Active fillers’ effect on in situ performances of foam bitumen recycled mixtures

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(Received 10 December 2015; accepted 20 May 2016)

Cold recycling is one of the most employed rehabilitation techniques for asphalt pavements and it is becoming more and more important as reducing emissions becomes a priority in the reduction of the greenhouse effect. The main advantages of asphalt cold recycling techniques are the use of reclaimed materials and the fact that there is no need of aggregate heating to make the mixtures. This paper describes the evolution with time of in-situ performances of different foam bitumen-stabilised mixtures made with different active fillers (cement and lime), monitored during the first year from construction. Results are part of a more extensive research programme aimed to investigate the effects of using lime as an active filler in cold-recycled mixtures. Mixtures have been laid down on a specifically designed trial section in Italy, close to Florence. Short-term bearing capacity, immediately after construction, has been evaluated using a light weight deflectometer while to evaluate the mid-term performances falling weight deflectometer (FWD) tests have been performed after 24 hours, 14 days, 28 days and 9 months from construction. During these 9 months the test road was not opened to traffic, so the mixtures experienced almost no traffic (only construction traffic loads). This fact allowed to have the curing process without any influences other than the temperature: it means same curing conditions for all mixtures. Subsequent FWD tests are still ongoing to evaluate the evolution over time of pavement bearing capacity due to traffic. Results obtained positively support the use of lime as an active filler in the foam bitumen-stabilised material and allow to underline the effect of different active fillers in the material behaviour, even if all the mixtures underline excellent performances under traffic loading. FWD tests are scheduled to be repeated every 6 months in order to monitor the stiffness evolution of the mixtures and evaluate the nature of traffic damage.

\textbf{Keywords:} foam bitumen; bearing capacity; light weight deflectometer (LWD); falling weight deflectometer (FWD); active filler; lime; cement

Introduction

Asphalt mixtures are the most common materials employed in the road pavements around the world and as all the materials used in constructions they face sustainability challenges. However, using asphalt mixtures road agency has the answers for the main questions that sustainability of constructions generally raises about materials (“How to re-use it?”, “How to manage it after demolition?”): asphalt mixtures can be fully recycled in plant or in field using hot recycling techniques or cold recycling techniques (Tebaldi et al., 2012).
Considering greenhouse emissions, impact on traffic and fuel consumption from the environmental point of view the most efficient technique is the in-place full-depth reclamation using a cold recycling technique. One of the most popular is the bitumen stabilisation with foam bitumen or bituminous emulsions: most probably, the reason is that bitumen-stabilised mixtures can be made with reclaimed asphalt (RA) aggregates from the bound layers mixed with the aggregates from the unbounded layers of pavement. Together with several advantages, the in situ bitumen stabilisation also brings forth some challenges. Among the problematics mainly discussed by pavement engineers and researchers is how to manage active fillers. Active fillers are used in the bitumen-stabilised mixtures mainly for the following reasons:

- to facilitate the dispersion of bitumen in the mixture: active filler’s particles catch the droplets of bitumen made by the blasting of the bubbles of foam bitumen or made by the flocculation of the emulsion’s bitumen and absorb them in the mixture;
- to have a quicker strengthening of the mixture and consequently to obtain quickly the necessary bearing capacity of the layer (for this purpose cement is mainly used);
- to maintain control over the moisture content;
- to treat fine plastic particles in the aggregates.

In addition to these functions, sometime in the full-depth reclamation it is necessary to stabilise clay particles raised in the unbounded layer from the subgrade. For this purpose, it is necessary to use lime and it generally means to have a blend of fillers (Asphalt Academy, 2009): lime for stabilisation of clay, cement to have quickly the necessary bearing capacity and mineral filler originally present in the granular material of unbounded layer.

The problems related with active fillers may be synthetised in the following questions:

- Which is the most appropriate active filler?
- What is the correct amount of active filler?
- In case of a blend of active fillers, what is the correct ratio between the components?

In spite of the fact that practical experience and some research give the examples that assist with practical answers to the above questions, from a scientific perspective, there are still unanswered questions. In particular, the relationship between active filler and performance of bitumen-stabilised material remains unclear. Limited literature is available regarding the effect on long-term performances of cold-recycled mixtures incorporating different blends of active fillers.

