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Calcium bentonite and sodium bentonite as stabilizers for roads unbound

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ABSTRACT

Several technologies are currently available to stabilize the unbound layers of road pavements. The use of these solutions, often manufactured by means of chemical processes, is steadily increasing worldwide. As an alternative natural resource, the use of bentonite represents a valid option when it comes to road stabilization and its application in this context is still relatively unexplored. This study characterises the use of calcium based bentonite and sodium based bentonite to stabilize a typical road base layer. Considering two types of aggregates with different geological origin, the laboratory investigation is performed on dry specimens by means of repeated load triaxial tests, which assess the enhancement in stiffness and resistance to permanent deformation. The findings show that both the investigated types of bentonite are suitable for road stabilization. Even if negligible from a road engineering standpoint, the performance stemming from calcium bentonite was slightly better than the one pertaining to sodium bentonite when it came to the increase in resilient modulus.

1. Introduction

The term bentonite designates a rock with highly plastic swelling clay belonging to the smectite mineral group and deriving from the alteration in situ of volcanic ashes and tuff. This type of clay was named after the location where one of the first findings occurred, namely Fort Benton in Montana (Hewett, 1917). Smectite mineral groups display a soft dioctahedral platelet structure characterized by two tetrahedral silica sheets and one octahedral alumina sheet adhering to each other (Grim, 1953). Montmorillonite is the best known smectite clay and its structural idealised formula is $M^{+}{}_{y}nH_2O(Al_{2y}Mg_y)Si_4O_{10}(OH)_2$. The alkaline earth ions Ca^{2+}/Mg^{2+} or the alkali metal ion Na^{+} present between the platelets form calcium bentonite and sodium bentonite, respectively. When wet montmorillonite clays undergo swelling and the dioctahedral units disjoin due to mutual repulsion. Based on the type of inter-platelet cations, the degree of this separation is larger with monovalent ions (e.g., Na^{+}) compared to polyvalent ions (e.g., Ca^{2+}/Mg^{2+}) (Luckham and Rossi, 1999).

Thanks to its remarkable swelling and the creation of a viscoelastic gel-like structure, bentonite is generally not employed as a main construction material for buildings or roadbeds, but rather for sealing and mining applications. In the context of civil engineering, bentonite is widely adopted for those tasks requiring some form of shuttering such as drilling wells, creating diaphragm walls or stabilizing the sides of trench panels (Pusch, 2015).

1.1. Stabilization of roads unbound

The road pavement is a structure composed of several layers whose main function is to carry the traffic loads and transfer them to the natural subgrade. Generally, the top layers (wearing course and binder course) are bound strata due to the presence of bitumen or cement, while the bottom layers (base course and subbase course) are unbound strata as they do not usually contain any binding agent and lie on natural substrate (Huang, 2004). Worldwide, the largest amount of road infrastructures does not actually comprise the top sealed layer but only an unbound layer directly serving as the wearing course (Douglas, 2016). This type of pavement is known as Low-Volume Road (LVR) due to the

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Table 1
Main physical properties of calcium bentonite (CaB) and sodium bentonite (NaB).

	Density	Liquid limit LL	Plastic limit PL	Plasticity index PI	Swell index
	(kg/ m^3)	(%)	(%)	(%)	(mL/2g)
CaB	1 125	244	100	144	17
NaB	1 048	505	80	425	29

Table 2
Main engineering properties of Crushed Rock Aggregate (CRA) and Natural Gravel Aggregate (NGA).

	Los Angeles coefficient LA	micro-Deval coefficient MDE	slake durability	
			I_{d1}	I_{d2}
	(–)	(–)	(–)	(–)
CRA	18.2	14.2	99.8	99.5
NGA	27.7	17.3	99.6	99.2

low average daily traffic and forms at least 65% of the global road network (Meijer et al., 2018).

The engineering properties of the aggregates used in road construction may not always fulfil the requirements specified by pavement design guidelines; e.g., the mechanical behaviour of a given layer needs to be improved to ensure a proper performance (Barbieri et al., 2017). In this regard, several different stabilizer additives exist to deliberately modify and enhance the performance of the road construction and in particular the unbound layers, where weak recycled aggregates, e.g., material generated during tunnel constructions (Barbieri et al., 2019) or demolition of structures (Arulrajah et al., 2013), can be employed. More and more nontraditional technologies solutions are being investigated in addition to the traditional stabilizers commonly represented by cement or bitumen (Plati, 2019). The largest part of the additives derives from specific industrial processes (Jones, 2017) and are characterized by different function and adhesion mechanisms (Tingle et al., 2007). Currently, the most popular nontraditional technologies are organic non-petroleum, e.g., lignosulfonate (Zhang et al., 2020), and polymer emulsions, e.g., acrylate, styrene butadiene, acetate (Tan et al., 2020).

