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Mechanical properties of roads unbound treated with synthetic fluid based on isoalkane and tall oil

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A R T I C L E I N F O

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A B S T R A C T

The unbound layers are an essential component of both highly trafficked and low-volume roads as their mechanical properties are of major importance when it comes to ensuring a well-performing pavement. However, as the aggregates employed as road construction materials naturally display a wide variation in the mechanical properties according to their geological origins, the pavement engineer may be interested in utilizing stabilization technologies to deliberately modify and adjust the behaviour of the road courses. This study sheds light on an innovative synthetic fluid technology composed of isoalkane and tall oil pitch. Repeated load triaxial tests investigate the resilient modulus and the deformation behaviour of samples treated with the synthetic system according to different percentages. Furthermore, cyclic triaxial tests are also performed after exposing stabilized specimens to a series of freeze–thaw cycles. The principle of the rolling bottle test is adopted to assess the integrity with stripping loss on loose aggregates coated by the product. The laboratory results show that evident variations in the mechanical properties can be attained once the aggregates are mixed with the synthetic agent and that a strong coating resistant to water and external actions is formed.

Introduction

A road pavement is a layered structure composed of several strata: the natural subgrade acts as the foundation above which unbound and bound courses are built. The main difference in the composition between unbound layers (subbase and base) and bound layers (binder and wearing) is that the latter ones generally contain a binding agent such as bitumen or cement, while the former ones are aggregates that are not usually mixed with other agents [1,2]. The mechanical properties of each layer are definitely relevant to ensure a well-performing road infrastructure encountering as few distresses as possible [3,4]. It is worth mentioning that the largest amount of the worldwide road network is actually composed of the so-called Low-Volume Roads (LVRs) [5], namely pavements characterised by low traffic where the unbound layers are directly exposed to vehicle and weather actions without the superposition of any bound courses [6,7].

The use of additive technologies is a useful practice in pavement engineering to deliberately modify the performance of construction materials to meet the requirements defined by pavement design codes or, in general, to achieve the desired performance during the service life of the road [8,9]. Several traditional and non-traditional additives showing promising results are available for both existing-in-place and new road infrastructures. The application of stabilising technologies in the unbound layers should ideally address and meet three important goals: (i) let the road course reach the desired mechanical properties, (ii) reduce the frequency of the costly maintenance procedures (often performed with surface blading for LVRs), (iii) properly attach the rock aggregate particles without being washed away due to external actions. In addition, a stabilising solution should represent a sustainable and environmentally friendly technology [10–12] entailing a relatively quick and economically convenient treatment [13–15].

Notwithstanding the huge amount of products currently available on

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Table 1
Main physical and chemical properties of the synthetic fluid.

Density	Flashpoint	Boiling point	Viscosity			Price
(g/mL)	(°C)	(°C)	(cP @ −18 °C)	(cP @ 0 °C)	(cP @ 30 °C)	(EUR/kg)
0.85 – 1	> 140	> 316	4500–5500	750–850	150–200	3.3

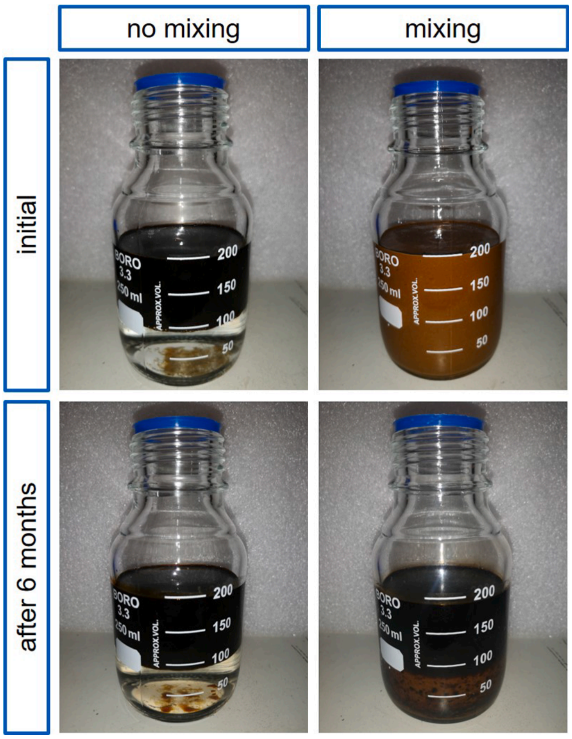

Fig. 1. Separation between synthetic fluid and water with and without initial mixing during a six-month time span.

the market (>200 referring to the US only [16]), the technologies can be efficiently classified according to the chemistry and mechanism of function they are based on [14,17–19]: cement [20–23], bitumen [24–26], chlorides [27–29], clays [30–32], electro-chemicals [33–35], organic non-petroleum products [36–41], organic petroleum products [42–44] and synthetic polymers [45–48]. Cement and bitumen represent traditional technologies, whereas the remainder corresponds to non-traditional solutions mostly developed in the last decades, with the latest inventions being related to polymeric and plant-based additives. It is also worth mentioning that manufacturers are following an increasing trend to blend different agents belonging to two or more categories [16]. Even if some performance-based laboratory tests have been tentatively created [49,50], currently there is a surprising paucity of official testing methods to characterise the performance of non-traditional road stabilizers. Therefore, the design guidelines issued by the road authorities do not generally cover the use of additives and this generally prevents pavement engineers from making informed choices regarding their potentials [51–54].

This study focuses on the performance of aggregates used in a typical road base layer with gradation ranging from 0 mm to 30 mm treated with a synthetic fluid based on isoalkane and tall oil pitch, which can be classified as a mixture of organic petroleum and non-petroleum technologies, respectively. The performance of the aggregate-agent mixture is investigated in this study by means of two laboratory tests: Repeated Load Triaxial Test (RLTT) and a modified version of Rolling Bottle Test (RBT). The RLTT enables a thorough assessment of the mechanical properties, namely resilient modulus and resistance against permanent deformation [55]. Furthermore, RLTTs are also performed after exposing stabilized specimens to a series of Freeze-Thaw (FT) cycles to assess any possible variations in the mechanical response due to freezing action. This is of particular interest for the cold regions over the world, where thaw weakening actions significantly affect the overall response of road pavements leading to major distresses such as reduction of bearing capacity [56,57]. The principle of the RBT is employed to evaluate the integrity with loss stripping of aggregates coated by the product [58]. In this regard, the appearance of the material surface before and after RBT is probed employing a microscope. This work sheds light on the characterization of this innovative technology by providing a rational comparison between the performance of untreated and treated geomaterials.

Materials and methods

Materials

The synthetic fluid investigated in this study is a heterogeneous nonaqueous mixture of isoalkane (CAS# 72623-86-0) and tall oil pitch (CAS# 8016-81-7) which is available in liquid state. The product is non-corrosive and is characterised by musty odour, Table 1 reports its relative density, flashpoint, boiling point, viscosity at different temperatures and indicative price. The technology is non-polar and immiscible in water, as documented in Fig. 1 illustrating the synthetic fluid either poured over water or blended with water using a rotating mixer; the emulsions showed in the picture are stored inside two borosilicate glasses without tops for 6 months at room temperature. Differently from other stabilizing agents, the peculiarity of the investigated technology is its ability to not set up and to not dry with time: the synthetic fluid can be reactivated by means of reshaping and ripping operations in the field as it turns from liquid into a waxy solid after application.