In an effort to develop a better understanding of the stiffness evolution of bitumen-stabilised materials over time, related to active filler or blends of active fillers used, a comprehensive research project was set by the University of Pisa, the University of Stellenbosch, the University of Parma and the University of Nottingham. This paper shows the results of a part of the project focused on the investigation of in-field mid-term performances of fully recycled mixtures produced with foam bitumen and different blends of fillers made by cement, lime and mineral filler.

Six mixtures made with 100% of reclaimed asphalt pavement (RAP) and different amounts of foam bitumen and different ratios of lime, cement and mineral were used to build six consecutive sections in an experimental road. The performances of the mixtures were investigated over the time using a light weight deflectometer (LWD) initially and a falling weight deflectometer (FWD) successively.

The results obtained when all the mixtures may be considered fully cured allow to make some preliminary considerations and some fundamental hypotheses on foam bitumen-stabilised
mixtures; these hypotheses are under verification in the ongoing phases of the project, in particular they will be verified considering weather and traffic effects.

Objective and scope
The objective of this research work is to investigate the evolution of in-place performance properties of cold-recycled mixtures made using the foam bitumen technique, containing different blends of fillers, made with cement, lime and mineral filler, over time. Even though the in-situ recycling can be considered the most appropriate technique for full-depth recycling, in this case, in order to minimise the variability and keep under control all the different components, the mixtures were produced with a mobile mixing plant using only sieved RAP and laid down with a paver.

The comparison between the performances of different mixtures was based on backcalculation of elastic modulus determined on the basis of deflectometric tests at different times after construction. All the tests were carried out using the FWD except for tests immediately after compaction undertaken with the LWD.

As it was not clear from the beginning the evolution over time of performances and what effect may have the traffic load on curing of different mixtures, the pavement was completed and road opened to traffic after 9 months when it was possible to consider all mixtures fully cured with curing process independent of traffic load. During the 9 months a specific surface treatment was used to keep under protection the layer made with bitumen-stabilised material (BSM) against weather damage. LWD and FWD tests were conducted after 4 and 24 hours to evaluate immediate performance and further FWD tests were conducted after 28 days when the setting reaction of cement may be considered completed and after 9 months, before last paving operations and traffic opening, to evaluate the mid-term performances. A multiple series of FWD tests campaign will be made in the future in order to have a mid-stage and long-term evaluation of pavement performances and effect of traffic. On the other hand, laboratory evaluation of fracture properties of recycled mixtures is still ongoing.

Materials and investigation method

Materials characterisation
Trial section comprises six foam bitumen-stabilised mixtures with two different active fillers: lime and cement. In specific, six different blends of filler (cement, lime and mineral filler) were used to keep constant the global amount of filler. In addition, to avoid differences made by the interaction between mineral filler and bitumen, the same limestone filler was used for all the mixtures. Two fractions of RA aggregates (one coarse and one fine) have been selected to form the stone skeleton of the mixes, results of which made with 100% RA aggregates. The two fractions have been mixed in order to have the same grading composition for all the mixtures analysed. (Figure 1)

Percentage of bitumen in the RA resulted significantly different for the two fractions. Values obtained (the ones reported in Table 1 is the average of tests on multiple specimens) by means of laboratory tests are reported in Table 2.

The two fractions of RA have been mixed in order to reach the subsequent final grading composition, optimised following the Italian common practice regarding cold recycling mixtures (Figure 2). Black refers to curve obtained before binder extraction while white refers to grading composition after binder extraction.

Compaction properties of the mixture have been evaluated by means of Modified Proctor tests: the optimum moisture content (OMC) of the RA is 3.3% (Figure 3).
Figure 1. RA grading composition of RA fraction used to produce the recycled mixtures.

Table 1. RA percentage of bitumen for coarse and fine part.

| Specimen              | Average percentage of bitumen (on the dry weight of the aggregate) |
|-----------------------|---------------------------------------------------------------|
| RA coarse aggregates  | 4.4%                                                          |
| RA fine aggregates    | 7.1%                                                          |

Table 2. Recycled mixtures composition.

| Mix ID | % Foam bitumen | % Cement | % Lime | % Mineral filler |
|--------|----------------|----------|--------|-----------------|
| 3A     | 2              | 1.0      | 2.0    | 1.5             |
| 3B     | 2              | 1.0      | 0.0    | 3.5             |
| 5C     | 3              | 2.5      | 2.0    | 0.0             |
| 5D     | 3              | 2.5      | 0.0    | 2.0             |
| 5E     | 3              | 0.0      | 2.0    | 2.5             |
| 5F     | 3              | 0.0      | 3.0    | 1.5             |

The total amount of filler in the mixtures, both active and mineral fillers, binder and ratio’s blends of fillers, was selected on the basis of the common practice in Italy. A standard grade bitumen (penetration 70–100 dmm) was used for the foaming process.