Generally, the employment of these additives should address various goals: reduce the use of natural resources (Gomes Correia et al., 2016), lower the generation of carbon footprint (Barbieri et al., 2021c) as well as ensure a relatively quick treatment to be economically competitive (Praticò et al., 2011). Furthermore, the technologies should not leach (Van Der Merwe Steyn and Visser, 2011) and should not represent ecological hazards (Kunz et al., 2021).

1.2. Bentonite application

Besides these solutions, the use of clay and in particular bentonite represents an alternative viable and environmentally sound approach (Spaulding et al., 2008) to stabilize the nonplastic aggregate particles composing the unbound road layers and typically displaying low fines content. There is a lack of literature dwelling on the use of bentonite as a binder in a pavement infrastructure. The few available researches have mainly documented its dust palliative potential preventing washboarding and ravelling of road surfaces built in ore mines (Barati et al., 2020) and forests (Parsakhoo et al., 2020). The stabilization properties have been partially investigated in combination with geosynthetics (Li et al., 2019). In this regard, the stabilization effect is achieved thanks to the physical bonding/cementation between bentonite clay and aggregate particles (Tingle et al., 2007).

The goal of this research is to shed light on the engineering application of bentonite to stabilize road unbound layers by comparing the performance of calcium bentonite and sodium bentonite in a laboratory trial. These two types of bentonite are mixed with an aggregate matrix typically used in a road unbound layer with particle gradation between 0 mm and 30 mm. Two types of aggregates with different geological origin are selected as construction material. The mechanical properties of the dry untreated and treated specimens are investigated by means of Repeated Load Triaxial Tests (RLTTs) (CEN, 2004), which thoroughly characterise the stiffness and deformation properties.

2. Materials and methods

2.1. Materials

The study investigates the potential of two bentonite types, namely Calcium Bentonite (CaB) and Sodium Bentonite (NaB), to serve as road stabilizer in the pavement unbound layers. The Atterberg limits and free swelling tests were performed to determine their Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI) (CEN, 2018) and swell index (ASTM International, 2019) as documented in Table 1. When comparing the physical properties of NaB with those pertaining to CaB, the values of LL, PI and swell index are remarkably higher. This trend is due to the larger degree of repulsion between the inter-platelets where monovalent ions such as Na^+ are present. The values of LL, PL, PI and swell index evaluated in this study are in line with other measurements performed on four types of bentonite clays (Dananaj et al., 2005) and several smectite clays (Spagnoli et al., 2018).

Two types of aggregates are employed in this research as possible construction materials for roads unbound. Crushed Rock Aggregate (CRA) and Natural Gravel Aggregate (NGA) derive from two quarries located close to Trondheim (Norway) and display igneous and metamorphic origin. As reported in Table 2, the Los Angeles value (LA) (CEN, 2010), micro-Deval value (MDE) (CEN, 2011) and slake durability index (I_{d1} and I_{d2}) (ASTM International, 2016) were assessed in order to measure the resistance of the aggregates to wear, fragmentation and disintegration, respectively. These parameters are commonly evaluated for road pavement engineering purposes (Dias Filho et al., 2015). Generally, aggregates can be employed in road unbound layers if the values of LA and MDE are lower than 30 and 20, respectively (NPRA, 2018, 2014). Therefore, CRA and NGA are largely adopted for construction purposes in the central part of Norway thanks to their good mechanical properties (Petkovic et al., 2004).