Being a synthetic hydrocarbon, the compound has little or no toxicity to human or ecological receptors, is unlikely to be transported in runoff water and has a limited potential for degradation [59–61]. Based on aquatic toxicity tests performed using a variety of organisms (rainbow trout, fatmucket mussels, crayfish, pond snails, and treefrog tadpoles) representing a typical roadside habitat, the additive shows a range of toxicity spanning from practically nontoxic to moderately toxic depending on the species and the exposure time; no photoenhanced toxicity after UV radiation weathering is reported [62]. Previous studies employing synthetic fluids have dealt with the stabilization of erodible sandy slopes [63] and dust suppression [40,64,65] showing promising results.

The synthetic fluid is a system based on isoalkane and tall oil pitch, which also contains a small amount of alkyl polyamines. Generally speaking, isoalkanes are organic petroleum products containing branched-chain saturated hydrocarbons where the next-to-last carbon atom is bonded to a single methyl group [66,67]. Isoalkanes typically promote aggregate compaction decreasing their moisture susceptibility [52] and have been used as effective dust palliatives [68,69]. Tall oil pitch is a non-volatile residue deriving from the distillation of crude tall oil, this organic non-petroleum agent is a by-product obtained during wood pulp manufacture known as Kraft process [70,71]. Moreover, tall oils can offer better resistance than other organic non-petroleum treatments such as lignosulfonate or reduced sugar [72–74] and are also employed for several high-value applications (i.e., emulsifiers and adhesives). Previous experiences have documented that the tall oil pitch is

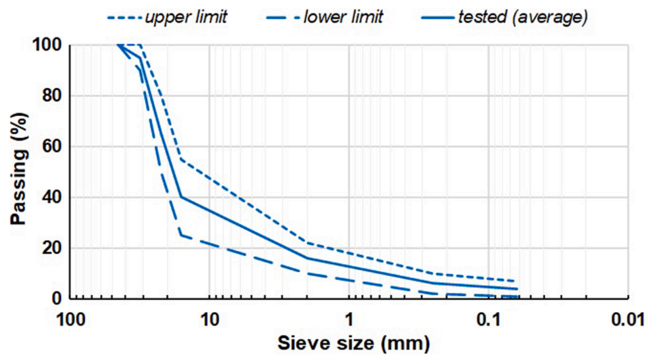

Fig. 2. Particle size distribution employed to perform RLTTs.

an effective unbound stabilizer and dust suppressant forming a water-resistant surface cementing the aggregate particles [75,76].

The aggregates mixed with the synthetic fluid in this research derive from a quarry located in the Vassfjellet area close to Trondheim, Norway. These rocks are mainly composed by fine-grained gabbro/meta-gabbro and are broadly used for road construction in the central part of the country thanks to their good mechanical properties [36,77,78]. These aggregates are characterised by Los-Angeles LA and micro-Deval MDE values equal to 18.2 and 14.2, respectively [79–81]; furthermore, they are highly resistant to freezing and thawing actions with mass loss $\leq$ 1% [82], thus corresponding to category F_1 [83].

Repeated load triaxial test

As a comprehensive approach to mimic the real stress state experienced in a road base layer, the Repeated Load Triaxial Test (RLTT) thoroughly characterises the mechanical properties and performance of both untreated and treated aggregates used for road construction [84–87].

Specimen preparation and testing

The particle distribution size adopted for specimen creation and testing corresponded to a typical road base layer [88,89] and is depicted in Fig. 2. Each cylindrical sample weighted approximately 12 kg and the height measuring 30 cm was twice the diameter; following the indications given by the standard, the maximum particle diameter suitable for testing was 30 mm [55].

Four different treatment amounts have been initially tested regarding the quantity of the synthetic fluid: 0% (UGM), 1.5% (SF-1), 2.5% (SF-2) and 4.5% (SF-3) in mass; overall, 8 specimens have been investigated with 2 parallel samples for each condition. The untreated samples were not mixed with the product nor water and therefore were tested as neat Unbound Granular Materials (UGMs). When preparing the treated specimens, the synthetic fluid was high shear mixed with a water amount corresponding to the Optimum Moisture Content (OMC), which was found to be $w = 5\%$ [90]; in this way, the additive agent could be uniformly blended with the aggregates. The amount of water inside the treated specimens during testing was $w = 1\%$.

Each RLTT sample was created inside a steel mould by sequentially compacting five batches of treated aggregates having the gradation displayed in Fig. 2. The five layers were tamped by means of a Milwaukee 2'' SDS Max rotary hammer (work per blow 27 N • m, hammer weight 12 kg, tamping time 25 s) and finally the sample was ejected from the mould and covered by two latex membranes. The treated specimens then rested for 30 days at room temperature in order to attain a uniform material distribution inside the aggregate matrix ($w = 1\%$) and were added two end-platens, four rubber O-rings and two hose clamps just before testing [91]. The appearance of the created RLTT samples is reported in Fig. 3.

The Multi-Stage Low Stress Level (MS LSL) loading procedure described in CEN standard "13286–7 Cyclic load triaxial test for unbound mixtures" [55,92] was utilized to assess both resilient and permanent deformation behaviour of the test specimens [93–96]. The triaxial σ_3 and deviatoric σ_d stresses were applied by pressurized water and hydraulic jack, respectively. The MS LSL is composed of five sequences, where a sequence comprises six loading steps. For a given step, σ_3 is constant ($\sigma_3 = 20$, 45, 70, 100 or 150 kPa for each sequence) while σ_d varies according to a sinusoidal pattern including 10 000 load pulses at 10 Hz. Three Linear Variable Differential Transducers (LVDTs) measured the axial deformations [97]; if the axial plastic deformation reached or exceeded 0.5%, the loading sequence was halted and the following sequence began. Fig. 4 illustrates the RLTT device.

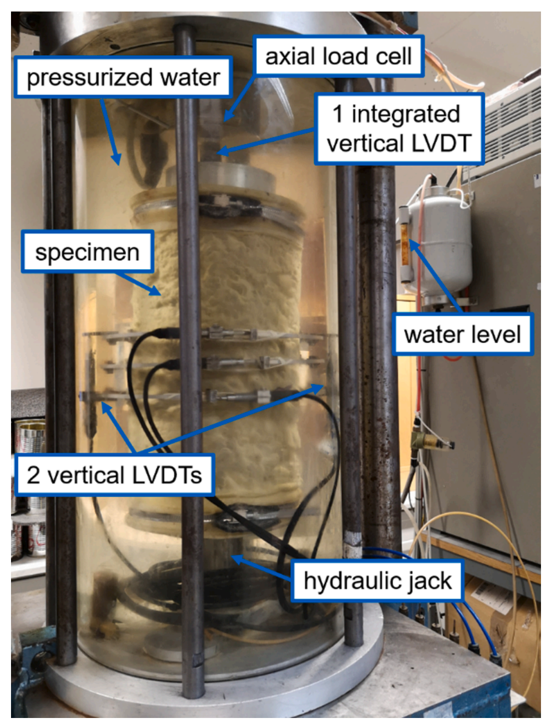

Fig. 4. Triaxial load cell with essential components highlighted.

