Stabilization of Coarse Aggregates with Traditional and Nontraditional Additives

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Abstract: High-quality coarse aggregates are routinely used for the surface, base, and subbase layers in paved roads or the surface course in unpaved low-volume roads. Unfortunately, high-quality aggregates meeting stringent material specifications are becoming increasingly costly and difficult to find within reasonable distances of road construction projects. Various stabilization technologies can be employed to improve the mechanical properties of available aggregate materials, providing environmental and economic benefits. This investigation used three laboratory test methods to evaluate and compare all the existing kinds of additive technologies suitable to stabilize a coarse-graded road unbound layer. Two traditional solutions (cement and bitumen) and eleven nontraditional solutions (categorized as either brine salts, clay binders, organic nonpetroleum products, organic petroleum products, or synthetic polymers) were included. Repeated load triaxial tests were performed to evaluate the dynamic behavior of the untreated and treated aggregates in terms of their resilient modulus and the resistance against permanent deformation. A modified version of the rolling bottle test was used to appraise the stripping resistance offered by each additive. A microscopic analysis was conducted to visually evaluate the propensity of the additives to adequately coat the surface of the aggregates. All the stabilization technologies improved the material stiffness, with the most significant improvements produced by calcium chloride salt, bentonite, lignosulfonate, and cement mixed with a mineral mixture. The stabilization additives effectively reduced permanent deformations, except for the specimens stabilized with polyurethane and bitumen. Finally, the polymer-based additives and bitumen demonstrated very good resistance to stripping, with polyurethane providing the smallest mass loss. This study documents that nontraditional stabilization technologies can provide effective alternatives to the traditional stabilizers and documents that a "one-size-fits-all" additive agent is unlikely to be developed. **DOI: 10.1061/(ASCE)MT.1943-5533.0004406.** *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, https://creativecommons.org/licenses/by/4.0/.*

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Introduction

Road Stabilization Technologies

Flexible pavements are designed as layered structures that distribute traffic loads from the surface to the natural subgrade. A typical flexible pavement includes a high-quality bound surface layer such as asphalt concrete, an unbound high-quality aggregate base layer, an unbound aggregate subbase layer, and the natural subgrade soil. The unbound aggregate base and subbase layers generally include coarse aggregates that can range up to 30 and 200 mm in size, respectively (Huang 2004; Thom 2014). In the case of low-volume roads (LVRs), namely roads with a low average daily traffic, the flexible pavement structure is often simplified as an unpaved road consisting of an unbound aggregate surface layer placed over the natural subgrade soil (Douglas 2016). Unpaved roads form approximately 65% of the global pavement network, thus playing a central role in the economy of both developed and developing countries (Meijer et al. 2018).

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As the primary load-bearing layer, the mechanical properties of the unbound strata are crucial in both paved (sealed) and unpaved (unsealed) roads to ensure efficient load distribution and avoid premature damage (Barbieri et al. 2017; Huang 2004; Mallick and El-Korchi 2013; Thom 2014). In some regions of the world, the locally available aggregates may not meet the specifications for a high-quality aggregate base material or there may be a need to improve the mechanical response to sustain the anticipated or actual traffic (Arulrajah et al. 2013). In these instances, different types of stabilization technologies can be employed to improve the performance of both existing and new roads. Furthermore, additive technologies can often be used for both stabilization and dust control depending upon the amount of additive and the method of application. For example, additive emulsions can serve to stabilize the aggregate material when mixed in (penetration 10–20 cm) or as dust palliatives when sprayed on (penetration 2–3 cm).

From an engineering point of view, the use of stabilizers should address three main objectives: (1) enhance the mechanical properties of aggregate materials, (2) resist traffic wear while not being prone to leaching, and (3) reduce the frequency of the maintenance operations. From an environmental point of view, stabilization technologies should not harm the environment and should be adopted considering the road life perspective (Barbieri et al. 2021b; Gomes Correia et al. 2016; Wang et al. 2021). From an operational point of view, a successful stabilization project should provide the desired engineering enhancements while being economically competitive compared to traditional construction methods (Praticò et al. 2011).

Research Motivation and Objective

There are a large number of proprietary road stabilizers on the global market [more than 200 in the US alone (Jones 2017)]. Although the individual products have proprietary features, they can be grouped based on their chemistry and mechanism of stabilization (Tingle et al. 2007): cement, bitumen, lime, fly ash, brine salt, clay, organic nonpetroleum, organic petroleum, synthetic polymer, and concentrated liquid.

Although many research efforts have investigated the mechanical properties of individual stabilization additives, there are relatively few well-documented works that effectively compare different stabilization solutions simultaneously in a single independent study. Table 1 lists the relevant experimental investigations available in peer-reviewed literature that compare the mechanical performance of various traditional and nontraditional stabilizers. In addition, some attempts to synthesize the results of soil stabilization research have been conducted (Kestler 2009; Lunsford and Mahoney 2001; White and Vennapusa 2013) and few performance-based laboratory tests have been developed to quantify the results (Visser 2007). Despite these syntheses and attempts to improve quantification of results, a widely recognized standard methodology for ranking the different additives has not been thoroughly developed yet. This study attempted to systematically evaluate the performance of different stabilization technologies in an endeavor to bolster confidence among road authorities and stakeholders (Tingle et al. 2007).

This investigation focused on evaluating the effectiveness of stabilization technologies in stabilizing coarse-graded aggregates typical of an unbound layer used in pavement design and construction. Additives that would be grouped as lime and concentrated liquid (comprising ionic or high-acidity emulsion and enzymatic or low-acidity emulsion) are not considered in this study because they are most suited for the stabilization of fine-graded soils with a high percentage of clay (Jones 2017; Tingle et al. 2007). This laboratory-based research used three different testing and analysis techniques. First, repeated load triaxial tests (RLTTs) were performed to evaluate the stiffness and the development of permanent deformation of the stabilized materials under dynamic loading conditions (CEN 2004). Second, an altered version of the rolling bottle test (RBT) was used to assess the stripping potential for each additive (CEN 2020; Grenfell et al. 2014). Finally, a microscope analysis was performed to examine the coated aggregate surface before and after the modified RBT.

As reported in Table 1, the largest part of the previous laboratory studies performed unconfined compression tests (UCTs) and California bearing ratio (CBR) tests to evaluate strength improvement of stabilized materials, whereas only one study used a (simplified) version of RLTT for a few different additives (Pierre et al. 2008). A logical reason for using the UCT or CBR tests is the relative ease of execution and speed of performing the tests compared to the RLTT, which requires meticulous sample preparation and more sophisticated cyclic triaxial testing equipment (Araya et al. 2010; Hoff et al. 2005). However, unlike the UCT and CBR investigations, RLTT enables thorough evaluation of the dynamic behavior of the

Table 1. Overview of the experimental investigations comparing the mechanical performance of various stabilizing additives simultaneously in a single study

		Investigated stabilization additives									Performed experimental tests								
		Traditional			Nontraditional						Laboratory					Field			
References	Material	CEM	BIT[a]	LIME[b]	BS	CLAY[a]	ONP	OP	SP	CL[b]	UCT	ITT	CBRT	CTT	AEM	FWD	LWD	DCP	RM
Bolander (1999)	Sandy gravel	—	—	—	X	X	X	—	X	—	—	O	—	—	—	—	—	—	—
Santoni et al. (2002)	Silty sand	X	X	X	—	—	X	X	X	X	O	—	—	—	—	—	—	—	—
Tingle and Santoni (2003)	Clay	X	—	X	—	—	X	X	X	X	O	—	—	—	—	—	—	—	—
Bushman et al. (2005)	Sandy gravel	—	—	—	X	—	X	—	X	—	—	—	—	—	—	—	—	—	O
Jones (2007)	Sand, clay	—	X	X	X	—	X	X	X	X	O	—	O	—	O	—	—	—	—
Pierre et al. (2008)	Sandy gravel	X	—	—	X	—	—	—	X	—	O	—	O	O	—	—	—	—	—
Mgangira (2009)	Sand	—	X	—	—	—	—	—	X	—	—	—	—	—	O	—	—	—	—
Blanck et al. (2014)	Silt	—	—	—	—	—	—	X	—	X	O	—	O	—	—	—	—	—	—
Beaulieu et al. (2014)	Gravelly sand	—	—	—	X	—	X	—	X	—	—	—	—	—	—	O	O	—	O
Li et al. (2019)	Silty sand	X	—	X	X	X	—	—	—	—	—	—	—	—	—	O	—	O	—

Note: CEM = cement; BIT = bitumen; BS = brine salt; ONP = organic nonpetroleum; OP = organic petroleum; SP = synthetic polymer; CL = concentrated liquid; UCT = unconfined compression test; ITT = indirect tensile test; CBRT = California bearing ratio test; CTT = cyclic triaxial test; AEM = abrasion and erosion measurement; FWD = falling weight deflectometer; LWD = light weight deflectometer; DCP = dynamic cone penetrometer; and RM = roughness measurement.

[a]Mostly effective for coarse-graded material.

[b]Mostly effective for fine-graded material.