To further characterise all the materials used in this investigation, X-Ray Diffractometry (XRD) and X-Ray Fluorescence (XRF) analyses were performed. Bruker D8 Advance instrument equipped with a cobalt tube with wavelength of 1.79 Å was used to identify the mineralogical composition (DIFFRAC.EVA software). The investigated materials were crushed, split, milled to a powder with dimension smaller than 10 μm. The samples were then scanned from 3° to 80° 2θ with a step size of 0.011° and with reading time per step equal to 0.6 s. The semi-quantitative proportions of the most abundant minerals evaluated according to the Rietveld analysis (DIFFRAC.TOPAS software) are displayed in Fig. 1. The XRF examination was performed using a PANalytical Zetium 4 kW X-ray spectrometer to determine the chemical composition and assess the major elements. After igniting 2.5 g of dry sample to 1 000 °C for 1 h, the Loss of Ignition (LOI) was determined gravimetrically. Prior to analysis, the sample pulps of 0.5 g were fused and dissolved in 5 g of a flux chemical made of lithium tetraborate and lithium metaborate. The XRF results presented in Fig. 2 show that the largest difference in composition between the two types of bentonite clays can be ascribed to the quartz (SiO_2) content, which is equal to 59.1% for CaB and to 52.4% for NaB. Other chemical compounds that significantly vary are CaO (0.8% for CaB and 5.5% for NaB), Fe_2O_3 (8.1% for CaB and 4.5% for NaB) and Al_2O_3 (14.7% for CaB and 17.5%