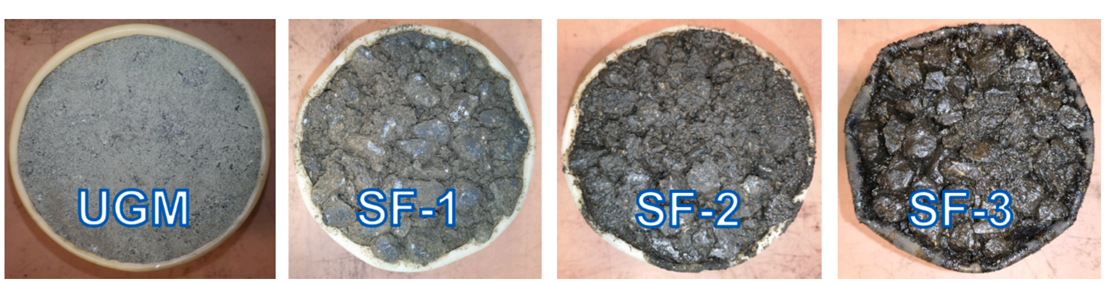

Fig. 3. RLTT samples treated with synthetic fluid according to different percentages: 0% (UGM), 1.5% (SF-1), 2.5% (SF-2) and 4.5% (SF-3), SF samples have $w = 1\%$.

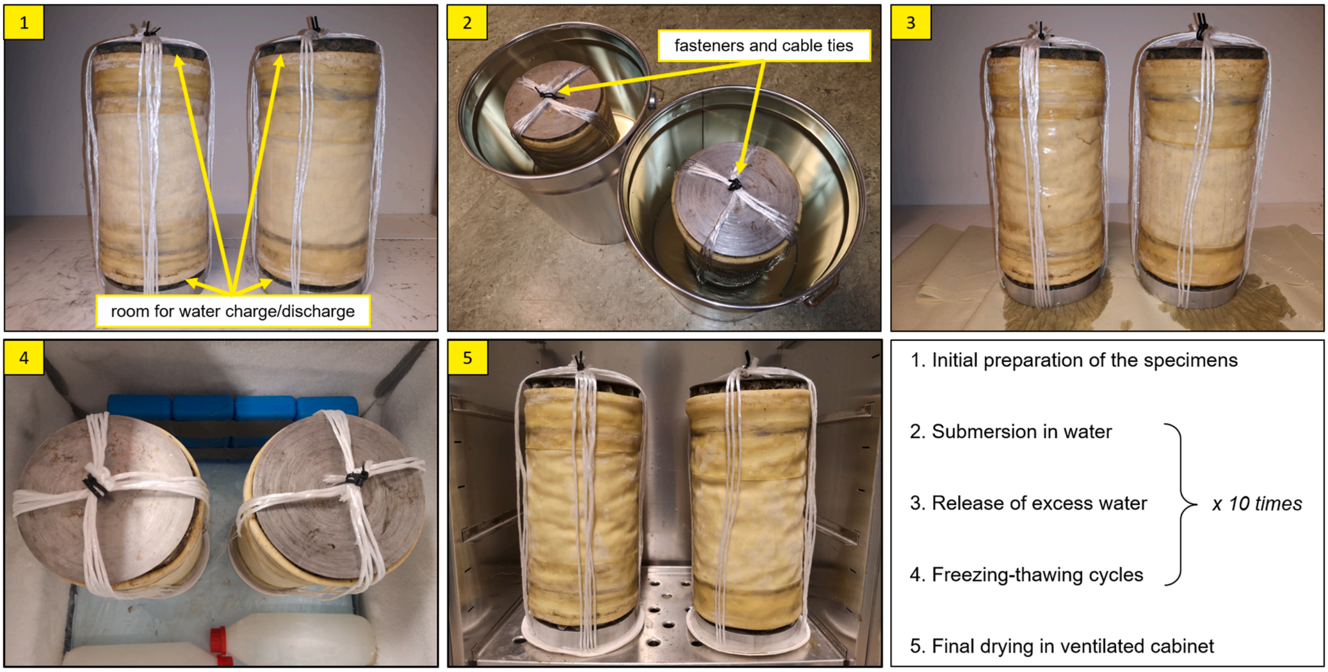

Fig. 5. Illustration of the main steps to perform FT cycles.

As the results described below in Sections 3.1.1 and 3.1.2 document that the additive application amount 1.5% (SF-1) leads to the most promising stabilization effect, the two SF-1 parallel samples were selected for further investigation related to freezing and thawing actions. These specimens were dried in a ventilated cabinet ($w = 0\%$) and tested with RLTT; successively, after exposing them to 10 FT cycles, they were newly dried ($w = 0\%$) and tested. The selected number of performed FT cycles was in line with previous research efforts [98–100] and sufficient to document the behaviour of the treated samples, also considering that the mechanical performance of coarse-graded UGMs tends to level off after a few repetitions of FT actions [101–103].

The achievement of a single FT cycle comprised the following operations: sample submersion (5 min, 23 °C), specimen retrieving and wait to release excess water (5 min, 23 °C), sample placement in a freezer (24 h, −15 °C) and thawing (24 h, 23 °C). The presence of a room for water charge/discharge was ensured both at the bottom and at the top of the specimens, and a system of fasteners and cable ties eased the displacement operations while limiting handling disturbances (Fig. 5). Considering the coarse-graded size of the aggregates particles, the samples were not susceptible to water capillary rise [104].

Results interpretation

The pavement engineer can assess two major mechanical properties of the road materials stabilized with the synthetic fluid by means of RLTTs, namely the resilient modulus M_R and the development of permanent deformations [105]. For a constant σ_3, M_R is defined as

$$M_R = \frac{\Delta\sigma_{d,dyn}}{\varepsilon_{el,a}} \quad (1)$$

with the numerator and the denominator being the variation in dynamic deviatoric stress $\sigma_{d,dyn}$ and the elastic axial strain, respectively. Considering the models available in literature to analyse RLTT results, the k-θ formulation proposed by Hicks & Monismith is probably the most common used to efficiently portray M_R as a function of bulk stress θ (θ is the sum of the principal stresses, the minimum and average principal stresses are equal for the performed MS LSL tests) [84,106].

$$M_R = k_{1,HM}\sigma_a\left(\frac{\theta}{\sigma_a}\right)^{k_{2,HM}} \quad (2)$$

being $k_{1,HM}$, $k_{2,HM}$ regression parameters and σ_a a reference pressure equal to 100 kPa. To broaden the results interpretation, Uzan model is also taken into consideration; this formulation puts the resilient modulus M_R in relationship with bulk stress θ and deviatoric stress σ_d [107]

$$M_R = k_{1,UZ}\sigma_a\left(\frac{\theta}{\sigma_a}\right)^{k_{2,UZ}}\left(\frac{\sigma_d}{\sigma_a}\right)^{k_{3,UZ}} \quad (3)$$

where $k_{1,UZ}$, $k_{2,UZ}$, $k_{3,UZ}$ are regression coefficients. When comparing the formulations proposed by Hicks & Monismith and Uzan, the latter model also considers σ_d in addition to θ and therefore can be represented in a 3D plot.