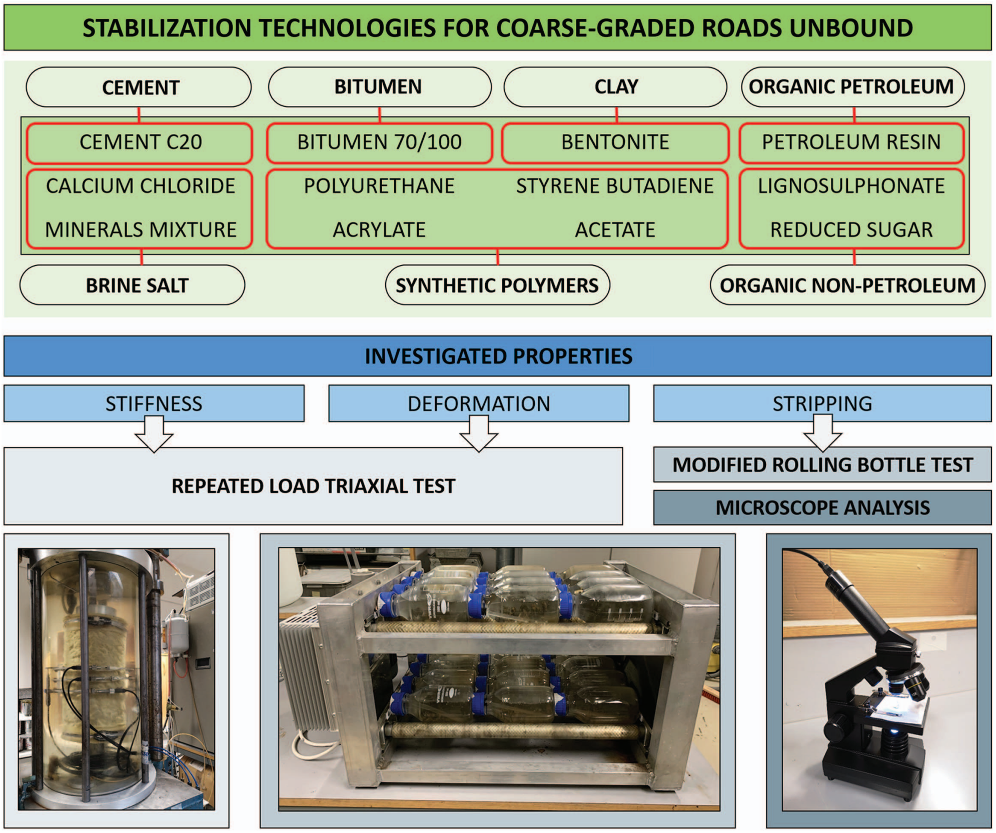

Fig. 1. (Color) Structure of the study.

stabilized materials (resilient modulus and resistance against permanent deformation), which is required for incorporation into modern mechanistically based pavement design approaches (Ghadimi and Nikraz 2017; Titi and Matar 2018). Because this study is focused upon the stabilization of the unbound aggregate layer within the pavement and this course is exposed to traffic and environmental loadings, the durability of the stabilized material is very important. Few of the investigations in the literature have focused upon quantifying the resistance to abrasion and erosion of stabilized aggregates (Jones 2007; Mgangira 2009). Although the apparatus employed in these studies was not standardized, RBT equipment can be commonly found in many pavement materials laboratories worldwide (Jørgensen 2002; Porot et al. 2016). Thus, RBT was employed here for the first time to evaluate the stripping loss of nonbituminous binders. The flow chart of the study is illustrated in Fig. 1.

Materials

The crushed rock aggregates used in this study were collected in a quarry located in the Vassfjellet area near Trondheim (Norway). These intrusive igneous rocks are largely employed in road constructions located in the Trøndelag region. The Los-Angeles (LA) and micro-Deval (MDE) values of the aggregates were 18.2 and 14.2, respectively (Adomako et al. 2021; CEN 2006, 2010).

Two traditional stabilization technologies are included in this investigation for comparison to the nontraditional additives, cement (CEM) and bitumen (BIT). Previous studies characterizing road layers stabilized with these products have documented a general increase in the mechanical performance for a wide spectra of geomaterials (Du 2018; Jiang and Fan 2013; Kamran et al. 2021; Lou et al. 2021a, b; Myre 2014; Siripun et al. 2010; Xuan et al. 2012). Eleven types of nontraditional stabilizers are included in this study: brine salt (two kinds, SAL-A, SAL-B), bentonite (BEN), lignosulfonate (LIG), reduced sugar (SUG), petroleum resin (RES), polyurethane (POL), acrylate (ACR), styrene butadiene (STB), and acetate (two kinds, ACE-A and ACE-B). Plant-based additives (LIG, SUG) and polymeric additives (POL, ACR, STB, ACE-A, ACE-B) represent the most recent stabilization technologies (Jones 2017). Table 2 summarizes pertinent information for the tested additives, including density, viscosity, water contained, and indicative cost (not including transport); their large part is characterized by low to very low toxicity (Kunz et al. 2021).

Two kinds of brine salts are included: calcium chloride (Monlux 2003; Monlux and Mitchell 2007; Shon et al. 2010) and an innovative mixture of chemicals and nonmetallic minerals composed of sodium chloride, calcium chloride, sodium triphosphate, sodium sulfate, sodium lignosulfonate, and sodium bicarbonate (Bost et al. 2016; Liu et al. 2020). Bentonite, also known as sodium montmorillonite, is a highly plastic clay that has demonstrated a good binding effect for road unbounds preventing washboarding and raveling (Barati et al. 2020; Parsakhoo et al. 2020). When it comes to the organic nonpetroleum category, lignosulfonate has shown positive results for stabilizing both clayey soils and coarse aggregates (Alazigha et al. 2018; Barbieri et al. 2019; Santoni et al. 2002; Zhang et al. 2020). Bansal et al. (2020) and M'Ndegwa (2011) reported improved mechanical properties for the use of reduced sugar, which is a mixture of organic sugars, starches, and insoluble minerals. Petroleum resin derived from the refining process of crude oil has shown good stabilization potential for fine aggregates (Onyejekwe and Ghataora 2015). Mineral oils and synthetic fluid, which also belong to the organic petroleum category, are not examined in this study due to their reported limited stabilization

Table 2. Denomination, density, viscosity, water contained, and price of the additives (data supplied by technical representatives)

Category	Type	Density (kg/m^3)	Viscosity (cP)	Water content (%)	Price (EUR/kg)
Cement	Cement C20 (CEM)	1,460	—	0	0.3
Bitumen	Bitumen 70/100 (BIT)	1,040	>90,000 at 60°C	0	0.5
Brine salt	Calcium chloride (SAL-A)	2,150	—	23	0.3
	Mineral mixture (SAL-B)[a]	2,620	—	7	11.0
Clay	bentonite (BEN)	2,650	—	0	1.2
Organic nonpetroleum	Lignosulfonate (LIG)	1,250	500–600 at 30°C	50	0.2
	Reduced sugar (SUG)	1,400	500–600 at 30°C	52	1.4
Organic petroleum	Petroleum resin (RES)	1,030	400–600 at 30°C	20	1.5
Synthetic polymer	Polyurethane (POL)	1,090	700–800 at 30°C	0	4.0
	Acrylate (ACR)[b]	1,015	200–500 at 30°C	48	0.6
	Styrene butadiene (STB)	1,060	200–450 at 30°C	40	3.9
	Acetate type A (ACE-A)	1,060	200–450 at 30°C	51	3.6
	Acetate type B (ACE-B)	1,060	200–450 at 30°C	44	3.7

[a]Used in addition to CEM.
[b]Bicomponent technology: 0.8 component C1 + 0.4 component C2.

potential (Santoni et al. 2002; Tingle et al. 2007). Finally, polymer additives typically consist of synthetic copolymers suspended in an emulsion by surfactants. Polymer additives can be classified according to four major families (Jones and Surdahl 2014; Tan et al. 2020): polyurethanes (Cong et al. 2019; Sun et al. 2020), acrylates (Barbieri et al. 2019; Daniels and Hourani 2009; Kumar et al. 2017; Padmavathi et al. 2018), styrene butadienes (Baghini et al. 2016, 2018), and acetates (Bolander 1999; Collins et al. 2014). Polymer-based additives have been used to stabilize both fine-graded and coarse-graded aggregates as well as erodible slopes.

Experimental Methodology

Repeated Load Triaxial Test

The repeated load triaxial test is a comprehensive testing approach that characterizes the dynamic mechanical behavior of the tested material. Stress level, moisture content, density, particle size distribution, and mineralogy are the most relevant conditions determining the mechanical response of rock aggregates (Lekarp et al. 2000a, b).