The characteristics of the mixtures analysed within the present research activity are reported in Table 2.
The amount of water added to the mixtures during the production phase was established using a common field practical approach. To do that the subsequent parameters have been taken into account:

- Moisture content of the RA around 1%;
- OMC of the RA resulted, as reported in Figure 3, around 3.3%;
- Total amount of filler in the mixes of about 4.5%.

Figure 2. RA mixture sieve size distribution before (black) and after the extraction (white) of the binder.

Figure 3. RA optimum moisture content evaluation.
On the basis of the above-mentioned parameters, the amount of water to be added to the mixtures (OMC) for production purpose was found to be 6%.

**Trial field characteristics**

Trial section was located on a constructing road near Florence (Italy) (Figure 4). The test pavement included a 17 cm base course made with foam BSM (study mixtures) placed in one layer over a lime-stabilised subgrade. Compaction was extended until reaching the reference level of 100% the modified proctor density using a combi-roller (front rubber and rear metallic drum). The pavement structure has been completed before being opened to traffic: now it has 4 cm of asphalt concrete (AC) wearing course laid directly over the recycled base layer. The entire pavement structure is not following the normal standard requirements: it was specifically designed with the only aim to reach the stress and strain distribution under load allowing researchers to clearly underline the different performances of tested mixtures.

Since the bearing capacity of subgrade may influence the effectiveness of the compaction of foamed bitumen-stabilised layers, an extensive LWD tests campaign was carried out on the lime-stabilised subgrade, selecting the test location in order to have a widespread coverage of the test area. This approach is followed to control bearing capacity and compaction level achieved on the unbound layer and underline the presence of weakness area (Marradi, Pinori, & Betti, 2014). Tests location used to characterise the pavement subgrade matched exactly that used for the analysis of foam bitumen-stabilised mixtures. Results obtained in terms of average surface modulus are presented in Figure 5.

Short-term performance of foam-stabilised mixtures was investigated performing LWD tests after 4 hours and FWD after 24 hours curing. Results obtained underline the well performances of the mixtures, exceeding the threshold stiffness values provided by the specification of Italian Road Authority (ANAS) (Betti et al., 2014) ($E_0 > 50$ MPa after 4 hours and $E_0 > 180$ MPa after 24 hours after construction).

Further FWD tests were carried out after 14 and 28 days, when the setting reactions of cement may be considered completed, and after 9 months, before last paving operations and traffic opening, to evaluate the mid-term performances. Measured deflections are usually used for the
backcalculation process. This process is a mechanistic evaluation of pavement surface deflection basins that matches measured with calculated surface deflection basins (within tolerable errors) by varying the associated layer moduli. The backcalculation process is usually iterative and normally done with software. The Method of Equivalent Thickness (MET, Odemark’s structural transformation method) suggested by Ullidtz (Betti et al., 2014) was used to backcalculate layers moduli and evaluate their evolution over time.

Since the backcalculation process is mainly dependent on the thickness of the tested pavement layers a fundamental assumption needed to be made regarding the pavement structure. As reported by different authors (Huang, 2004; Lytton & Chou, 1988; Ullidtz & Coetzee, 1995), special care should be taken when analysing thin layers (less than 10 cm). Huang (2004) reports that

two agencies using the same computer program derived very different backcalculated results for the same pavement cross section. This is especially true for thin layers because the deflection basin is insensitive to their moduli and good match between computed and measured deflection can be obtained even if totally unreasonable moduli are derived for these thin layers. (p. 415)

For this reason, as suggested by the same author, engineering judgements should be used when analysing deflection of pavement with thin layers.

Due to the limited AC thickness, in order to perform a reliable backcalculation analysis, the trial field pavement was modelled as a two-layer system: layer one combines the 4 cm wearing course with the recycled layer while layer two represented the subgrade half space. By combining together wearing course and recycled mixes in one single layer in the model, its layer modulus backcalculated from the analysis becomes a composite value with the contribution of both layers. However, the wearing course thickness is constant along all the test section; hence, the change in performance underlined by the different sections can only be attributed to the change in the stiffness of the recycled materials.