The resistance against permanent deformation is assessed according to the Coulomb approach [96], which evaluates the extent of shear strength and the maximum shear strength defining the elastic limit angle ρ and failure limit angle φ, respectively. Considering the amount of plastic deformation developed per load cycle $\dot{\varepsilon}_{pl}$ according to the strain rates reported in Table 2, three ranges are identified for the material behaviour: elastic, elasto-plastic and plastic [85,108].

Table 2
Values of the plastic strain rate $\dot{\varepsilon}_{pl}$ used to assess the resistance to permanent deformation of the tested materials.

Plastic strain rate	Range
$\dot{\varepsilon}_{pl} < 2.5 \cdot 10^{-8}$	elastic
$2.5 \cdot 10^{-8} < \dot{\varepsilon}_{pl} < 1.0 \cdot 10^{-7}$	elasto-plastic
$\dot{\varepsilon}_{pl} > 1.0 \cdot 10^{-7}$	plastic (incremental failure)

Rolling bottle test

The Rolling Bottle Test (RBT) is a standard approach to evaluate the adhesion between bituminous binder and aggregates. According to the indications provided by CEN standard “12697–11 Determination of the affinity between aggregate and bitumen”, the affinity is assessed thanks to a visual assessment of the coverage extent related to loose aggregate particles initially completely coated by bitumen and exposed to rotational and stirring actions while immersed in water for 6 h and 24 h at

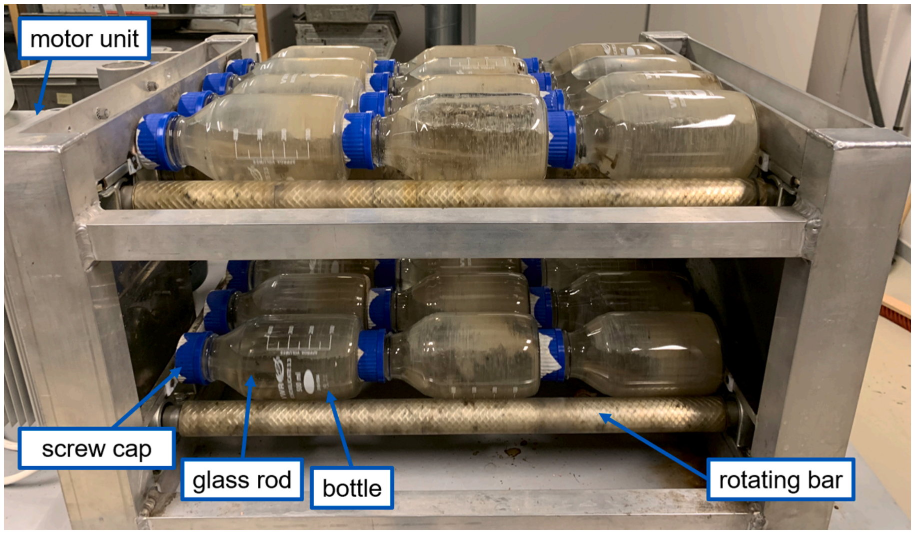

Fig. 6. Rolling machine with test bottles.

room temperature [58]. Considering this premise, the study has performed a modified version of RBT while applying the same rotating and stirring actions to evaluate the susceptibility to stripping of the aggregates covered by the synthetic fluid. This expresses the propensity of the product to adhere to the rock aggregates and is an indirect measure of the abrasion and the erosion resistance properties in presence of water [49].

Each RBT sample was created by carefully mixing manually 150 g ± 1 g of aggregates (fraction 8 mm–11.2 mm) and 4.5 g of the synthetic fluid (3% in mass of the aggregate weight). After creation, the samples rested at room temperature avoiding direct exposure to sunlight for 30 days prior to testing. The loose aggregates forming each sample were placed in borosilicate bottles filled with distilled water; moreover, a glass rod was placed inside each bottle to provide the mechanical stirring action and prevent the formation of lumps between the coated aggregates. Afterwards, the bottles were placed on the rolling machine providing a rotation of 60 rounds per minute (Fig. 6). All the specimens rotated according to fourteen different time intervals: 1 h, 2 h, 3 h, 4 h, 5 h, 6 h, 7 h, 8 h, 10 h, 12 h, 14 h, 16 h, 20 h and 24 h. Considering that three parallel specimens were created for each time interval, a total of 84