Specimen Preparation and Testing

The grading curve of the aggregates selected to create each RLTT specimen is shown in Fig. 2 and corresponds to a typical coarse-graded base layer (NPRA 2014, 2018). The diameter and the height of each sample were 15 and 30 cm, respectively; the approximate weight was 12 kg. The maximum aggregate dimension was 3 cm, which also corresponds to one-fifth of the sample diameter (CEN 2004). This study investigated two replicate specimens for each

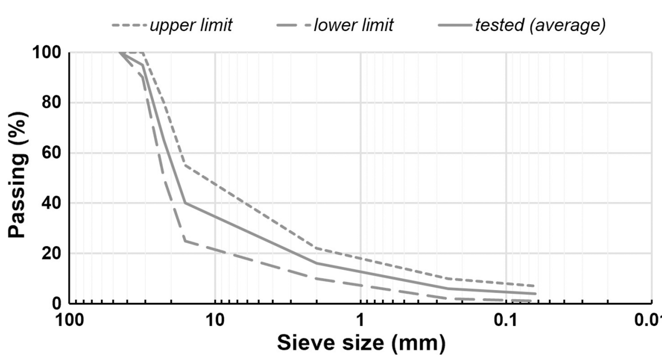

Fig. 2. Grain size distribution curve for RLTT specimens.

additive treatment; furthermore, untreated aggregates, namely unbound granular material (UGM), were also tested for comparison purposes. A total of 28 RLTT samples were prepared and subjected to cyclic loading.

Table 3 lists details for each RLTT specimen, including the amount of each additive (expressed as a weight percentage), as well as information about the curing process. All the samples were tested in dried conditions. The quantity of each additive was not optimized for performance or cost but chosen upon trial-and-error tests to ensure complete cover of the aggregates' surface and after discussion with technical representatives. Whenever possible, the amount of each stabilizing agent was held constant to allow an "apples-to-apples" comparison; in fact, it can be seen in Table 3 that the most common additive content used was 1.2%. The percentage of cement CEM and bitumen BIT was higher, namely 4% (W/C ratio = 0.12) and 3% respectively, based upon current practice (Myre 2014; Plati 2019; Tan et al. 2020). In addition, 0.2% of brine salt SAL-B was blended with cement to evaluate the combined effect on performance. Except for samples treated with cement CEM, bitumen BIT, mineral mixture salt SAL-B, and polyurethane POL, the quantity of water initially present in each specimen was equal to optimum moisture content (OMC) $w = 5\%$ (CEN 2003). A total of 0.4% of bentonite BEN by mass was selected to attain a workable slurry when mixed with water at OMC.

Table 3. Additive quantity, initial water content at specimen creation, curing time, curing temperature, and bulk density of the RLTT samples

Additive (code)	Additive content (% mass)	Initial water (% mass)	Curing Time (day)	Curing Temperature (°C)	Bulk density (t/m^3)
UGM	—	5	7	55	2.4
CEM	4.0	2.4	28	22	2.4
BIT	3.0	0	2	22	2.2
SAL-A	1.2	5	7 + 1	55 + 22	2.3
SAL-B[a]	0.2	2.4	28	22	2.4
BEN	0.4	5	7 + 1	55 + 22	2.3
LIG	1.2	5	7 + 1	55 + 22	2.4
SUG	1.2	5	7 + 1	55 + 22	2.4
RES	1.2	5	7 + 1	55 + 22	2.5
POL	4.5	0	2	22	2.3
ACR	1.	5	7 + 1	55 + 22	2.6
STB	1.2	5	7 + 1	55 + 22	2.5
ACE-A	1.2	5	7 + 1	55 + 22	2.5
ACE-B	1.2	5	7 + 1	55 + 22	2.4

[a]Used in addition to CEM.

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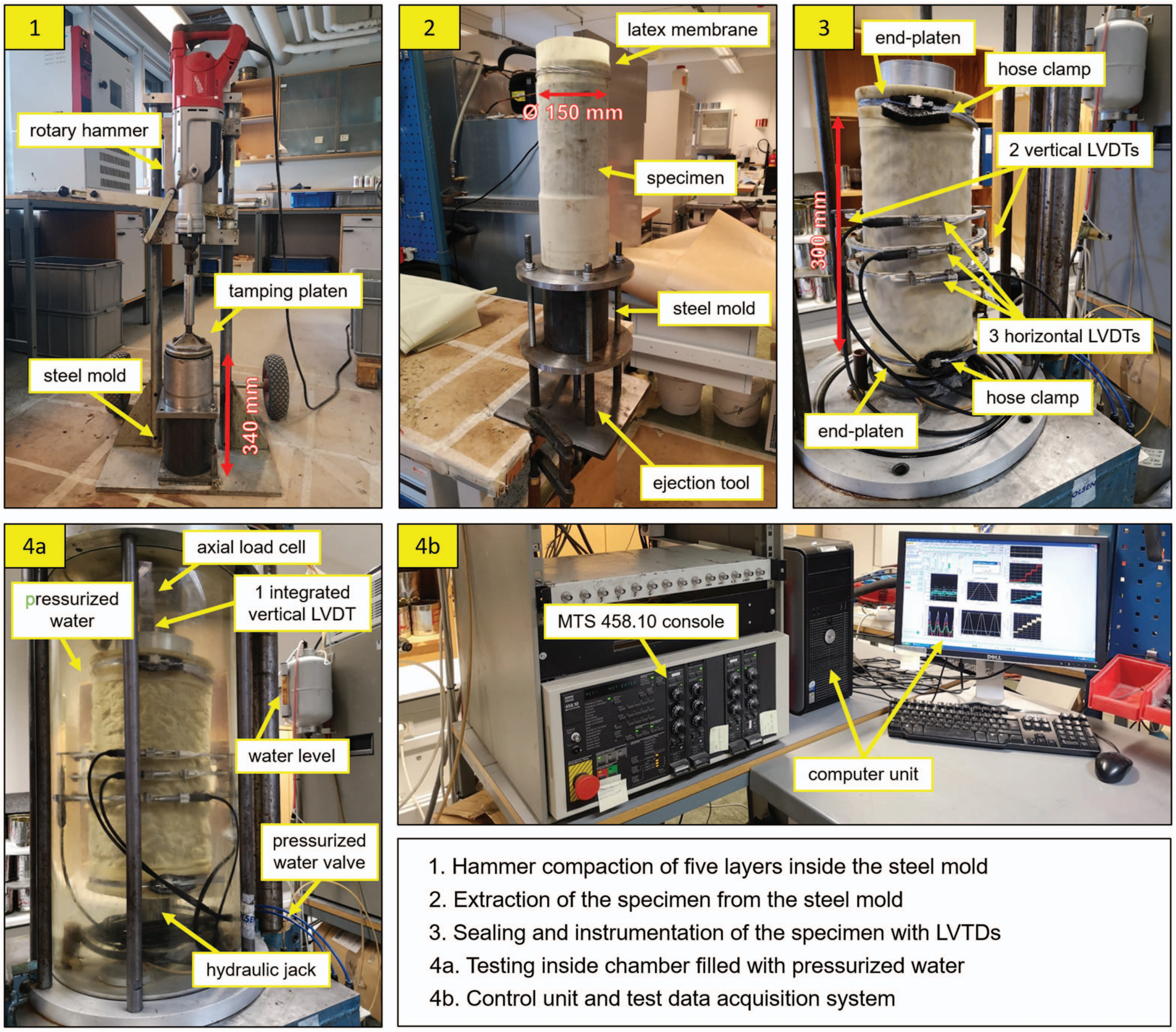

Fig. 3. (Color) Creation of RLTT sample and RLTT setup.

In order to create the samples at OMC, the amount of water already present in the concentrated form of each additive was considered, and the additives were uniformly blended with a high-shear mixer.

To create a RLTT specimen, five batches of treated aggregates placed inside as many transparent plastic bags were carefully shaken manually. This procedure was performed at room temperature, except for the samples added with bitumen, which required preheating at 155°C and machine mixing. Afterward, the five batches were sequentially compacted for 25 s inside a steel mould using a Milwaukee 2" Slotted Drive Shaft (SDS) Max rotary hammer (Brookfield, Milwaukee, Wisconsin), removed from the mould, and protected by two latex layers. At this stage, the specimen underwent curing, which was necessary for the water to evaporate and to let each stabilizer attach properly to the aggregate particles. Before testing, each sample was added two end platens and sealed by four rubber O-rings and two hose clamps. The RLTT apparatus performed the multistage low stress level (MS LSL) loading procedure (CEN 2004; Gidel et al. 2001). Each specimen was subjected to a triaxial or confining stress σ_3 and a deviatoric or vertical stress σ_d, which were respectively exerted by means of pressurized water and hydraulic jack. The MS LSL comprised five loading sequences corresponding to as many σ_3 values ($\sigma_3 = 20$, 45, 70, 100, 150 kPa). For a given confining pressure σ_3, σ_d was applied using a dynamic sinusoidal pattern consisting of 10,000 load pulses with frequency equal to 10 Hz. A total of three linear variable differential transducers (LVDTs) measured the axial deformations. For each RLTT, the time needed to mount the triaxial cell and run the test was equal to approximately 11 h. The triaxial apparatus was built at Norwegian University of Science and Technology (NTNU, Trondheim, Norway) during the seventies and has been gradually upgraded. Fig. 3 illustrates the specimen preparation and RLTT setup.

