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Aggregates properties.</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Bulk density (kg/m³)</td>
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<tr>
<td>Water absorption (%)</td>
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<tr>
<td>Crushed aggregates (%)</td>
</tr>
<tr>
<td>Bitumen content (%)</td>
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</table>
0.34 kg/h. This relationship was obtained from an earlier empirical study carried out with the same laboratory equipment [19].

Panasqueira Waste Mud (PWM) samples were sourced from Panasqueira mud deposits located in the extreme south of the Serra da Estrela mountain near the Zêzere river in the central region of Portugal. This mine is considered to be one of the largest tungsten deposits in Europe. These wastes are composed mainly of silica and aluminum [20]. Prior to its incorporation into the cementitious grout formulations, the waste mud was milled in a Los Angeles abrasion equipment for 6 h to obtain fine material with a particle size less than 125 μm.

2.2.3. Alkali-activators

The geopolymeric grouts consisted of samples of PWM chemically activated using a mixture of Na₂SiO₄ and NaOH in solution. The quantities of each compound were established according to different ratios, as presented in Table 5.

2.2.4. Grouts compositions

The cement based grouts were produced by using a Portland cement CEM I 42.5R. The particle size analysis of the cement, waste mud and milled glass, was carried out with a Beckman Coulter LS 200 laser analyser. Table 3 presents the bulk density and specific surface area results of each material.

Table 3
Bulk density and specific surface area of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Bulk density (kg/m³)</th>
<th>Specific surface area (m²/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement</td>
<td>3031</td>
<td>365.5</td>
</tr>
<tr>
<td>Milled glass</td>
<td>2975</td>
<td>170.4</td>
</tr>
<tr>
<td>Panasqueira Waste Mud</td>
<td>2555</td>
<td>239.6</td>
</tr>
</tbody>
</table>

Table 4
Weaker and stronger grouts compositions (% of cement mass).

<table>
<thead>
<tr>
<th>Grouts nomenclature</th>
<th>Water cement/mortar</th>
<th>Superplasticiser (%)</th>
<th>Cement (%)</th>
<th>Panasqueira Waste Mud (%)</th>
<th>Milled glass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weaker</td>
<td>W20PWM</td>
<td>0.6</td>
<td>3</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>W30PWM</td>
<td>70</td>
<td>–</td>
<td>30</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>W40PWM</td>
<td>60</td>
<td>40</td>
<td>–</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>W20MG</td>
<td>80</td>
<td>–</td>
<td>–</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>W30MG</td>
<td>70</td>
<td>–</td>
<td>30</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>W40MG</td>
<td>60</td>
<td>–</td>
<td>40</td>
<td>–</td>
</tr>
<tr>
<td>Stronger</td>
<td>S20PWM</td>
<td>0.28</td>
<td>1</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>S30PWM</td>
<td>70</td>
<td>30</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>S40PWM</td>
<td>60</td>
<td>40</td>
<td>–</td>
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<tr>
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<td>80</td>
<td>–</td>
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<td></td>
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<td>70</td>
<td>–</td>
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<td>–</td>
</tr>
<tr>
<td></td>
<td>S40MG</td>
<td>60</td>
<td>–</td>
<td>40</td>
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</tr>
</tbody>
</table>

through the cone is proportional to the grout viscosity. Flow time increases with an increase of the viscosity, and thereby it becomes an index of fluidity. Anderton [12] recommended flow time values between 8 and 10 s for the cementitous grouts whilst Collop and Elliott [13] recommended values between 12 and 16 s. It should be noted that the Marsh flow cone type dimensions used in this study were slightly different from the dimensions used in references [12,13].

3.1.2. Rheological parameters

The fresh grouts were additionally tested using a Viskomat NT rheometer having a maximum torque capacity of 250 Nmm and the ability to control the mixture temperature during the test. All grout mixtures were tested using the same 6 min speed profile. In this profile the rotation speed is increased from 0 to 120 rpm in 3 min and it is reduced back to 0 over the following 3 min.

The mixtures test temperature was kept constant at 20°C. The rheological parameters from both the Bingham and Herschel-Bulkley models were obtained using the descendent torque and rotational speed values which is in line with earlier investigations [21,22]. The rheological model chosen to characterize each grout was the one that showed the highest correlation with the experimental results.

3.2. Grouted macadam characterization

Four mechanical tests were utilized to assess the properties of the various grout formulations proposed: Indirect Tensile Stiffness Modulus, Marshall stability, Compressive strength and Wheel-tracking test.