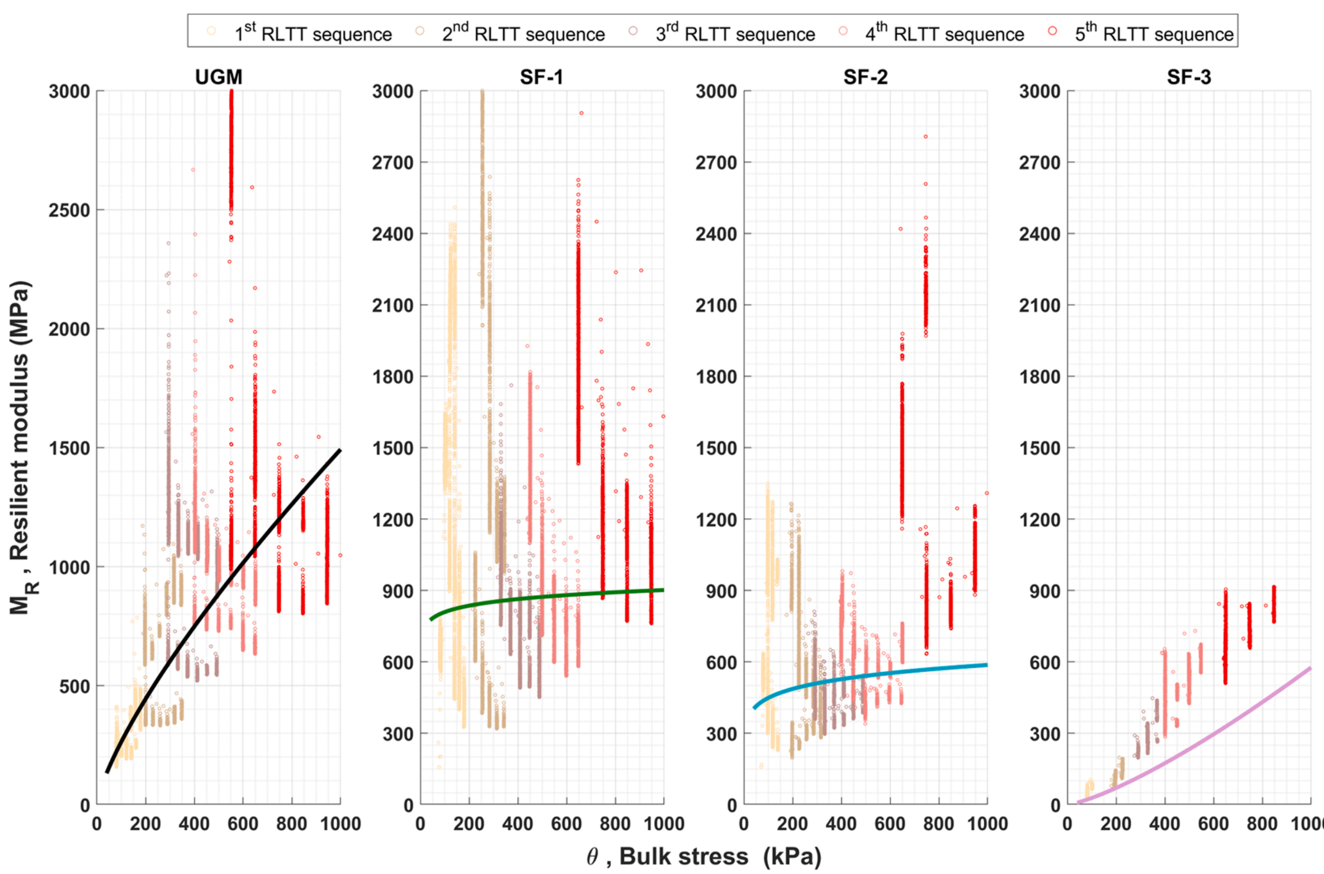

Fig. 7. Experimental data and corresponding trends of resilient moduli M_R according to Hicks & Monismith model.

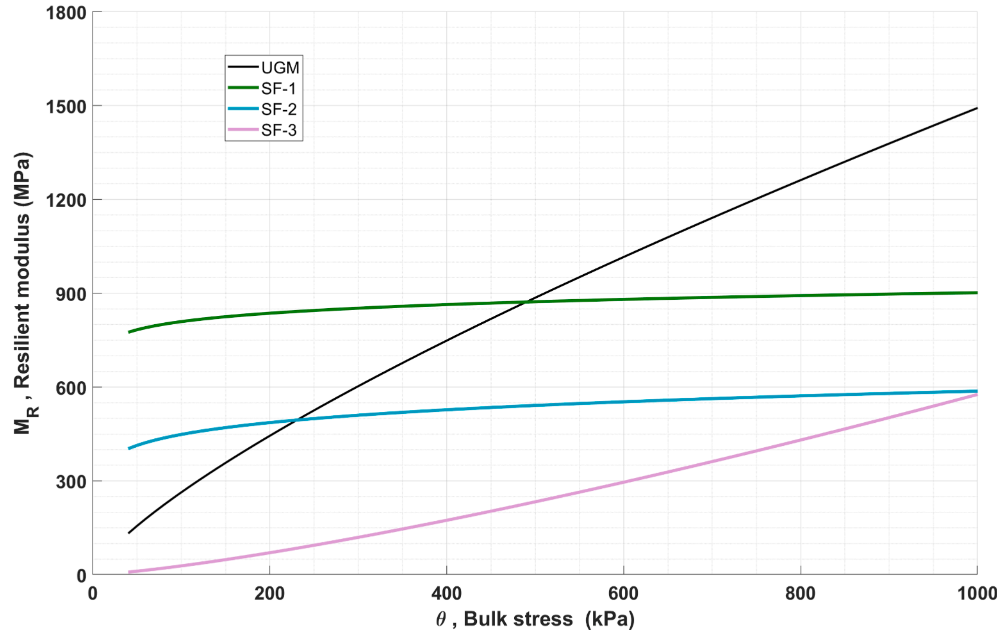

Fig. 8. Comparison between the trends of resilient moduli M_R evaluated according to Hicks & Monismith model.

samples were created and tested [105].

After the completion of the test, the materials contained in the borosilicate bottles were extracted and dried at room temperature; once the mass reached a constant value, the aggregates were weighted and the mass loss ML_{RBT} was calculated as

$$ML_{RBT} = \frac{M_1 - M_2}{M_1}(\%) \tag{4}$$

with M_1 and M_2 being the weight of the dried coated aggregates before and after testing, respectively. It is important to stress that the main difference between the original procedure of RBT described in the standard code and the modified version of RBT achieved in this study is that the former one is a visual assessment of the degree of bituminous coverage and therefore can lead to unprecise results, while the second one hinges upon an objective weight measurement to express the integrity with stripping loss after coating the rock aggregates with an additive agent that is not bitumen [109–112]. Finally, to obtain a better visual understanding of the extent of the coated surface and the corresponding degradation process, the appearance of untreated and treated aggregates before and after RBT was examined with a microscope.

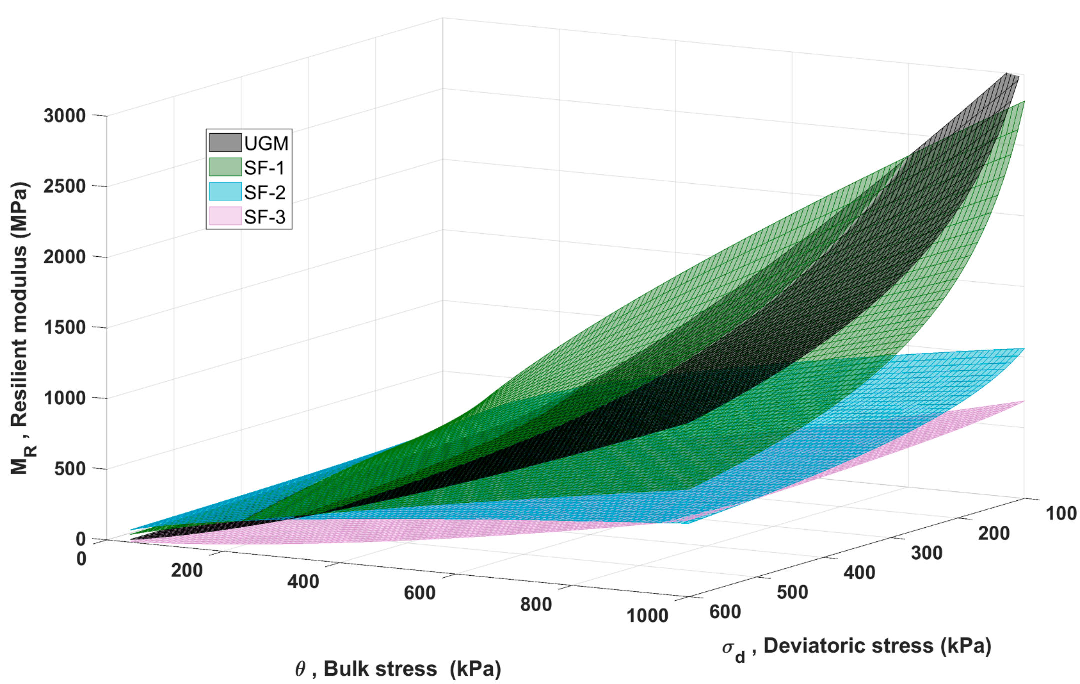

Fig. 9. Comparison between the trends of resilient moduli M_R evaluated according to Uzan model.

Table 3
Regression parameters for Hicks & Monismith and Uzan models.