Interpretation of Results

The RLTT is used to characterize the behavior of geomaterials under dynamic loads and derive two important mechanical properties: resilient modulus M_R and resistance against permanent deformation. For a constant confining pressure σ_3, M_R is defined as

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

where the numerator = variation in the dynamic deviatoric stress $\sigma_{d,\text{dyn}}$; and the denominator = elastic axial strain. The resilient modulus is used by road engineers to characterize the dynamic loading behavior of pavement materials for different stress states using mechanistic models. Among the several formulations used to describe the behavior of the geomaterial under loading, the k–θ model developed by Hicks and Monismith estimates M_R in relation with bulk stress θ (θ is obtained summing the principal stresses or $\sigma_1 + \sigma_2 + \sigma_3$; σ_2 is equal to σ_3) (Hicks and Monismith 1971; Lekarp et al. 2000a)

$$M_R = k_1 \sigma_a \left(\frac{\theta}{\sigma_a}\right)^{k_2} \quad (2)$$

where k_1, k_2 = regression coefficients; and σ_a = reference pressure (100 kPa).

For geomaterials, the application of a load pulse generally creates both resilient (elastic) strain ε_{el} and permanent (plastic) strain ε_{pl}. The latter is responsible for many long-term distresses related to accumulation of fatigue damage, particle crushing, further compaction, or material migration (Lekarp et al. 2000b). Among the models describing the accumulation of plastic axial deformation $\varepsilon_{pl,a}$, the formulation proposed by Hyde establishes a relationship between $\varepsilon_{pl,a}$, the deviatoric stress σ_d and the triaxial stress σ_3 as follows (Hyde 1974)

$$\varepsilon_{pl,a} = a_{HY} \frac{\sigma_d}{\sigma_3} \quad (3)$$

where a_{HY} = regression coefficient.

Another approach considered to characterize the deformation behavior is the Coulomb formulation (Hoff et al. 2003), which derives from the shakedown theory (Werkmeister et al. 2001). The deformation response of a specimen is classified according to three ranges for each RLTT step: Range A (plastic shakedown), Range B (plastic creep), and Range C (incremental collapse). In Range A, the response is plastic for a finite number of load applications beyond which no further permanent strain occurs afterward. Range C defines the increment in plastic strain with each load cycle to collapse. Range B is an intermediate response between Ranges A and C and is characterized by a steady state in which each load application produces a small consistent amount of plastic deformation. Each load step is categorized considering the average rate of plastic strain $\dot{\varepsilon}_{pl}$ for the last 5,000 to 10,000 cycles, as illustrated elsewhere (Barbieri et al. 2021a; Uthus et al. 2007).

Rolling Bottle Test and Microscope Analysis

The rolling bottle test is a standardized laboratory procedure to assess the adhesion between aggregate and bituminous binder. The affinity is evaluated by the visual assessment of the degree of bitumen coverage on loose aggregate particles originally covered by bitumen and then again exposed to a standardized amount of rotations and stirring actions in presence of water (CEN 2020). The susceptibility of the aggregates to stripping of the binder is related to its adhesion potential and durability (Grenfell et al. 2014). Based on these premises, this research has adopted the same rotating and stirring principles to perform an altered version of RBT. The modified approach used in this study relies on quantifiable weight measurements to appraise the stripping loss, whereas the original procedure hinges upon subjective visual estimations giving room to possible imprecise results (Porot et al. 2016). Furthermore, the modified RBT considers coating the surface of the aggregates with additives that are not necessarily bitumen.

Every RBT specimen was fabricated by attentively blending 150 g of aggregates (8–11.2 mm) and 4.5 g of a given additive (concentrated, without dilution water), namely 3% by mass of the dry aggregate weight as calculated based on the water contents reported in Table 2. The aggregates for each RBT sample were spread evenly as loose particles onto a sheet of polythene paper. Except for the technologies that did not contain emulsion water (untreated UGM, cement CEM, bitumen BIT, mineral mixture salt SAL-B and polyurethane POL), all the specimens were cured at 55°C for 3 days to let the water evaporate. The samples coated by cement CEM and mineral mixture salt SAL-B were allowed to cure for 28 days. Afterward, all the specimens were conditioned at room temperature without exposure to sunlight for at least 2 days prior to testing.

The RBT samples were put inside borosilicate glass bottles containing approximately 500 ml of distilled water. A glass rod was also inserted to supply the necessary mechanical stirring action and avoid the creation of lumps. The bottles were then sealed with a screw-on cap and placed on the rolling machine (Swedish National Road and Transport Research Institute, Linköping, Sweden), where the specimens rotated at 60 revolutions per minute based on 14 different time intervals: 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 20, and 24 h. Three replicate samples were investigated for each combination of additive type and rotation time. A total of 588 specimens were created and tested. The preparation and test setup are reported in Fig. 4.

After rotation, the samples were removed from the bottles and dried at 55°C for 3 days. The aggregates were then weighed, and the mass loss ML_{RBT} was evaluated as

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

where M_1 and M_2 = weights of the coated aggregates in dry condition respectively referring to before and after testing; and ML_{RBT} can be expressed as a percentage. A 40x microscope (Bresser, Rhede, Germany) with KL 1600 LED lighting (Olympus, Tokyo) were employed to probe the appearance of the aggregate surfaces prior to and following RBT. These analyses can be useful in characterizing the RBT results visually and qualitatively inspecting the relative durability by scrutinizing the coated area.

Results and Discussion

Repeated Load Triaxial Test

This section presents the results of the RLTTs in terms of the calculated resilient modulus and permanent vertical deformation. Fig. 5 shows the appearance of the samples after testing.

Resilient Modulus

For each stabilization treatment, the calculated resilient moduli M_R and their trends extrapolated according to the Hicks and Monismith regression model are depicted in Fig. 6 as grey dots and colored lines, respectively. The values of the model's regression constants k_1 and k_2 are reported in Table 4. Fig. 7 compares the different extents of the increase in stiffness with the background colors of the areas above and below the line corresponding to the UGM shaded as blue and brown, respectively. According to the Norwegian Public Roads Administration (NPRA) (NPRA 2011), resilient moduli corresponding to an average bulk stress θ between 200 and 400 kPa can be considered to quantify the performance of the different stabilizers for road applications. All the technologies ameliorate the stiffness of coarse-graded aggregates. The four additives that improved M_R most significantly were SAL-A, LIG, BEN, and cement mixed with SAL-B. When comparing CEM alone to the cement mixed with SAL-B, it is apparent that the salt provided a beneficial impact, as demonstrated by an increase in the resilient modulus. The two additives that produced the smallest increase in M_R were ACR and POL.

In contrast to most of the k–θ relationships displayed in Fig. 7, the trend lines of CEM and SAL-B, CEM, and POL are remarkably almost horizontal. This finding indicates that the M_R of the aggregates treated with these three additives was nearly independent from the considered interval of bulk stress θ. Consequently, the coefficients of determination R^2 of cement mixed with SAL-B, CEM,

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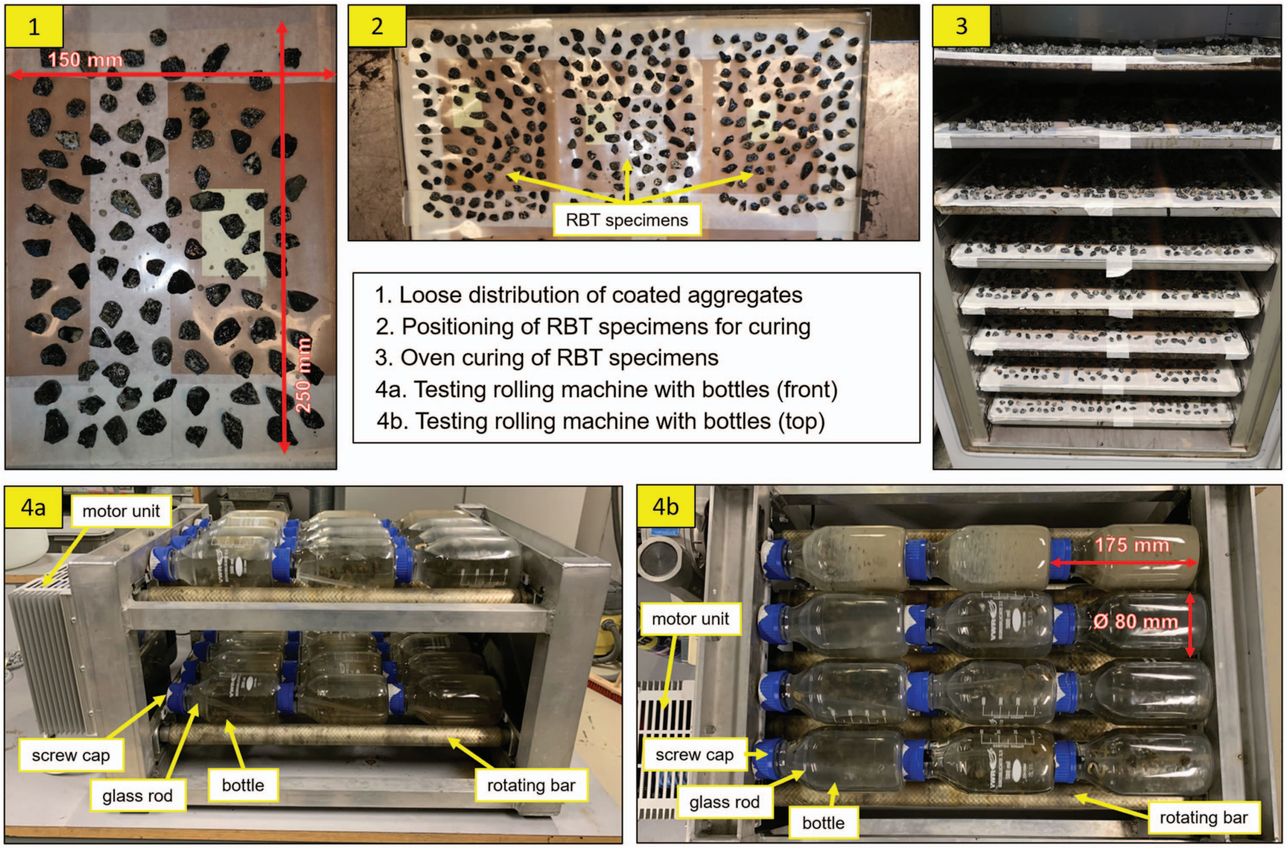

Fig. 4. (Color) Creation of RBT sample and RBT setup.