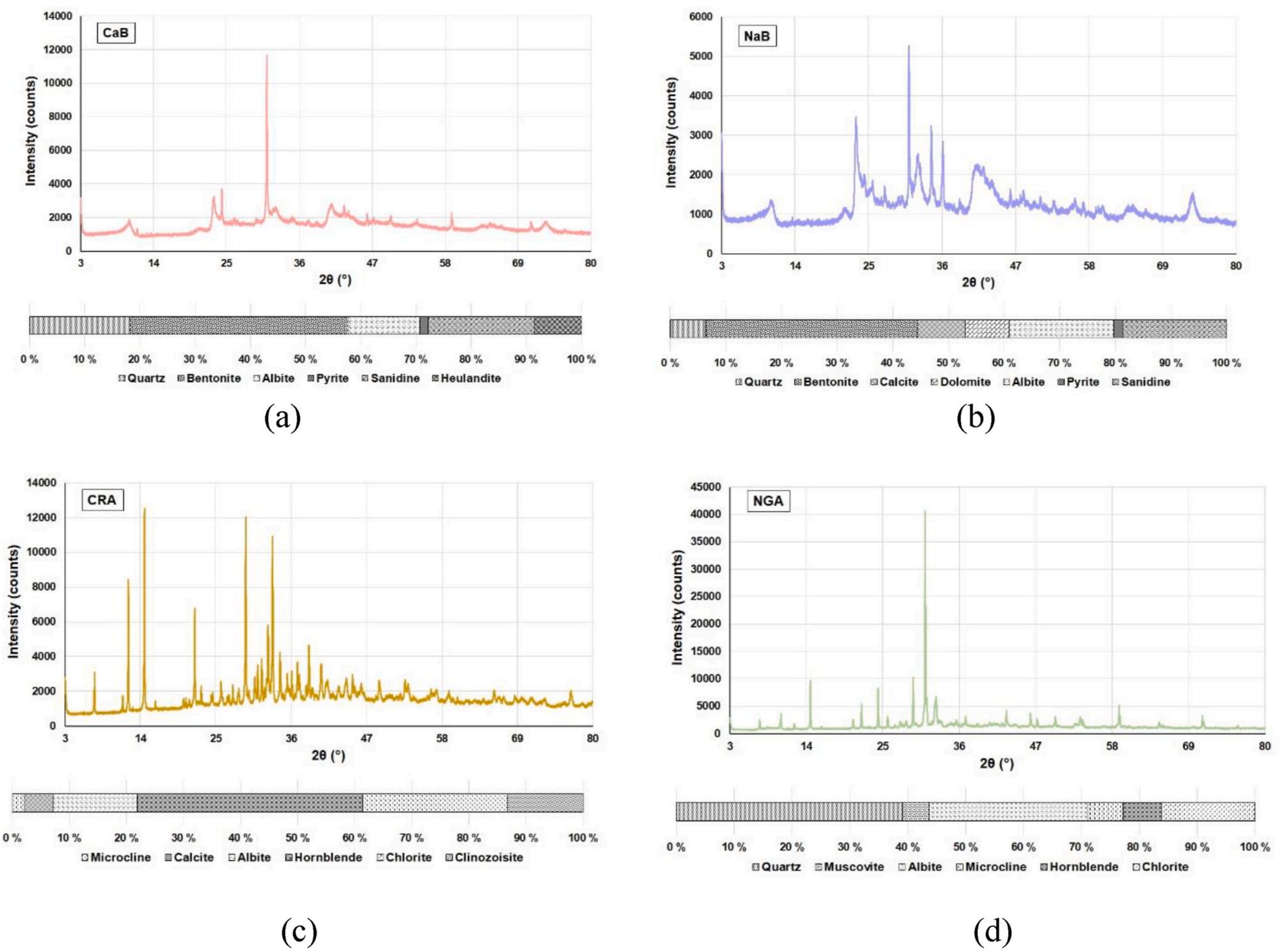


Fig. 1. Bulk mineralogy of CaB (a), NaB (b), CRA (c) and NGA (d).

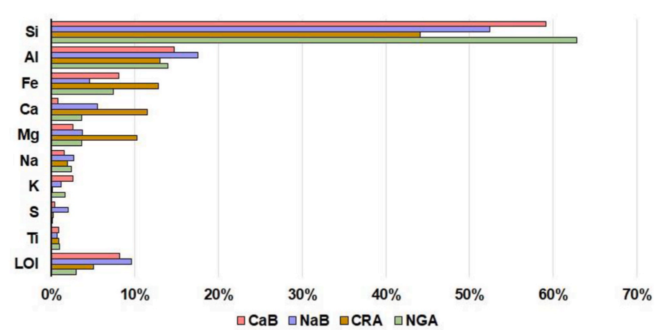


Fig. 2. Spectrum of CaB, NaB, CRA and NGA chemical composition. (expressed as weight percent of major oxides).
Element abbreviations: Si/silicon, Al/aluminium, Fe/iron, Ca/calcium, Mg/magnesium, Na/sodium, K/potassium, S/sulphur, Ti/titanium.

for NaB). These discrepancies can anticipate that CaB and NaB are likely to display different geotechnical properties (as documented in Table 1) as well as different mechanical response, although the chemical analyses cannot clearly quantify them (Dananaj et al., 2005). When it comes to the aggregates CRA and NGA, the most relevant difference is ascribable to the quartz (SiO_2) content, which is equal to 44.1% for CRA and to 62.8% for NGA. On the contrary, CRA is richer in other chemical compounds, which are mainly CaO (11.5% for CRA and 3.7% for NGA), MgO (10.2% for CRA and 3.6% for NGA) and Fe_2O_3 (12.8% for CRA and 7.4% for NGA). In particular, the significant difference in quartz content can anticipate a poorer mechanical response of NGA compared with CRA in terms of compressive strength, tensile strength (Sun et al., 2017) and LA, MDE coefficients (Adomako et al., 2021).

Table 3
Particle size distribution selected for creation of RLTT specimens.

Sieve (mm)	45	31.5	22.4	16	2	0.25	0.063
Passing (%)	100	95	65	40	16	6	4

2.2. Repeated load triaxial test

The Repeated Load Triaxial Test (RLTT) was used to characterise the mechanical properties of both untreated and treated aggregates. RLTT mimics the stress status of a road layer and examines its performance concerning stiffness (Lekarp et al., 2000a) and deformation (Lekarp et al., 2000b).

2.2.1. Specimen preparation and testing

The gradation selected to create each RLTT specimen corresponds to a typical base layer (NPRA, 2018, 2014). The sieve openings and the respective percentage passing are shown in Table 3. The height and the diameter of a cylindrical specimen were 30 cm and 15 cm, respectively, and the weight was approximately 12 kg (CEN, 2004).

The quantity of dry bentonite present in each specimen was 0.4% by mass. The bentonite powder was carefully blended with the Optimum Moisture Content (OMC) of the selected grading curve w=5% (CEN,

Table 4
Details of tested RLTT specimens: denomination, bentonite content, initial water content, curing process and bulk density; Crushed Rock Aggregate (CRA), Natural Gravel Aggregate (NGA), Unbound Granular Material (UGM), Calcium Bentonite (CaB) and Sodium Bentonite (NaB).