Treatment	Hicks & Monismith		Uzan		
	$k_{1,HM}$ (-)	$k_{2,HM}$ (-)	$k_{1,UZ}$ (-)	$k_{2,UZ}$ (-)	$k_{3,UZ}$ (-)
UGM	2637	0.75	1576	1.30	−0.51
SF-1	8094	0.05	4273	0.82	−0.73
SF-2	4487	0.12	2953	0.56	−0.40
SF-3	286	1.31	238	1.46	−0.14
before FT	12,364	0.44	12,416	0.44	0.004
after FT	7994	0.70	5969	1.02	−0.30

Results and discussion

Repeated load triaxial test

Resilient modulus

The experimental data and respective trends of resilient moduli M_R evaluated according to the Hicks & Monismith regression model are displayed in Fig. 7; the values of the regression parameters $k_{1,HM}$, $k_{2,HM}$ are assessed performing a least square regression considering the five groups of experimental data, which derive from as many loading sequences of MS LSL testing [55,91]. It is evident that the synthetic fluid technology entails a modification in the elastic properties of the treated aggregates to different extents based on the application percentages. As

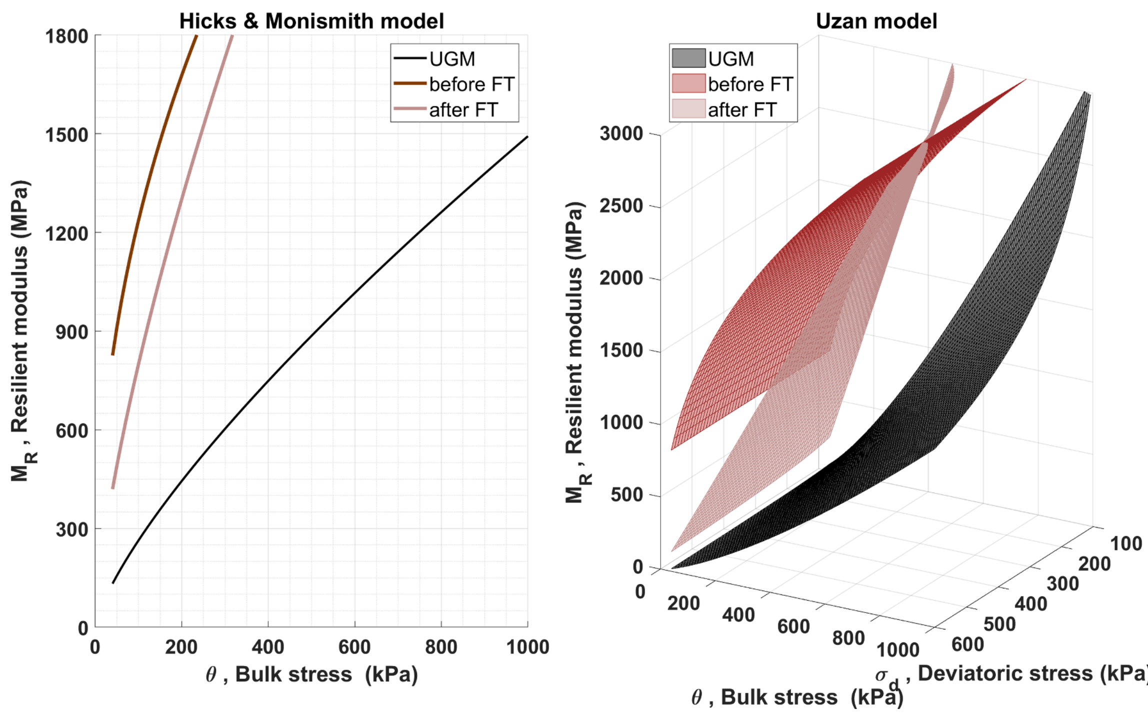

Fig. 10. Trends of resilient moduli M_R for SF-1 specimens tested before and after 10 FT cycles ($w = 0\%$).

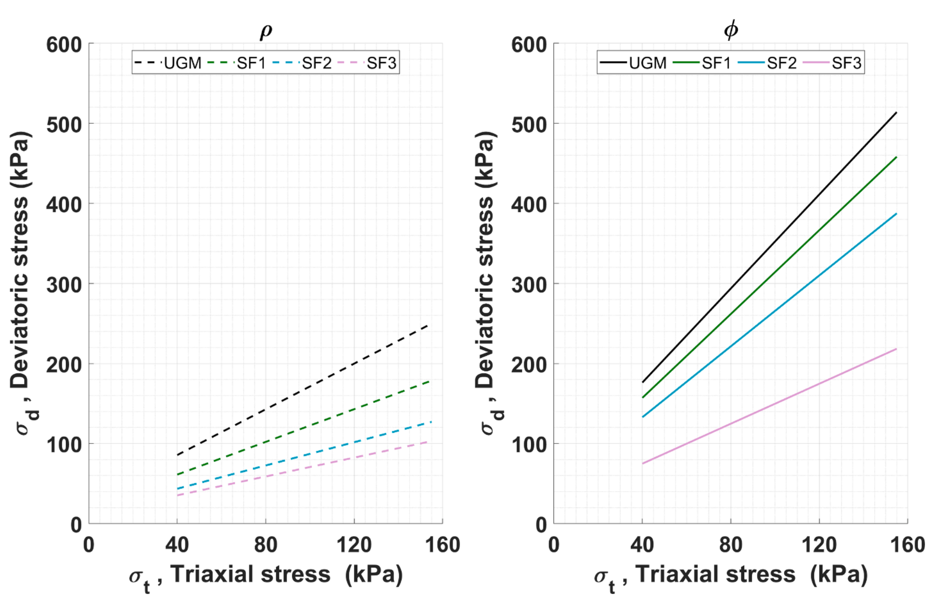

Fig. 11. Elastic limit angle ρ and failure limit angle φ.

Table 4
Values of elastic limit angle ρ and failure limit angle φ.

Treatment	ρ (°)	φ (°)
UGM	55.0	71.2
SF-1	45.6	69.1
SF-2	36.0	65.7
SF-3	30.5	51.3
before FT	70.3	73.5
after FT	71.1	74.2

better represented in Fig. 8 depicting all the curves in the same plot, a higher percentage of the additive agent entails a more remarkable lowering of M_R with $w = 1\%$. This result is an interesting finding as the technologies largely investigated in literature for road stabilization do actually increase the elastic stiffness and this outcome can be connected to the lubricating effects of the synthetic fluid [14,17–19]. Similar considerations can be also made when inspecting the three-dimensional representation corresponding to Uzan model displayed in Fig. 9, where the surface related to the untreated sample is generally higher than the other surfaces related to the specimens treated with the synthetic fluid. Table 3 details the regression parameters of Hicks & Monismith and Uzan formulations.