**Materials temperature sensitivity analysis**

During field tests variable pavement temperatures were experienced. In order to take account of changes in material’s response under different climate conditions, future tests will be undertaken in different seasons thus in different temperature conditions of the pavement. This involves the need to develop a procedure to correct moduli at test temperature to the 20°C reference value.
Previous research on cement-treated mixtures with high content of RA aggregates underline a variation of layer moduli from tests carried out in different seasons (winter and summer), revealing a sort of temperature sensitivity due to only presence of RA (Isola, Betti, Marradi, & Tebaldi, 2013). Regarding bitumen-stabilised materials, Plati, Loizos, Papavasiliou, and Kaltsovounis (2010) present a specific equation, based on laboratory results, to correct layer moduli to 20°C reference temperature. More recently, the effect of temperature on resilient modulus of foam bitumen-stabilised mixtures with different amount of RA aggregates have been investigated: results obtained underline that high percentage of RA aggregates could lead to early fatigue in the pavement as well as permanent deformation (Dal Ben, 2014).

Within the present research activity an innovative procedure to evaluate temperature variation of foam bitumen-stabilised layer moduli is presented, basing assessments on FWD tests. The basic idea is to perform FWD tests in the same day (same curing level), on the same test location with significant difference in the pavement temperatures.

Measured deflection, recorded for each mixture, has been backcalculated to estimate layer moduli and estimate their variation due to only temperature. Resulting moduli at different temperatures were then used to calibrate a specific value for temperature sensitivity parameter “$α$” for each mixture, provided by the generalised version of the equation for temperature correction provided by the Asphalt Institute (Harichandran, Ramon, & Baladi, 2000; Tebaldi et al., 2012).

$$ET_s = 10^α(T^s−T^t) × E,$$

where $ET_s$ is the layer modulus at the reference temperature, $E$ is the modulus at test temperature, $T$ (°F) is the test temperature, $T_s$ (°F) is the reference temperature and $α$ is a temperature sensitivity parameter. Asphalt Institute suggests a value of $1.47362 \times 10^{-4}$ for $α$ to be used for correction of new road asphalt mixtures layer moduli (Harichandran et al., 2000).

This kind of procedure was applied to all the mixtures in order to find six different values of $α$ to be used for correction of foam bitumen layer moduli, evaluated during the previously mentioned four steps of curing (24 hours, 14, 28 days and 9 months), at the 20°C reference temperature. To correct moduli evaluated on the complete pavement (after last paving operation) a single average value was used, taking into account both influence of the recycled layer and asphalt wearing course. Results obtained are reported in Figure 6, where the trend in temperature variation of recycled layer moduli is compared to the ones obtained using equation provided by Plati et al. (2010), Asphalt Institute equation for new asphalt mixtures (Equation (1)) (Harichandran et al., 2000) and equation provided by the HD 29/08 Standard for new constructed asphalt pavement (HD 29/08, 2001).

Results underline the significantly lower temperature sensitivity of the foam bitumen-stabilised mixtures analysed in this research work compared to variations typical of asphalt mixtures. Moreover, the trend seems to be comparable with the one provided by Plati et al. (2010) allowing to confirm the reduced temperature sensitivity of this kind of mixtures.

This behaviour may have an important implication in pavement design; in warm climate areas, like the one experienced in Italy, stiffness variation over the year due to air temperature variation from cold to hot seasons can be considered quite low.

The resulting average moduli for each period of testing ($ET_T$ at the test temperature) is presented in Table 3 together with average moduli at the 20°C reference temperature ($ET_{Ts}$). The layer temperatures, measured through a thermometer placed on a drilled hole inside the pavement, are also reported.

The approach proposed involves some approximation and is probably the reason for some scatter in the results obtained which is needed in order to have performances directly comparable.
Results and discussion

Backcalculated layer moduli of test carried out before wearing course laying operation (9 months from construction) are reported in Figures 7–11 comparing values obtained on each mixtures for the four series of tests carried out at different curing times. Results are organised to show both values obtained on each test location (eight tests location per mixture) and average values for the four curing levels. LWD tests results on the subgrade are also presented in order to underline its influence on recycled mixtures’ performances.