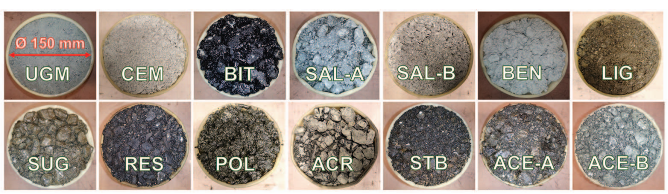

Fig. 5. (Color) RLTT samples: unbound granular material (UGM), cement (CEM), bitumen (BIT), calcium chloride salt (SAL-A), mineral mixture salt (SAL-B), sodium bentonite (BEN), lignosulfonate (LIG), reduced sugar (SUG), petroleum resin (RES), polyurethane (POL), acrylate (ACR), styrene butadiene (STB), and acetate type A (ACE-A) and type B (ACE-B).

and POL were significantly smaller than the R^2 values of the other technologies, as reported in Table 4. The relatively constant modulus of elasticity of concrete at low stress levels can explain the behavior observed for the specimens stabilized with cement mixed with SAL-B and CEM alone (Kim et al. 2002; Mahboubi and Ajorloo 2005; Siripun et al. 2010). When it comes to POL, a similar response was previously observed by Barbieri et al. (2020b) for stabilization of railway ballast. This result buttresses the hypothesis that the polymer-based additive and not the aggregate matrix dominates the load transfer mechanism, at least for the considered curing/aging time interval.

The findings of this investigation can be compared with the outcomes of Tingle's studies, which also characterized the stabilization potential of several additive technologies, albeit for fine-graded particles (Santoni et al. 2002; Tingle and Santoni 2003). Even though this research has employed RLTTs, whereas Tingle's investigations used UCTs, both studies documented the enhancement of mechanical properties attained by cement, bitumen, petroleum resin, and polymer additives. On the contrary, the high increase in resilient modulus engendered by lignosulfonate differs from the medium to low stabilization potential documented in Tingle's works. This dissimilarity is likely due to the use of wet testing procedures in Tingle's studies; in that condition, lignosulfonate is prone to leaching and reduced strength.

Resistance to Permanent Deformation

Hyde formulation was used to model the accumulation of plastic axial deformation $\varepsilon_{\mathrm{pl},a}$, and the trends are represented in Fig. 8. Because the RLTTs use five loading sequences, an average value $\bar{a}_{\mathrm{HY}}$ was calculated as the mean of the five corresponding regression parameters a_{HY} for each stabilization technology (Table 4). Fig. 9 compares the average plastic axial deformation $\bar{\varepsilon}_{\mathrm{pl},a}$ for all the additives based on their computed $\bar{a}_{\mathrm{HY}}$. To better visualize the degree of stabilization attained by the different technologies, the line corresponding to the UGM subdivides the plot background in two areas colored in brown above and blue below.

The majority of the additives were shown to be effective in reducing the permanent deformation because the strain rate of the UGM is substantially higher than the strain rates of the stabilized specimens. One remarkable exception is the performance of POL, which was the only treatment that produced higher deformations than the untreated aggregates. Also, the stabilization of samples treated with bitumen BIT was not very significant because its trend line was similar to the trend line of the UGM. Other than the POL-stabilized and BIT-stabilized results, the reductions in permanent deformation attained by all the additive technologies were similar. The four additives that exhibited the

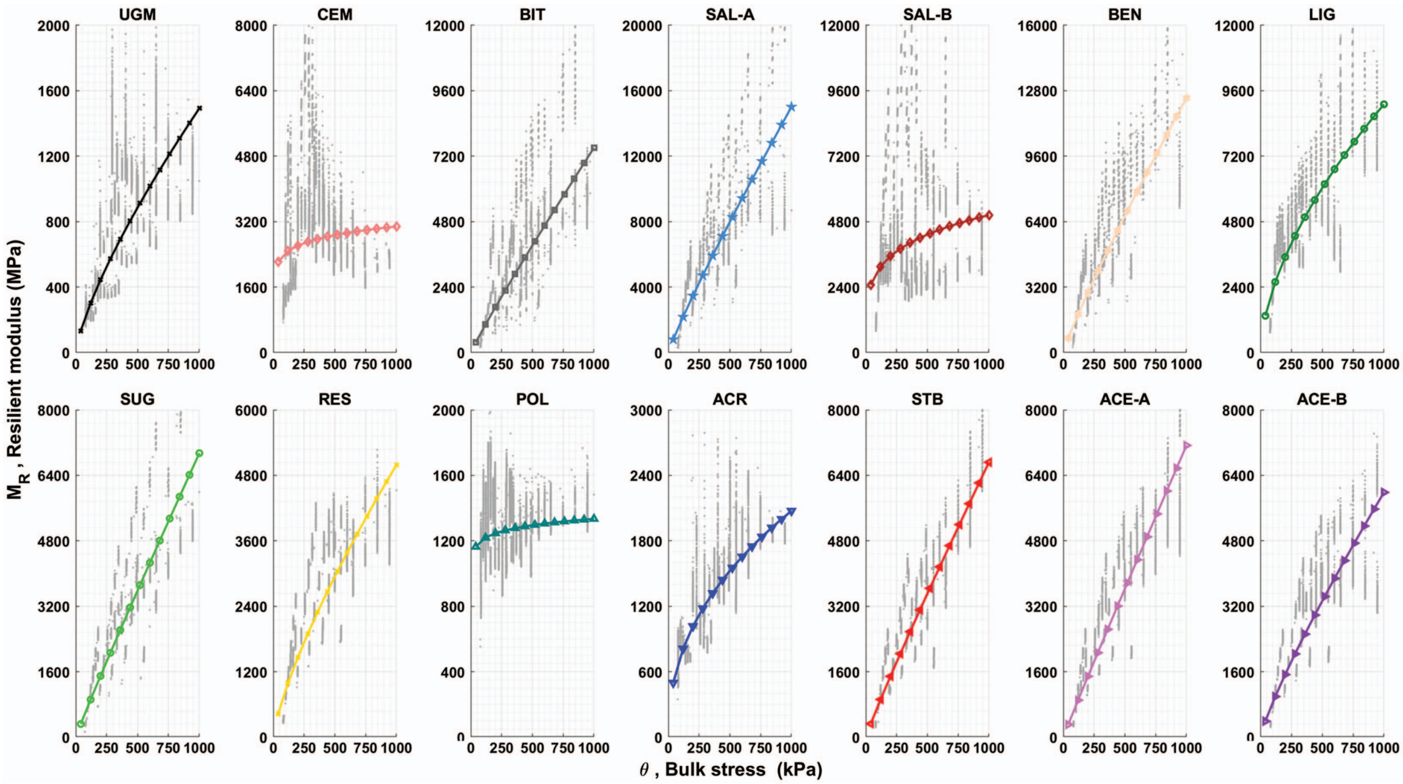

Fig. 6. (Color) Experimental data of resilient modulus M_R and calculated trend according to Hicks and Monismith model.

Table 4. Values of regression parameters and associated coefficients of determination R^2: k_1, k_2 for resilient modulus evaluated according to the Hicks and Monismith model, and average $\bar{a}_{HY}$ for permanent deformation evaluated according to the Hyde model

Additive (code)	Hicks and Monismith model			Hyde model	
	k_1	k_2	R^2	$\bar{a}_{HY}$	R^2
UGM	2,637	0.75	0.66	0.165	0.63
CEM	24,350	0.10	0.12	0.020	0.70
BIT	8,693	0.94	0.68	0.144	0.81
SAL-A	18,448	0.91	0.72	0.041	0.68
SAL-B[a]	30,345	0.22	0.17	0.037	0.76
BEN	15,803	0.90	0.75	0.064	0.72
LIG	23,212	0.59	0.69	0.022	0.70
SUG	7,723	0.95	0.79	0.009	0.83
RES	8,653	0.76	0.70	0.074	0.76
POL	12,100	0.04	0.13	0.387	0.78
ACR	7,480	0.44	0.71	0.065	0.73
STB	7,766	0.94	0.79	0.039	0.79
ACE-A	7,564	0.97	0.81	0.027	0.84
ACE-B	8,506	0.85	0.72	0.052	0.76

[a]Used in addition to CEM.

largest reduction in plastic axial deformation were SUG, CEM, LIG, and ACE-A.