When associated to the presence of water as in the tested specimens ($w = 1\%$), the synthetic product does not offer a significant improvement in M_R for SF-2, SF-3 but provides a limited enhancement for SF-1 considering low values of bulk stress θ approximately up to 400 kPa. The additive does not supply a remarkable chemical or physical bonding as mentioned in other few studies dealing with isoalkanes employed as

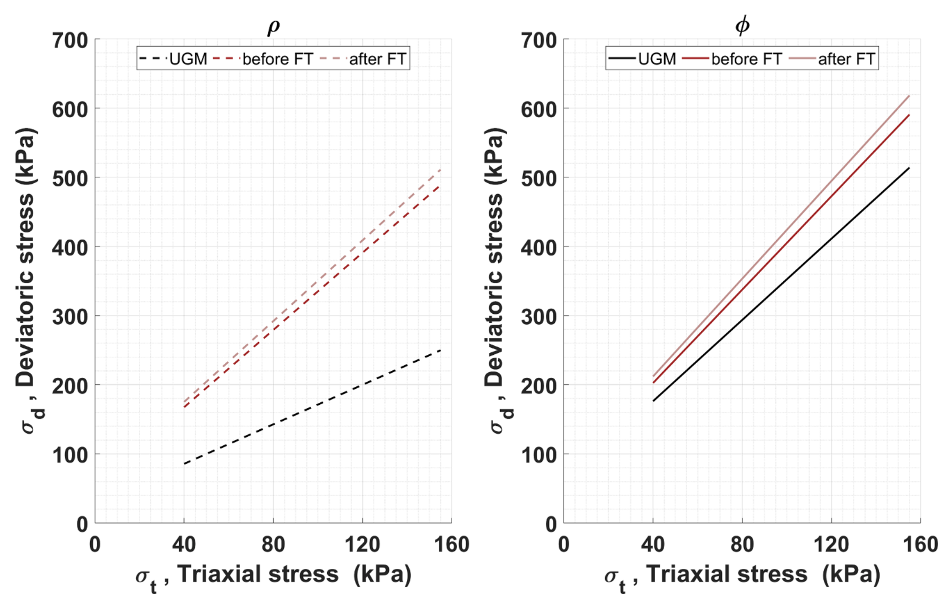

Fig. 12. Elastic limit angle ρ and failure limit angle φ for SF-1 specimens before and after 10 FT cycles ($w = 0\%$).

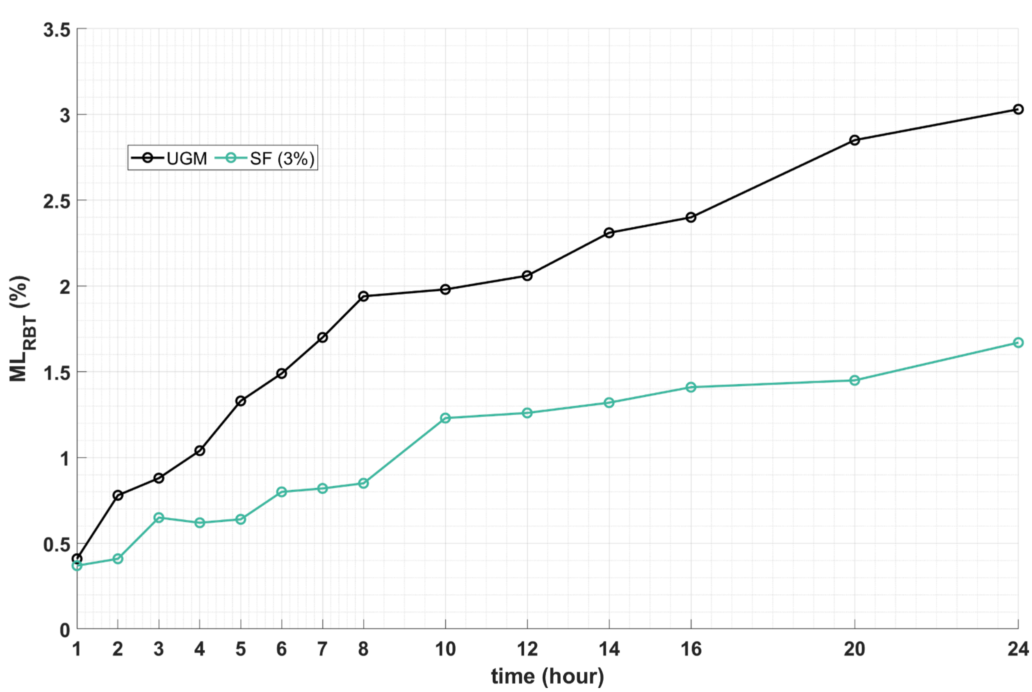

Fig. 13. Mass loss ML_{RBT} for each tested time interval for uncoated aggregates and aggregates coated with the synthetic fluid.

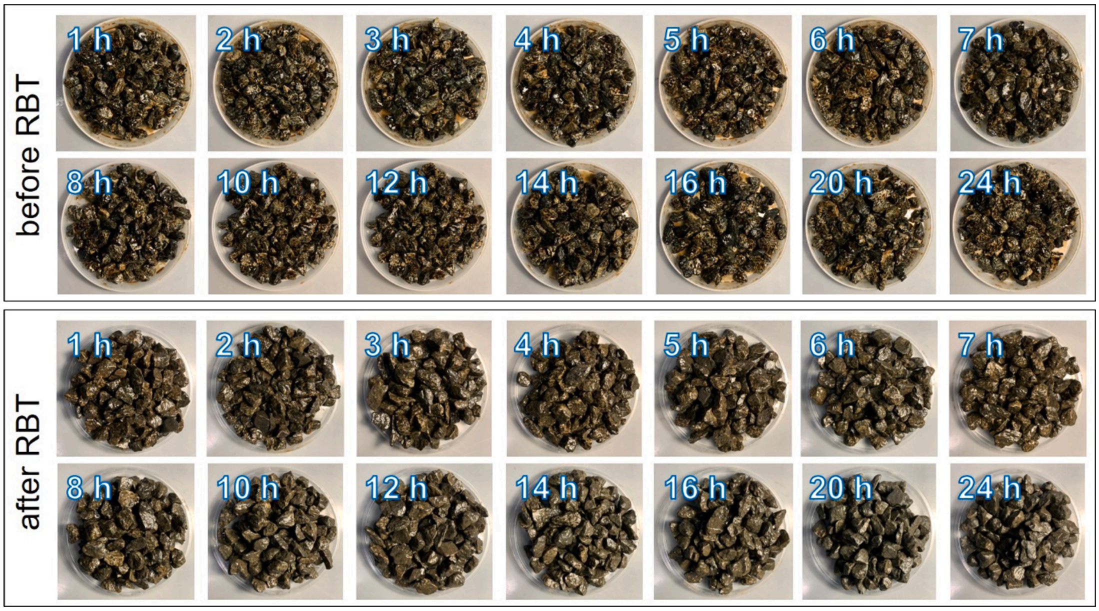

Fig. 14. Appearance of fourteen RBT samples before and after testing according to as many rotating time intervals.

compaction aids [52,113]. Moreover, specimens in wet condition are generally associated with poorer mechanical response when compared with dried condition [93].

As the SF-1 samples offered the best performance, they were completely dried and newly tested before and after the achievement of 10 FT cycles as described in Section 2.2.1. Fig. 10 and Table 3 report on the resilient moduli M_R assessed according to both Hicks & Monismith model and Uzan model. In this case ($w = 0\%$), a significant stabilization effect is found both before and after the exposure to the freezing-thawing actions. Moreover, as the synthetic fluid does not freeze, its effectiveness does not seem to be impaired by rigid temperatures in harsh environments and therefore can be adopted in remote communities in cold regions as documented in few other studies [114–116].