Deflectometric tests after compaction (LWD tests after 4 hours from compaction) are required by the Italian prescriptions to evaluate soundness of construction work in terms of the compaction achieved. For instance, the Italian Road Authority (ANAS) requires to have surface modulus provided by LWD tests greater than 45 MPa after 4 hours from compaction (Betti et al., 2014). Since mixtures compaction may influence the stiffness growth of mixtures containing cementitious binder (Lancieri, Marradi, & Mannucci, 2006), LWD average modulus obtained after 4 hours from compaction is also presented.

All the tests have been carried out before opening to traffic, during the first 9 months from construction. For this reason, all the mixes can be considered completely cured in the same manner, without any influence of traffic load on the curing process and without traffic post-compaction effect. This avoids the introduction of additional variables related to the traffic influence on the curing process and the possibility to have different behaviours with different active fillers and different strengthening processes. Moduli reported in the next graphs are all corrected to 20°C reference temperature, applying the procedure previously reported.

After 9 months of curing, without traffic effect, performances of the mixes are almost the same except for mixture 5F which shows the lowest value of layer moduli (Figure 12). This can be partially explained by the effect of subgrade weakness (Figure 5) to compaction effectiveness, as also confirmed by the lowest value of surface modulus (LWD test) after 4 hours from construction.
Table 3. Temperature variation of foam bitumen layer moduli.

| Curing time     | $E_{IT}$ (MPa) | $T$ (°C) | $E_{IT}/E_{ITs}$ | $\alpha$ | $E_{ITs}$ (MPa) (@20°C) | $E_{IT}$ (MPa) | $T$ (°C) | $E_{IT}/E_{ITs}$ | $\alpha$ | $E_{ITs}$ (MPa) (@20°C) |
|-----------------|----------------|----------|------------------|----------|-------------------------|----------------|----------|------------------|----------|------------------------|
| 24 Hours curing | 842            | 24.9     | 1.09             | 0.000030 | 919                     | 573            | 25.3     | 1.11             | 0.000032 | 634                   |
| 14 Days curing  | 1322           | 27.8     | 1.16             | 0.000030 | 1531                    | 1588           | 27.6     | 1.16             | 0.000032 | 1846                  |
| 28 Days curing  | 1487           | 17.3     | 0.96             | 0.000030 | 1423                    | 1690           | 17.5     | 0.96             | 0.000032 | 1619                  |
| 9 Months curing | 1421           | 30.0     | 1.21             | 0.000030 | 1722                    | 1291           | 30.6     | 1.24             | 0.000032 | 1608                  |
| 24 Hours curing | 1057           | 25.5     | 1.06             | 0.000019 | 1126                    | 834            | 26.2     | 1.24             | 0.000057 | 1035                  |
| 14 Days curing  | 1600           | 27.3     | 1.09             | 0.000019 | 1743                    | 1431           | 26.5     | 1.26             | 0.000057 | 1799                  |
| 28 Days curing  | 1812           | 17.8     | 0.98             | 0.000019 | 1770                    | 1842           | 18.3     | 0.95             | 0.000057 | 1746                  |
| 9 Months curing | 1508           | 27.8     | 1.10             | 0.000019 | 1654                    | 1185           | 28.7     | 1.36             | 0.000057 | 1615                  |
| 24 Hours curing | 898            | 26.3     | 1.18             | 0.000043 | 1061                    | 581            | 26.4     | 1.16             | 0.000038 | 674                   |
| 14 Days curing  | 980            | 26.4     | 1.18             | 0.000043 | 1159                    | 1171           | 26.2     | 1.16             | 0.000038 | 1353                  |
| 28 Days curing  | 1318           | 18.4     | 0.96             | 0.000043 | 1269                    | 1314           | 18.5     | 0.97             | 0.000038 | 1274                  |
| 9 months curing | 1376           | 29.6     | 1.30             | 0.000043 | 1789                    | 957            | 31.1     | 1.31             | 0.000038 | 1258                  |

Mix 5D_3%FB_2.5%C_0%L_2%MF Mix 5E_3%FB_0%C_2%L_2.5%MF

Mix 3B_2%FB_1%C_0%L_3.5%MF Mix 3A_2%FB_1%C_2%L_1.5%MF

Mix 5C_3%FB_2.55C_2%L_0%MF Mix 5F_3%FB_0%C_3%L_1.5%MF
Figure 7. Performance over time: mixture 5D (corrected values to 20°C).

Figure 8. Performance over time: mixture 5E (corrected values to 20°C).

Figure 9. Performance over time: mixture 3B (corrected values to 20°C).