3.2.1. Indirect tensile stiffness modulus

The test was carried out according to EN 12697-26 standard, using the NAT equipment (Nottingham Asphalt Tester). Thirty-two cylindrical specimens were cored (104.4 mm diameter) from a number of grouted macadam slabs. The specimens were tested individually at different curing ages (7, 14 and 28 days at ambient temperature). The test conditions were: test temperature 20°C, Poisson’s ratio 0.35, rise time 124 ms and a target peak transient horizontal deformation of 5 μm.

The mixtures stiffness is obtained through the application of predetermined repeated loads to each test specimen and by measuring the respective recorded transient deformations by LVDT sensors (Linear Variable Displacement Transducer).

3.2.2. Marshall stability

Thirty-two cylindrical cored grouted macadam specimens (100 mm diameter) were tested using the traditional Marshall stability test after 28 days of environmental curing. The test was conducted in accordance with EN 12697-34 standard.

3.2.3. Compressive strength

The compressive strength test, according to the EN 1015:11 standard, was used to evaluate twenty-five cubic specimens (50 × 50 × 50 mm) extracted from 28 days ambient cured grouted macadam slabs. The load application rate was 0.35 kN/s and the test equipment used was an ELE 30000 kN hydraulic press equipped with a TDS-602 data logger.
4. Results and discussion

4.1. Grouts characterization

The described tests results form the basis for selecting the best solution among the various cementitious grouts trialed containing either PWM or MG, or alternatively geopolymeric grouts, all designed for porous asphalt impregnation purposes.

4.1.1. Flow time

Fig. 1 presents the flow time test results of the weaker and stronger cementitious grouts. The highest fluidity presented by the weaker grout group could be explained by their higher water/cement ratio and the styrene–butadiene admixture plasticizing action. In the stronger grouts group, increasing the content of milled glass significantly reduces the flow time values. Incorporating milled glass particles with their impermeable and low specific surface areas indicates that at the same water/cement ratio water is available to fluidize the grouts. As far as the geopolymeric grouts were concerned, the only grout composition that was found to have any measurable flow properties when using the flow cone was the GEO I grout which had a flow time value of 467 s. This flow time is considered to be very high for grout impregnation into the bituminous skeleton.

4.1.2. Rheological parameters

Fig. 2 shows the results of the stronger and weaker grout flow behavior. Both grouts displayed thixotropic behavior showing a well-defined hysteresis loop. For scale reasons, this area is clearly visible in the case of the stronger grout. The yield stress values obtained both by the Bingham and Herschel–Bulkley models are of the same order of magnitude, but in the case of the weaker grout the plastic viscosity was significantly lower. The rheological model which best characterizes the weaker grout is the Bingham model, with a relative plastic viscosity 0.059 Nmm min. On the other hand, the stronger grout is better characterized by the Herschel–Bulkley model. This change in the rheological behavior may be attributed to the superplasticiser polycarboxylate-based admixtures incorporated in the stronger grout. In the Herschel–Bulkley model equation, an exponent higher than 1 indicates a grout shear thickening behavior (i.e., grout viscosity increases with the rate of shear strain). In order to compare grouts plastic viscosities, a Herschel–Bulkley model linear regression was used, as suggested by Larrard et al. [23], resulting in a 1.214 Nmm min relative plastic viscosity.

The rheological behavior of both the stronger and the weaker grouts variations, formulated according to Table 4, was also analyzed and kept constant in relation to the base grouts. The S20MG and S30MG grouts showed the best relative plastic viscosity values of 0.358 and 0.239 Nmm min, respectively. However, the S30MG grout was chosen for impregnating the asphalt mixtures because when compared with the S20MG it demonstrated a reduced flow time.

Fig. 3 presents the GEO I grout rheological behavior which is represented by the Herschel–Bulkley model. In this case, the Herschel–Bulkley equation exponent was lower than 1, indicating that the grout has a pseudoplastic behavior, i.e., when a shear stress is applied the particles rearrange themselves to facilitate the movement. The relative plastic viscosity obtained was 1.725 Nmm min. The yield stress negative values presented have no physical meaning, because they feature a null stress. This grout was selected among the geopolymeric formulations for impregnation of the porous asphalt skeleton by being the only geopolymeric grout with acceptable results.