As an alternative method of characterizing the development of permanent deformations, the Coulomb shakedown approach was employed to assess the amount of RLTT loading steps (30 in total) corresponding to response Ranges A, B, and C, as reported in Fig. 10. For the UGM, the number of steps lying within Ranges A, B, and C were 15, 5, and 10, respectively. Compared to the UGM, the application of additives led to a general increase in the amount of loading steps belonging to the plastic shakedown range, thus delaying the onset of plastic creep and incremental failure. The only exception is represented by POL. Its performance was poorer than the UGM because its deformation behavior was characterized by 7.5 steps in Range A, 7 steps in Range B, and 15.5 steps in Range C. The additive attaining the best performance was SUG because the strain response was entirely within the plastic shakedown range. The performance rankings evaluated according to the Hyde model and the Coulomb shakedown model were in agreement. For example, both formulations indicated that SUG and CEM produced the best results, whereas the worst responses were from POL and BIT.

Rolling Bottle Test and Microscope Analysis

The results of the RBT in terms of mass loss ML_{RBT} are depicted in Fig. 11. The ML_{RBT} of the UGM is related to the self-crushing and wearing down of rock particles; it can therefore be considered the baseline for evaluating the stripping potential of the additives. The mechanical degradation of the UGM occurred at a higher rate during the first 8 h, whereas its rate slowed over the remaining rotation times. This phenomenon occurs as the initial shape of the aggregates is progressively smoothed followed by a reduction in the mass loss as the material becomes rounded (Erichsen et al. 2011). The degradation of the treated aggregates follows a similar trend to different extents depending upon the stabilization additive used. The technologies demonstrating a loss of integrity smaller than the UGM are displayed on a blue background in Fig. 11. The POL-stabilized specimens produced the best results; moreover, POL was the only additive that performed better than the traditional BIT stabilizer. Each point plotted in Fig. 11 is the mean obtained from three replicate samples. For the generic ith additive treatment, the value $\overline{SD}_i$ was defined as the average of the standard deviations

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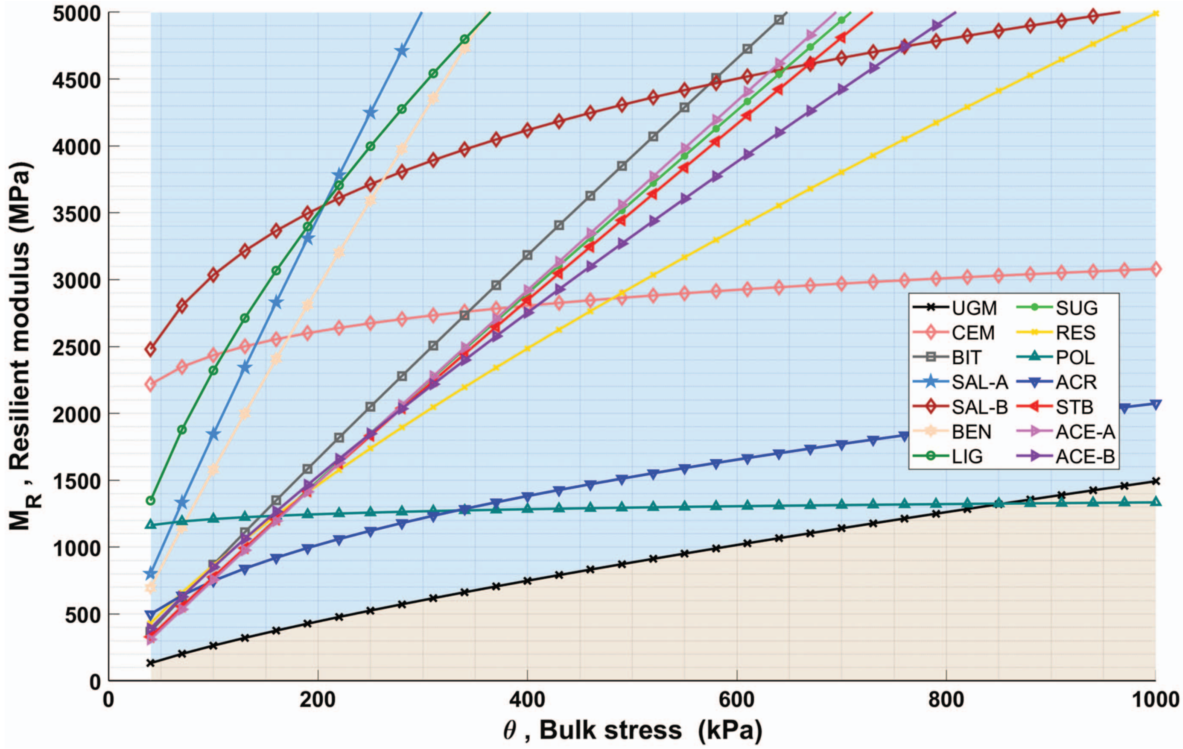

Fig. 7. (Color) Comparison between the resilient moduli M_R of stabilized aggregates.

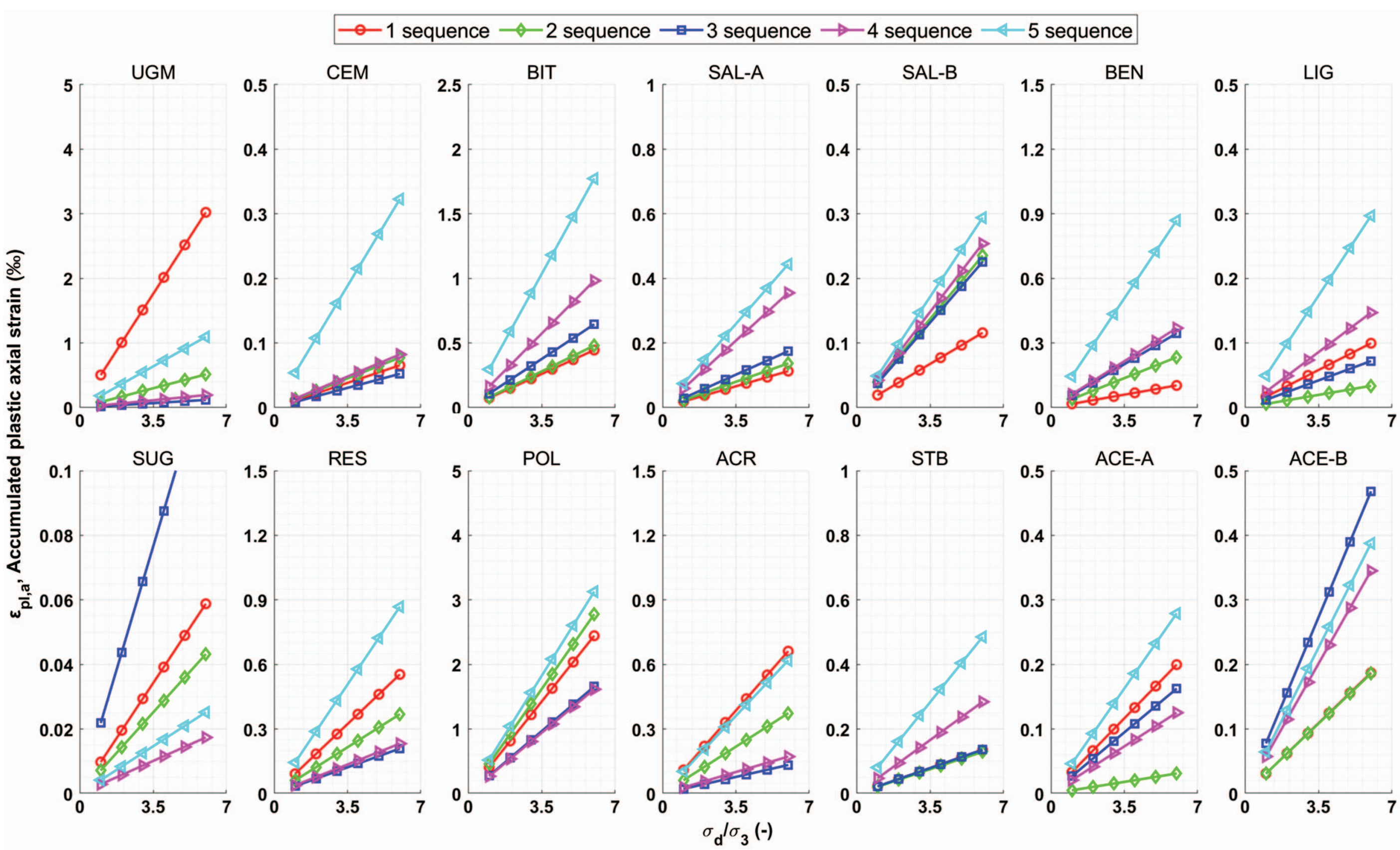

Fig. 8. (Color) Accumulated plastic axial strain $\varepsilon_{\mathrm{pl},a}$ modeled according to Hyde model.