Figure 10. Performance over time: mixture 3A (corrected values to 20°C).
To compare the performance evolution over time of all the mixtures analysed and evaluate the influence of the different blends of active fillers, the layer moduli at different curing times are plotted together in Figure 13.

Results presented in Figure 12 show that mixtures stiffness increase rapidly in the first 14 days of curing, except for mixture 5C, and remain almost stable in the next period. Moreover, the increase in stiffness appears to be lower for mixtures with a high content of cement (2.5%) than the others. The presence of lime seems to reduce the rate of stiffness increase when blended with a high content of cement (mixture 5C) while without cement the mixtures stiffness increases very quickly in the first period (Mixture 5E, Mixture 3A and Mixture 5F). Mixtures with a high content of cement (2.5%, Mixture 5D and Mixture 5C) have the higher stiffness at the end of curing (9 months) even if the rate of stiffness growing seems to be lower: this is especially true for Mixture 5C and is probably due to the presence of lime.

To further analyse the influence on mixtures’ behaviour of using lime with/instead of cement, a comparison has been made between the subsequent mixtures:

3B (2% foam bitumen (FB), 1% cement (C), 0% lime (L), 3.5% mineral filler (MF))
3A (2% FB, 1% C, 2% L, 1.5% MF)
and
5D (3% FB, 2.5% C, 0% L, 2% MF)
5E (3% FB, 0% C, 2% L, 2.5% MF) (Figures 14 and 15)

The comparison underlines that both pairs of mixtures have almost the same trend of stiffness evolution and the ultimate bearing capacity is of the same order of magnitude. From a general point of view, the order of magnitude of layer moduli appear to be reasonable, according the common practice experience for road type as the one we used in this case to place the trial field.
This value, according to the Italian experience on roads of the same importance, appears to be reasonable.

All these comments are regarding performance that was evaluated after only 9 months from construction (without traffic). Special attention will be devoted to the effect of traffic and the consequent failure of the material in terms of fatigue cracking (reduction of stiffness for a continuously bound material) or in terms of permanent deformation (stiffness increase over time for an unbounded or un-continuously bonded material) (Isola et al., 2013).
In the present study, a comparison between foam-recycled mixtures with cement and lime and different amount of active fillers has been analysed. Results are based on FWD tests carried out on a specifically designed trial section monitored within the first year of construction. Even if the investigated technique is appropriate for full-depth recycling, to minimise the variability and to keep under control all the different components to have as much as possible homogeneous mixtures, all the mixtures were produced with a mobile mixing plant using only sieved RA aggregates and laid down with a paver.

During the 9 months, the layer made with BSM was protected by weather effects with a specific surface treatment. LWD and FWD tests were made after 4 and 24 hours to evaluate immediate performances and further FWD tests were made after 14 and 28 days when the setting reaction of cement may be considered completed and after 9 months, before last paving operations and traffic opening, to evaluate the mid-term performances.

To compare moduli obtained in different temperature conditions an innovative procedure, based on FWD tests was followed allowing authors to correct moduli at the 20°C reference temperature. Results obtained underline the lower temperature sensitivity of the foam bitumen-stabilised mixtures compared to what is typically expected for asphalt mixtures; the moduli variation with temperature result however comparable with that provided by other authors and specifically devoted to foam-recycled mixtures. From a practical point of view, these results allow consideration of the stiffness variation over the year due to air temperature variation from cold to hot seasons quite low. Regarding the temperature sensitivity, foam bitumen-stabilised materials seem to perform more likely a “super-performing granular material” (Collings & Jenkins, 2011) than an AC.

After 9-month curing, without traffic effect, no significant differences in mixtures performances can be recognised, except for the mixture having a weaker subgrade (Mixture 5F). The rate of stiffness growth seems to be quicker in the first period (14 days), remaining stable after that. This is especially true for mixtures with no or low content (1%) of cement. Increased growth of mixtures stiffness with high content of cement (2.5%) is lower than other mixtures even if, after 9 months of curing, the absolute moduli are higher than mixtures with low or no content.
of cement. Furthermore, the presence of lime in those mixtures (Mixture 5C) seems to further reduce the rate of stiffness growth. These results led to conclusion that the behaviour of mixtures with 2.5% of cement is more likely to be that of a “continuously bound” material, able to increase stiffness over time as the primary effect of curing. On the other hand, mixtures with low content of cement appear to behave like a non-continuously bound material capable of increased stiffness rapidly in the very short-term period (14 days) and remain almost constant after that. Moreover, the comparison between mixtures 3B-3A and 5D-5E underlines that both pairs of mixtures have almost the same trend of stiffness evolution and the ultimate bearing capacity is still comparable. This confirms that, at the end of 9 months of curing, the use of lime in combination with cement (mixtures 3B-3A) or as substitution of cement (mixtures 5D-5E) can lead to equivalent results in terms of layer moduli.