Specimen	Bentonite content	Initial water	Curing		Bulk density
			Temperature	Time	
	(% mass)	(% mass)	(°C)	(day)	(t/m^3)
CRA-UGM	0	0	–	–	2.4
CRA-CaB	0.4	5	55+22	7+1	2.2
CRA-NaB	0.4	5	55+22	7+1	2.2
NGA-UGM	0	0	–	–	2.1
NGA-CaB	0.4	5	55+22	7+1	2.0
NGA-NaB	0.4	5	55+22	7+1	2.0

2003) by means of a high shear mixer to achieve a workable slurry, which was then carefully mixed with the aggregates. After the blending operation, a RLTT specimen was created inside a steel mould by sequentially compacting five layers of aggregates using a Milwaukee 2″ SDS Max rotary hammer (tamping time 25 s, weight 12 kg, work per blow 27 N m). After ejection from the mould, the sample was covered by a latex membrane and put in an oven at 55 °C for seven days to let the water evaporate. The specimen was then kept at room temperature for one day before testing; detailed information regarding the material preparation is reported elsewhere (Barbieri et al., 2021a). In addition, untreated samples, namely Unbound Granular Materials (UGMs), were tested for comparison purpose with w=0%. Table 4 summarizes the main characteristics of the tested materials and documents that the bentonite stabilization treatment determined a slight decrease in the bulk density (measured immediately after creation of the specimens). Fig. 3 displays the top views of the cylindrical samples having diameter equal to 150 mm and thus depicts the different appearance of treated and untreated aggregates. Two replicate specimens were investigated for each combination.

The RLTTs were performed according to the stress paths defined by the Multi-Stage Low Stress Level (MS LSL) loading procedure (CEN, 2004). Triaxial σ_3 and deviatoric σ_d stresses were applied by pressurized water and hydraulic jack, respectively. Five loading sequences, each composed of six loading steps, defined the MS LSL test. For every step, the triaxial pressure was constant (σ_3 = 20, 45, 70, 100 or 150 kPa for each sequence) and σ_d varied following a sinusoidal pattern with 10 000 load pulses applied at 10 Hz. The axial deformations of the sample were recorded by three Linear Variable Differential Transducers (LVDTs). The RLTT device is illustrated in Fig. 4; the components that are most fundamental in the test execution (e.g., LVTDs and hydraulic jack) are highlighted.

2.2.2. Results interpretation

The two main mechanical properties assessed by a RLTT are the resilient modulus M_R and the resistance against permanent deformation. Given a constant σ_3, M_R is defined as

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

where the numerator and the denominator are the variation in dynamic deviatoric stress $\sigma_{d,dyn}$ and the elastic axial strain, respectively. Among the formulations available in literature, the k-θ model assesses M_R as a function of bulk stress θ (the sum of the principal stresses is equal to θ and the average and the minimum principal stresses have the same values in the performed MS LSL tests) (Hicks and Monismith, 1971)

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

where k_1, k_2 are regression parameters and σ_a is a reference pressure equal to 100 kPa. In addition to Hicks & Monismith model, Uzan model is another formulation commonly adopted to describe the experimental data by putting the resilient modulus M_R in relationship with both bulk