4.2. Grouted macadam characterization

From all the grout formulations investigated, four compositions were finally selected for impregnation into the porous asphalt skeleton. Initially, the effect on mechanical performance between the W and S cementitious grouts in hot mixtures was compared, to define a reference grouted macadam. Afterwards, the S30MG grouts (cementitious grout) and the GEO I (geopolymeric grout) were chosen to impregnate the cold asphalt mixtures with altered granite and RAP.

4.2.1. Indirect tensile stiffness modulus

Based on the analysis of Table 6, the 8/12.5 hot mixture was the chosen solution to be used as a conventional mixture. As expected, the S grout stiffness values were higher than those of the W grout, which is in line with earlier results reported by Anderton [12] and Setyawan [15]. Cold asphalt mixtures have a lower stiffness modulus when compared to hot mixtures. These results are partially due to the higher penetration of the emulsion (220 dmm) when compared with the bitumen 100/150 (128 dmm).

4.2.2. Marshall stability

Fig. 4 shows the Marshall stability test results. Hot mixtures have very similar stability values, except for the hot mixture which contains the weaker grout. When considering the results of the 8/12.5 cold mixtures with altered granite, it was clear that the influence of grouts was highly significant, i.e., a cementitious grout like the S30MG, with better mechanical properties and better voids...
filling properties, improved the mixture overall behavior when compared to the geopolymeric grout composite performance. All the cold asphalt mixtures composed of RAP achieved similar stability values significantly lower than those achieved by the hot mix asphalt skeletons. When comparing the results obtained from this investigation with earlier results present in the literature, e.g. Deshmukh [24] mixture with 22.7 kN stability, all the hot mixtures presented in Fig. 4 show better results.

4.2.3. Compressive strength

The compressive strength results of various grouted macadam formulations are presented in Fig. 5. By comparing 5/15 hot mix-
Wheel-tracking test results for grouted macadams. Lower results due to the grout type. The use of the geopolymeric grouts requires further studies, particularly as cure conditions are concerned. Nevertheless, this paper has shown that these are impregnation capacity grouts, which present high viscosities. The 8/12.5 cold mixture with altered granite and cementitious grout (S30MG) obtained the best result of total permanent deformation (0.06 mm). Cold mixtures with altered granite obtained the largest deformations.

4.2.4. Permanent deformation

The resistance to permanent deformation results are presented in Table 7. It was evident that all mixtures showed a good behavior to permanent deformations, showing only residual deformations. The 8/12.5 with RAP cold mixture and cementitious grout (S30MG) obtained the best result of total permanent deformation (0.06 mm). Cold mixtures with altered granite obtained the largest deformations.

5. Conclusions

This paper develops a new grouted macadams technique which incorporates recycled materials in cold mixtures and the grouts with waste impregnation. Using recycled aggregates was one of the primary goals of the study and it was achieved by taking into account the relevant values obtained in some of the tests performed. This technique has advantages for the road industry, in particular the low-cost production and the contribution to sustainability, since these are environmental friendly mixtures. The obtained results in tests enable these mixtures implementation in different types of pavements. In this paper, the studied mixtures solutions are compared with conventional hot mixtures. This investigation main conclusions are the following:

(1) The good performance of cold mix porous asphalt, with incorporation of RAP and altered granites, in the stiffness and wheel-tracking tests shows the feasibility of the solutions studied for grouted macadams.

(2) The grouts have big influence on semi-flexible pavements. The stronger grout obtained the best viscosity and compressive strength results. The milled glass added to the stronger grout was the waste which got better results, having the S30MG grout been adopted to incorporate as cementitious grout.

(3) The use of the geopolymeric grouts requires further studies, particularly as cure conditions are concerned. Nevertheless, this paper has shown that these are impregnation capacity grouts, which present high viscosities.

(4) The 8/12.5 cold mixture with altered granite and cementitious grout (S30MG) was the mixture with best results of stiffness and Marshall stability, and the 8/12.5 cold mixture with RAP and cementitious grout (S30MG) obtained the best permanent deformation and compressive strength.

The tests represent preliminary studies in this area, and it is necessary to go on with this investigation, in order to enhance the development of directly applicable solutions to the road and airport construction industry. However, it was verified that the bituminous mixtures containing secondary materials (waste/ recycled) are a good alternative to conventional hot semi-flexible pavement mixtures, thus representing an evolution in the resistant pavements area, as the ones applied in airports.

References