For all of the analyses, differences in the rate of cement gain between cement and lime active fillers should be considered in conjunction to the curing (moisture reduction) of the BSM. Moreover, the order of magnitude of layer moduli, from a general point of view, appears to be reasonable. For instance, assuming 20 years as the service life horizon, the allowable commercial traffic magnitude reaches 3 million passages.

Results obtained at this stage of the research allow to confirm that the use of lime instead of cement led to equivalent results in terms of mixtures bearing capacity. Moreover, layer moduli seem not to be negatively affected by the use of a cement/lime active fillers blend. This led to conclude that, from a practical point of view, lime can be used instead of cement when excess water content in the mixtures need to be reduced (in-plant recycling) or in combination with cement when the presence of clay particles require stabilisation (in-situ recycling).

To verify these assumptions and evaluate the possible reduction of brittleness due to the presence of lime, the trail section will be monitored in the future in order to evaluate the long-term performances of the mixtures. Especially attention will be devoted to the effect of traffic and the consequent type of damage in the material.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Asphalt Academy. (2009). Technical guideline: Bitumen stabilised materials. A guideline for the design and construction of bitumen emulsion and foamed bitumen stabilized materials. Pretoria: Asphalt Academy.

Betti, G., Pinori, U., Marradi, A., Cocurullo, A., Airey, G., Picariello, F., . . . Jenkins, K. (2014). Short term bearing capacity of foam bitumen recycled mixtures using lime as active filler. 3rd international conference on transportation infrastructure, ICTI 2014, Pisa, Italy.

Collings, D., & Jenkins, K. (2011). The long term behaviour of bitumen stabilised materials (BSMs). Proceedings of the 10th conference on asphalt pavement for Southern Africa, CAPSA.

Dal Ben, M. (2014, January). Resilient response and performance of bitumen stabilized materials with foam incorporating reclaimed asphalt (PhD Thesis). Stellenbosh University, Stellenbosh.

Harichandran, R., Ramon, C., & Baladi, G. (2000). Michback user manual. Department of Civil and Environmental Engineering, Michigan State University.

HD 29/08. (2001). Structural assessment methods. vol. 7, Section 3. Design Manual for Road and Bridge.

Huang, Y. H. (2004). Pavement analysis and design (2nd ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Isola, M., Betti, G., Marradi, A., & Tebaldi, G. (2013). Evaluation of cement treated mixtures with high percentage of reclaimed asphalt pavement. Construction and Building Materials, 48, 238–247. London.

Lancieri, F., Marradi, A., & Mannucci, S. (2006). C&D waste for road construction: Long time performance of roads constructed using recycled aggregates for unbound pavement layers. Proceedings of the 3rd international conference on waste management and the environment, Waste Management, Malta.
Lytton, R. L., & Chou, Y. J. (1988). *Modulus backcalculation exercise*. Informal report to TRB committee A2B05, strength and deformation characteristics, Transportation Research Board, Washington, D.C.

Marradi, A., Pinori, U., & Betti, G. (2014). Subgrade and foundation dynamic performance evaluation by means of light weight deflectometer. *Transportation Research Record, Journal of the Transportation Research Board*, 2457(1), 51–57.

Plati, C., Loizos, A., Papavasiliou, V., & Kaltsounis, A. (2010). *Investigation in situ properties of recycled asphalt pavement with foamed asphalt as base stabilizer*. Advances in Civil Engineering. Article ID 56924. doi:10.1155/2010/565924

Tebaldi, G., Dave, E., Marsac, P., Muraya, P., Hugener, M., Pasetto, M., . . . Bocci, M. (2012). *Classification of recycled asphalt (RA) material*. 2nd international symposium on asphalt pavements & environment, ISAP TC APE, Fortaleza, Brazil, October 1–3.

Ullidtz, P., & Coetzee, N. F. (1995). *Analytical procedures in NDT pavement evaluation*. TRB session structural modeling application in pavement analysis and design. Transportation Research Board, Washington, D.C.