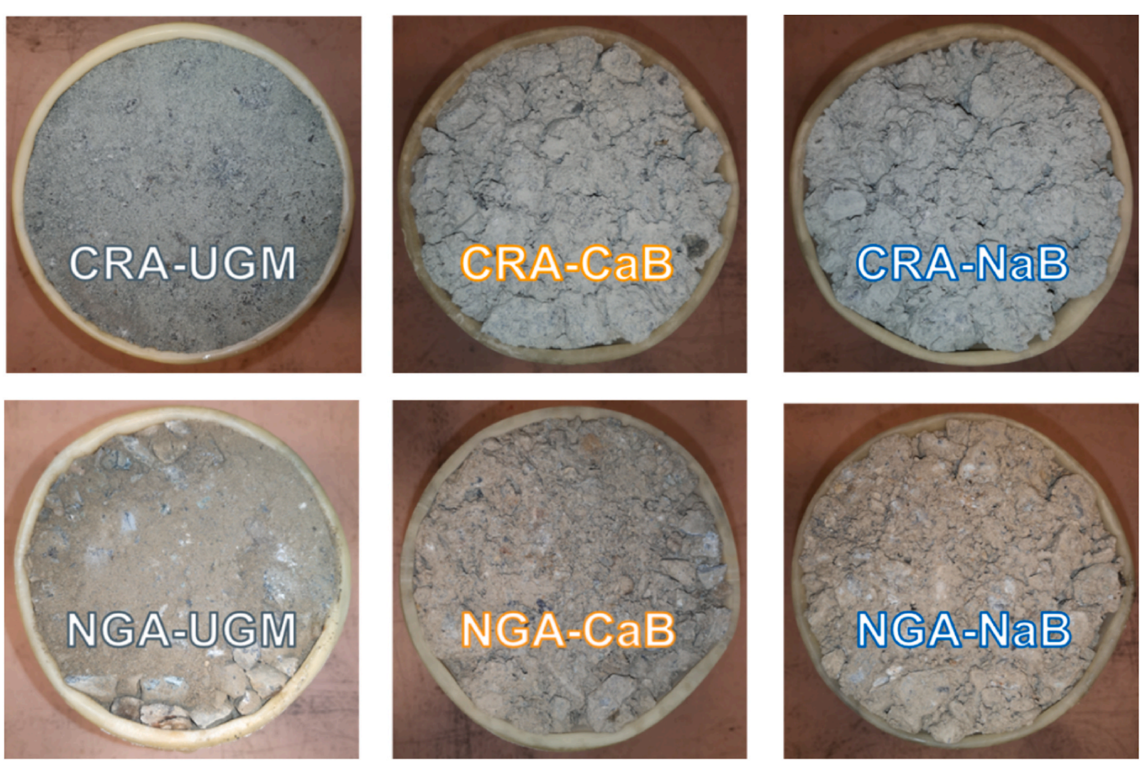


Fig. 3. RLTT samples; Crushed Rock Aggregate (CRA), Natural Gravel Aggregate (NGA), Unbound Granular Material (UGM), Calcium Bentonite (CaB) and Sodium Bentonite (NaB).

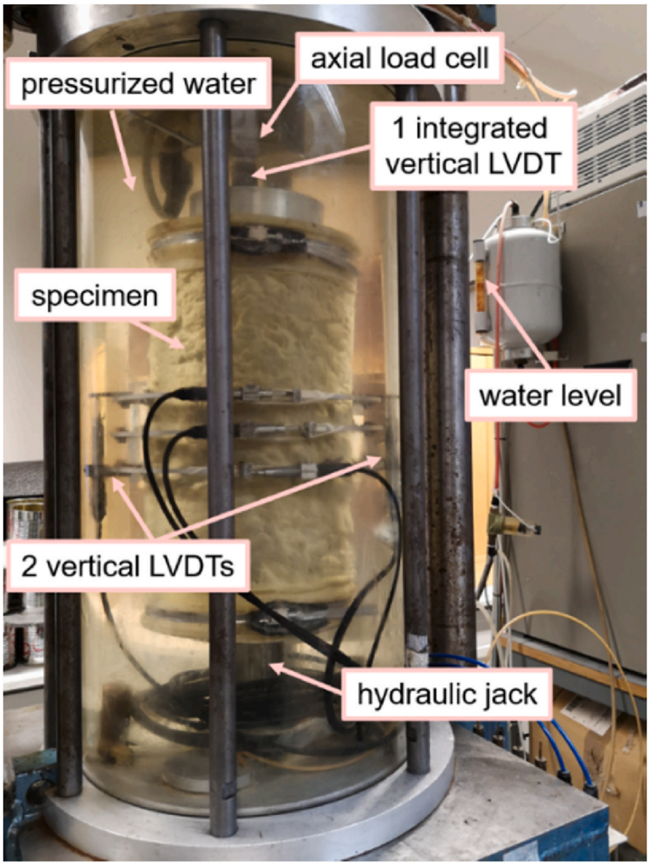


Fig. 4. Triaxial load device with essential components highlighted.

Table 5
Material behaviour and corresponding values of the plastic strain rate.

Material behaviour	Plastic strain rate
plastic shakedown	$\dot{\varepsilon}_{pl} < 2.5 \cdot 10^{-8}$
plastic creep	$2.5 \cdot 10^{-8} < \dot{\varepsilon}_{pl} < 1.0 \cdot 10^{-7}$
incremental collapse	$\dot{\varepsilon}_{pl} > 1.0 \cdot 10^{-7}$

stress θ and deviatoric stress σ_d (Uzan, 1985)

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

with $k_{1,UZ}$, $k_{2,UZ}$, $k_{3,UZ}$ regression coefficients. The formulations proposed by Hicks & Monismith model and Uzan can be efficiently portrayed in a 2D and 3D plot, respectively (Barbieri et al., 2021b).