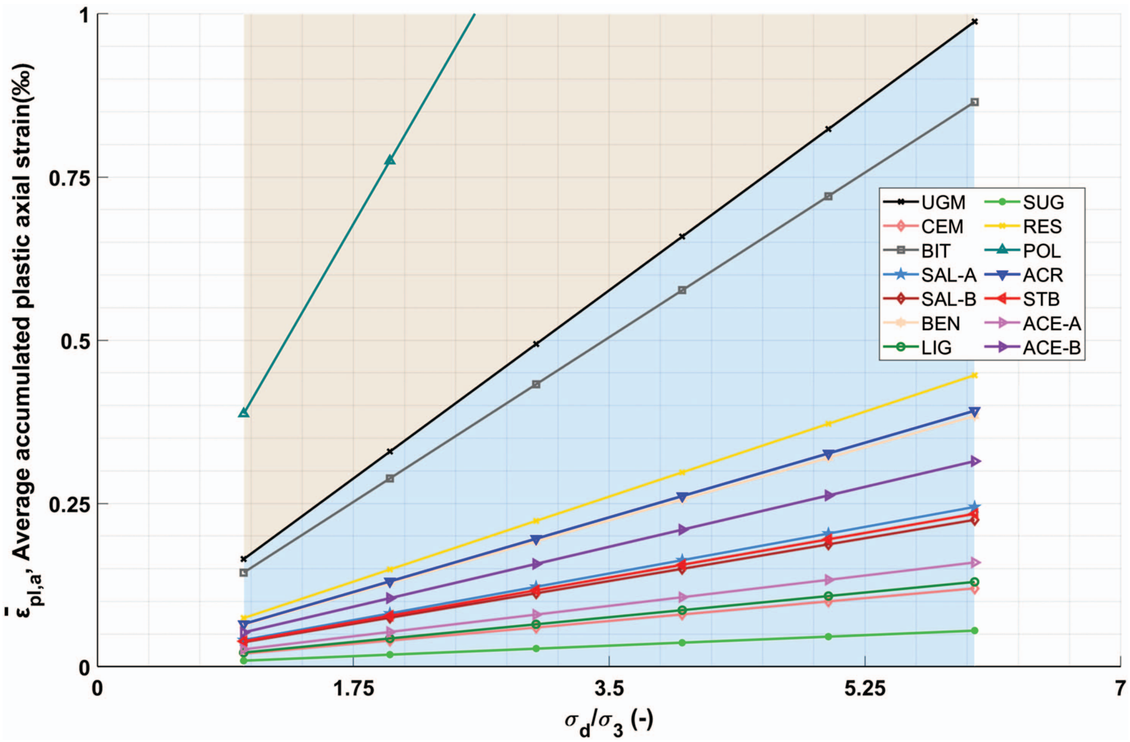

Fig. 9. (Color) Average accumulated plastic axial strain $\bar{\varepsilon}_{\mathrm{pl},a}$ of stabilized aggregates modeled according to Hyde formulation.

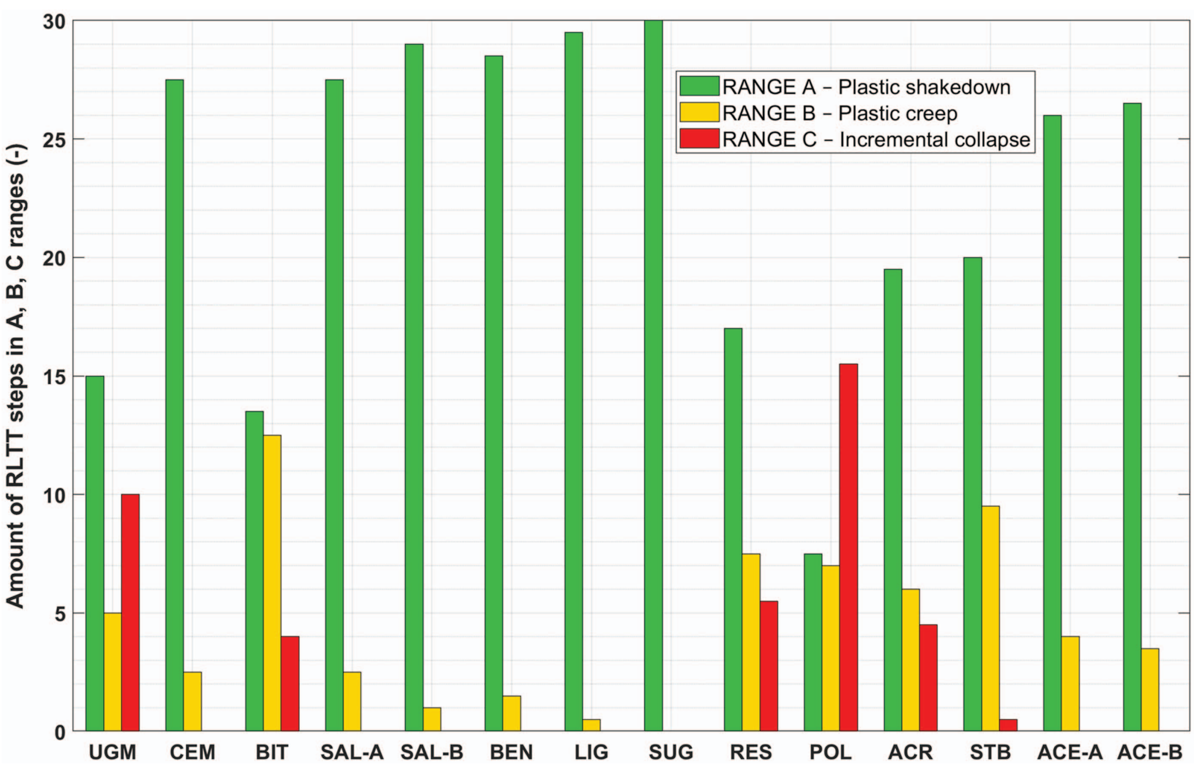

Fig. 10. (Color) Classification of RLTT steps according to Coulomb shakedown approach.

SD_j assessed for all the corresponding points (both i and j varied from 1 to 14). POL and BIT were characterized by the smallest amount of data dispersion ($\overline{\mathrm{SD}}_{\mathrm{POL}} = 0.05$, $\overline{\mathrm{SD}}_{\mathrm{BIT}} = 0.07$), whereas the highest variation was observed for BEN and cement mixed with SAL-B ($\overline{\mathrm{SD}}_{\mathrm{BEN}} = 0.23$, $\overline{\mathrm{SD}}_{\mathrm{SAL-B}} = 0.19$). The mean of all 14 $\overline{\mathrm{SD}_i}$ values was 0.13.

The SAL-A–stabilized specimens produced the highest amount of stripping. Compounding this outcome along with the highest

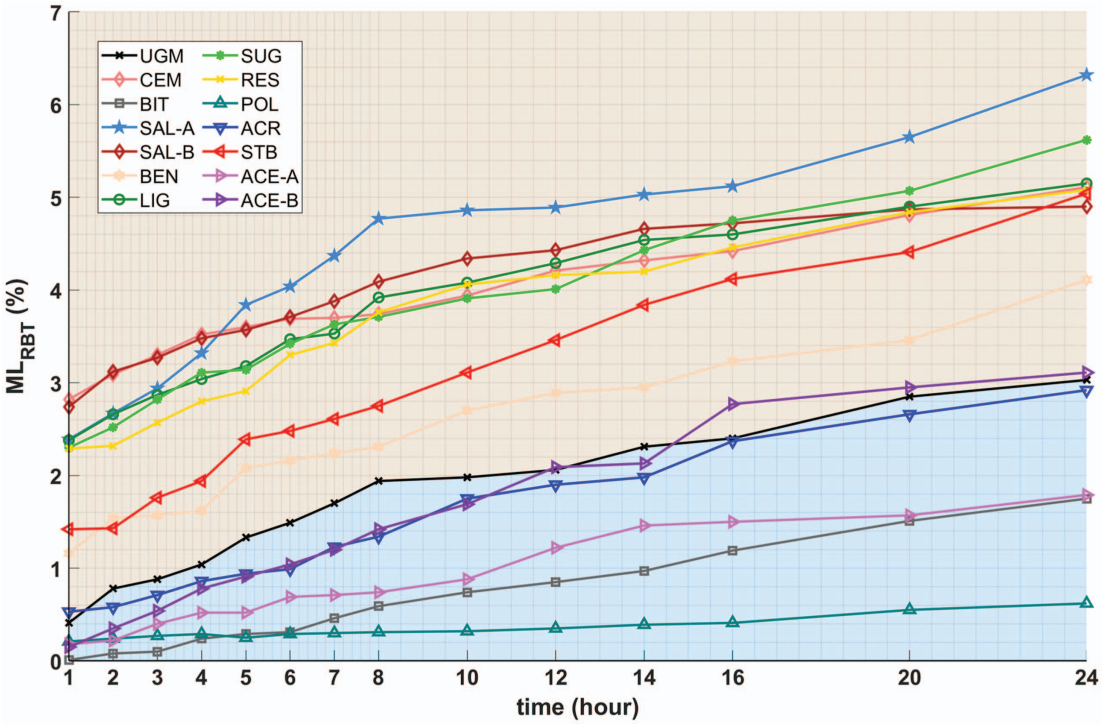

Fig. 11. (Color) Mass loss ML_{RBT} of aggregates coated by each investigated additive technology.

increase in M_R found for the SAL-A–stabilized samples, the road engineer should be careful when considering this salt as an effective stabilizer. A similar consideration is valid for the other additives displaying a higher loss of integrity than UGM, namely BEN, RES, LIG, and SUG. These results are displayed on a brown background in Fig. 11. This outcome can be correlated to their high leaching potential under wet conditions and associated low waterproofing abilities, as documented in Tingle's studies (Santoni et al. 2002; Tingle et al. 2007; Tingle and Santoni 2003). In contrast, the RES-treated samples demonstrated a moderately high sensitivity to water, which did not agree with the high waterproofing capacity reported in Tingle's works. This discrepancy may be ascribed to different chemical compositions in the investigated petroleum products. Depending on the moisture level anticipated in the actual road scenario, it may be necessary to perform periodical applications of additives that are water soluble and exhibit shorter durability.