Resistance to permanent deformation

The resistance to permanent deformation is reported in Fig. 11 depicting the elastic limit angle ρ and the failure limit angle φ according to the Coulomb approach. In line with the general reduction in the value of resilient modulus observed in the previous subsection, it is possible to observe a drop also in the performance related to the resistance to permanent deformation [52,113]. Considering the results pertaining to SF-3, SF-2 and SF-1, the development of permanent deformations reduces as a lower percentage of synthetic fluid is applied. Table 4 details the values of the elastic limit angles ρ and the failure limit angles φ.

In this regard, it is important to highlight that even if an increase in stiffness entailing a reduction in the permanent deformation is the goal of the largest amount of road stabilization technologies, in some contexts having the opportunity to achieve a lower resilient modulus and

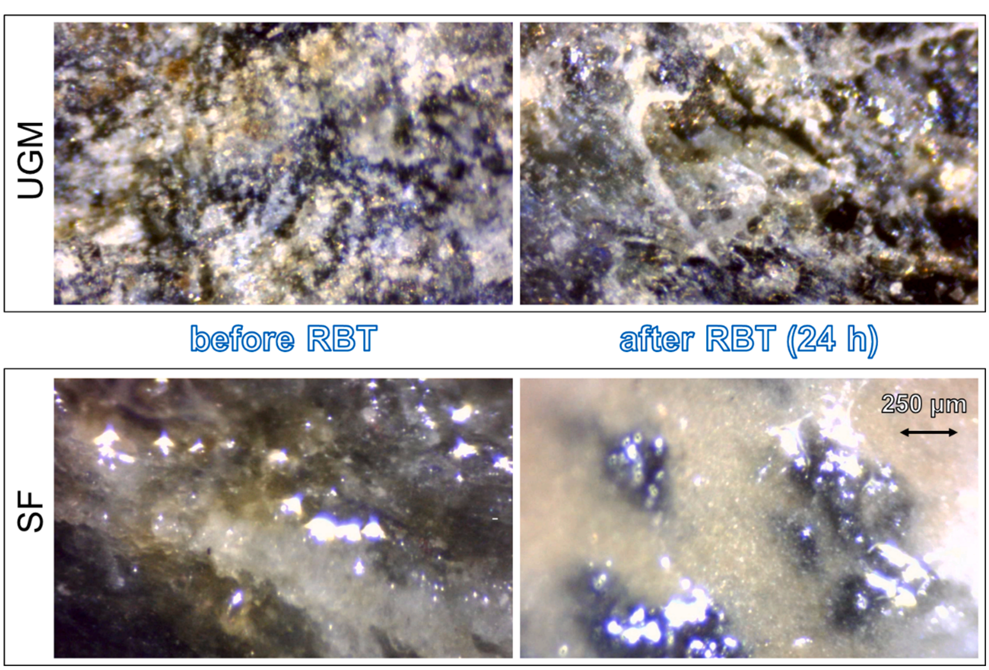

Fig. 15. Surface appearance probed with microscope before RBT and after RBT (24 h).

easily regrade the particle aggregates covered by an agent which does not set up may represent a preferable condition.

The specimens show better deformation properties than UGM when no water is present. Like the results achieved for the stiffness, the treated samples do not display a significant variation before and after 10 FT cycles also when it comes to the resistance to permanent deformation. In fact, the angles ρ and φ are very similar before and after the freezing-thawing actions as documented in Fig. 12 and Table 4. It is worth mentioning that, contrarily to what one may expect, the values of both these angles slightly increase after FT cycles: as observed in a few other studies [102,117], it can be hypothesized that this occurs due to the external actions inducing further compaction during freezing-thawing and corresponding slight modification of the aggregates structure.

Rolling bottle test

The experimental results displaying the mass loss ML_{RBT} for each investigated time interval are reported in Fig. 13 for both untreated and treated rock aggregates. In the former case, ML_{RBT} takes place because of the self-crushing and wear of the materials and therefore represents a useful baseline when considering the results of the particles treated with the additive. In the latter case, the synthetic fluid technology engenders a very small loss of integrity as ML_{RBT} of coated aggregates is significantly lower than ML_{RBT} of uncoated aggregates. In this regard, Fig. 14 displays the appearance of fourteen samples tested according to as many rotating time intervals before and after RBT. Thanks to the reduced amount of stripping, it is possible to state that the synthetic fluid adheres well with the aggregate particles when subjected to high moisture level or external actions in general.

Fig. 15 portrays the surface appearance investigated using a microscope at 40x magnification. The main minerals composing the aggregates, namely amphibole, epidote and plagioclase laths, can be identified both before and after testing [36]. When it comes to the materials initially treated with the mixture of isoalkane and tall oil pitch, the surface is completely covered and some gas bubbles can be observed. After the completion of RBT at 24 h, the synthetic fluid does still cover the surface and some underlying aggregates become slightly exposed.

Conclusions

The study has characterised the use of an innovative synthetic fluid based on isoalkane and tall oil pitch mixed with rock aggregates to be used as construction material for a road base layer. Generally speaking, synthetic fluids are products with limited documented real applications when it comes to stabilize road pavements; therefore, this research has contributed to their characterization with a thorough laboratory investigation. This study has tested treated and untreated samples by means of Repeated Load Triaxial Tests (RLTTs). The results document a meaningful variation in both resilient modulus and resistance to permanent deformation of the treated specimens [55], ranging from significant reduction to significant improvement of the mechanical properties depending on the quantities of synthetic fluid and water. Furthermore, RLTTs were performed after exposing stabilized specimens to a series of 10 Freeze-Thaw (FT) cycles to investigate the variation in the mechanical response due to freezing action. The study has also focused on quantifying the integrity with loss stripping by means of a modified version of the Rolling Bottle Test (RBT). In this regard, the results of this research have hinged upon objective weight measurements to express the degree of stripping rather than subjective visual assessments as defined by the code currently in force [58]. Based on the performed laboratory tests, the following conclusions can be drawn:

- The studied synthetic fluid entails modification of the mechanical properties of aggregates for road construction with varying results based on the application rate and the water amount.
- A general decrease in the mechanical properties is evident when a high quantity of synthetic fluid and water are mixed with the rock aggregates as the particle matrix becomes waxier.
- The properties of the treated aggregates do not significantly change after the exposure to freezing-thawing actions, thus representing a promising solution for road construction in cold climate regions.
- The synthetic fluid properly adheres to the aggregates when exposed to severe mechanical actions also in wet conditions and therefore exhibits very limited leaching potential.

Some indications for future research revolving around the use of the synthetic fluid may comprise testing of more aggregate types (i.e., frost-susceptible) and gradation curves to possibly generalize the results as well as performing a field test to determine correlations with the laboratory results.

CRediT authorship contribution statement

Diego Maria Barbieri: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Project administration. **Baowen Lou:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **Robert Jason Dyke:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing. **Hao Chen:** Investigation, Resources, Writing – review & editing, Visualization. **Fusong Wang:** Writing – review & editing, Visualization. **Billy Connor:** Methodology, Writing – review & editing, Visualization, Supervision. **Inge Hoff:** Conceptualization, Methodology, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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