For additives that are less susceptible to water exposure, the stripping effect mainly occurs due to mechanical degradation. The technologies can be ranked according to their performance as follows: POL, BIT, ACE-A, ACR, ACE-B, STB, CEM, and cement with SAL-B. This order matches the ranking of the same additives according to their deformation properties (Fig. 9). Thus, the stabilization technologies that engender larger plastic deformations were more likely to display better resistance against stripping. This finding buttresses the hypothesis that a "harder" coating is more fragile and thus worn off more easily when exposed to mechanical actions, whereas the ability to deform plastically leads to a smaller stripping potential. The stabilization mechanisms of cementitious, bituminous, and polymeric additives are mainly mechanical, leading to a glue-like physical reinforcement (Tingle et al. 2007; Xu et al. 2018; Zang et al. 2015). Thus, their adhesion potential can vary based on the chemical bonding (Awaja et al. 2009; Cui et al. 2014; Ollivier et al. 1995).

The results presented here can be compared with the outcomes of other similar studies. Though they employed different testing equipment and investigating finer aggregate particles, the tests performed by Jones (2007) and Mgangira (2009) focused on the assessment of abrasion and erosion. Generally, the results of this study are in good agreement with those conducted by Jones and Mgangira for the additive technologies that are in common in all the trials: organic nonpetroleum products perform more poorly than control samples, whereas polymer additives exhibit a better response.

Fig. 12 depicts the appearance before and after testing (24 h) of 14 RBT samples, one specimen for each stabilization technology. To better scrutinize the coated surface, Fig. 12 also displays microscope pictures at magnification equal to 40×. For the UGM, it is possible to recognize the principal minerals such as amphibole, plagioclase, and zoisite (Barbieri et al. 2020a). Samples treated with CEM and cement mixed with SAL-B displayed similar rough surfaces. The polygonal structures created by LIG and SUG formed an irregular beehive-shaped mesh. All the polymer-based technologies exhibited spherical formations due to gas bubbles generated during the foaming process. After 24 h of testing, the surface of the UGM became completely stripped of the additives that performed poorly, such as SAL-A, BEN, LIG, and SUG. The coating provided by RES showed elongated clusters, which are a residual of the petroleum paraffin resin. The bubble-shaped structures of the polymer-based additives were partly interconnected and punctured. STB displayed the most extended perforations, and ACR also generated elongated crystallized formations.

Conclusions

The stabilization of unbound aggregates used as road construction materials can provide significant benefits in terms of improved mechanical performance and relieve the demand for high-quality aggregates. A review of the literature related to the stabilization of coarse aggregates indicates that the previous studies were not comprehensive or complimentary, resulting in a lack of comprehensive

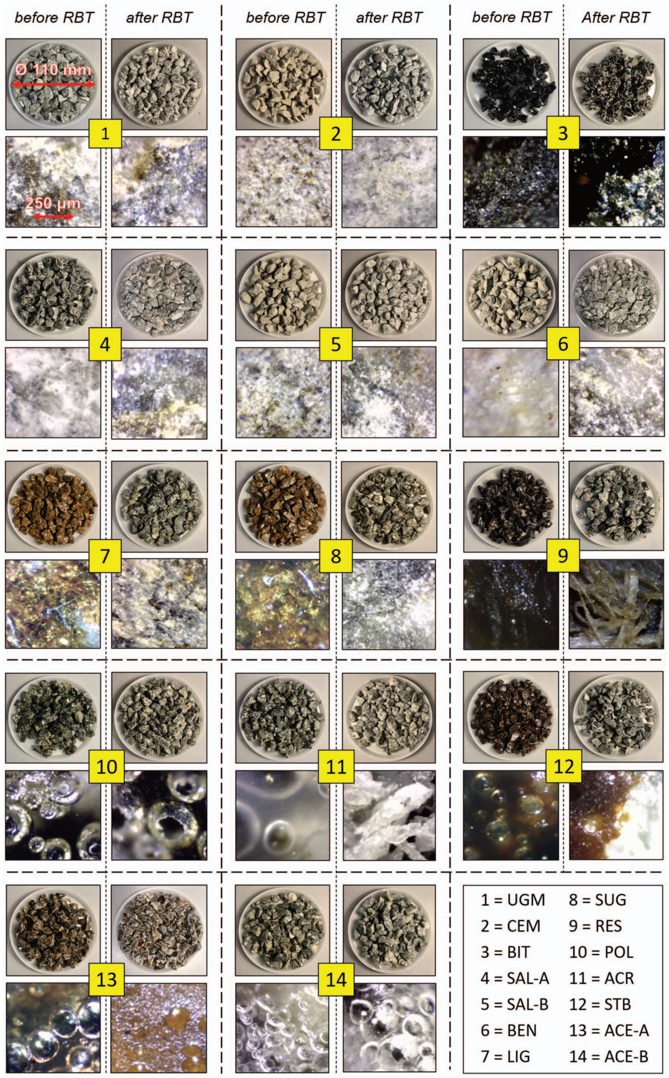

Fig. 12. (Color) Appearance of aggregate surface before and after RBT.

guidelines. Therefore, road engineers are often reluctant to use non-traditional stabilization technologies (often marketed as "one-size-fits-all" products).

The objective of this research has been to characterize and systematically compare all the existing types of additive technologies suitable to stabilize coarse-graded aggregates used in road construction. The mechanical behavior has been evaluated in terms of resilient modulus, resistance against permanent deformation, and stripping potential. Three types of laboratory investigations were performed: the repeated load triaxial test, a modified version of the rolling bottle test, and microscope analysis. Table 5 summarizes the results of the comparative evaluation of the investigated additive technologies. The main conclusions are as follows:

1. All the stabilization technologies improved the stiffness of the aggregates under dry test conditions. Calcium chloride salt SAL-A, bentonite BEN, lignosulfonate LIG, and cement mixed with mineral mixture salt SAL-B produced the highest increase in the resilient modulus for an average bulk stress level between 200 and 400 kPa typical of road applications.
2. The resistance against permanent deformation was largely improved for the stabilized aggregates. Reduced sugar SUG provided the best result, whereas the specimens treated with polyurethane POL and bitumen BIT did not significantly increase the resistance to permanent deformation.
3. The permanent deformation results interpreted according to the Hyde model and the Coulomb shakedown model were in agreement given that both analyses resulted in the same performance rankings for the stabilization additives.
4. All polymer-based additives except for styrene butadiene STB and bitumen BIT displayed good resistance to stripping, with the polyurethane POL-treated materials generating the smallest mass loss. All the other additive categories showed poor resistance to stripping given that they were gradually removed from the aggregate surfaces.

Table 5. Suitability assessment of the investigated additives for coarse-graded aggregates

	Suitability assessment		
Additive	Increase in resilient modulus	Decrease in permanent deformation	Resistance to stripping
CEM	Medium	High	Low
BIT	Medium	Low	High
SAL-A	Very high	High	Very low
SAL-B[a]	High	High	Low
BEN	Very high	Medium	Low
LIG	High	High	Low
SUG	Medium	Very high	Low
RES	Medium	Medium	Low
POL	Low	Very low	Very high
ACR	Low	Medium	Medium
STB	Medium	High	Low
ACE-A	Medium	High	High
ACE-B	Medium	Medium	Medium

Note: CEM = cement; BIT = bitumen; SAL-A = calcium chloride salt; SAL-B = mineral mixture salt; BEN = sodium bentonite; LIG = lignosulfonate; SUG = reduced sugar; RES = petroleum resin; POL = polyurethane; ACR = acrylate; STB = styrene butadiene; ACE-A = acetate type A; and ACE-B = acetate type B.
[a]Used in addition to CEM.

Based upon the results presented in this study, additional research can be performed to further characterize the stabilization technologies for aggregates to be used as road construction materials:

1. Aggregates with different geological origin and grain size distribution can be investigated to verify the compatibility of individual stabilization additives with different minerals. Moreover, tests performed at different curing/aging time intervals could offer valuable information in appraising the temporal development of the stabilization effects and possible aging.
2. The RLTT specimens can be retested after exposure to wet–dry or freeze–thaw cycles to assess the durability of the stabilized materials when exposed to variations in water content and alternating thermal distresses.
3. A full-scale evaluation of the stabilizing technologies can be used to verify the laboratory results and find correlations. In this regard, recommendations for pavement design guidelines and cost-benefit analyses can also be developed.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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