The resistance against permanent deformation is evaluated according to the Coulomb approach (Hoff et al., 2003), which derives from the shakedown theory (Werkmeister et al., 2005). The Coulomb formulation expresses the mobilized shear strength and the maximum shear strength by means of the elastic limit angle ρ and failure limit angle φ, respectively. The material behaviour can be classified according to three ranges, namely plastic shakedown, plastic creep and incremental collapse, based on the average strain rate value per cycle $\dot{\varepsilon}_{pl}$ as reported in Table 5 (Hoff et al., 2003).

3. Results and discussion

The surfaces of untreated and treated aggregates were qualitatively probed using a microscope at 40x magnification (Fig. 5) to preliminarily observe the coating supported by CaB and NaB. Being Fig. 5 a qualitative representation of the aggregate surfaces covered by bentonite clays, no further considerations can be made regarding the aspect of the Interfacial Transition Zone (ITZ), which can be scrutinized by means of other laboratory equipment. Nevertheless, the cyclic triaxial testing campaign focused on the mechanical response of stabilized aggregates evaluated at a macroscale level; the outcomes are presented and discussed in the two following subsections (Barbieri et al., n.d.).

3.1. Resilient modulus

The experimental values of resilient modulus M_R and their trends evaluated according to Hicks & Monismith regression model for CRA and NGA are depicted in Fig. 6a and Fig. 6b, respectively. To better compare the results, the modelled M_R trends are reported in Fig. 7a and Fig. 7b for CRA and NGA, respectively. Overall, it is evident that the use of bentonite clays does significantly improve the stiffness of the material and therefore it represents a valid stabilization solution for roads unbound. Fig. 8 portrays the resilient modulus M_R evaluated according to Uzan model in a three-dimensional space where each result is represented by a surface. Both Hicks & Monismith and Uzan formulations

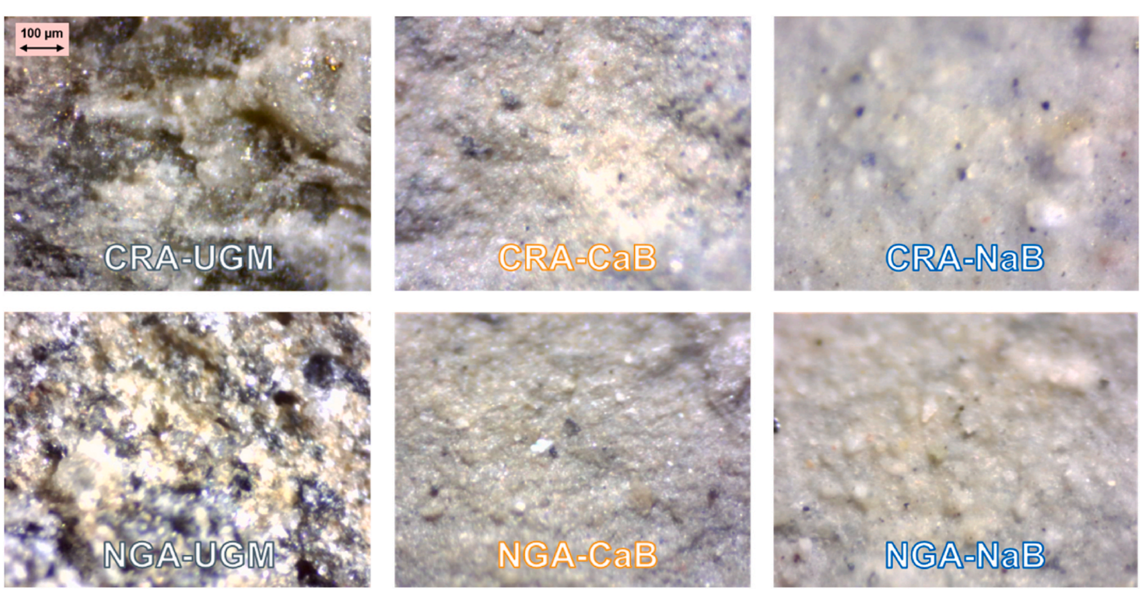


Fig. 5. Appearance of uncoated and coated aggregate surfaces examined with microscope.

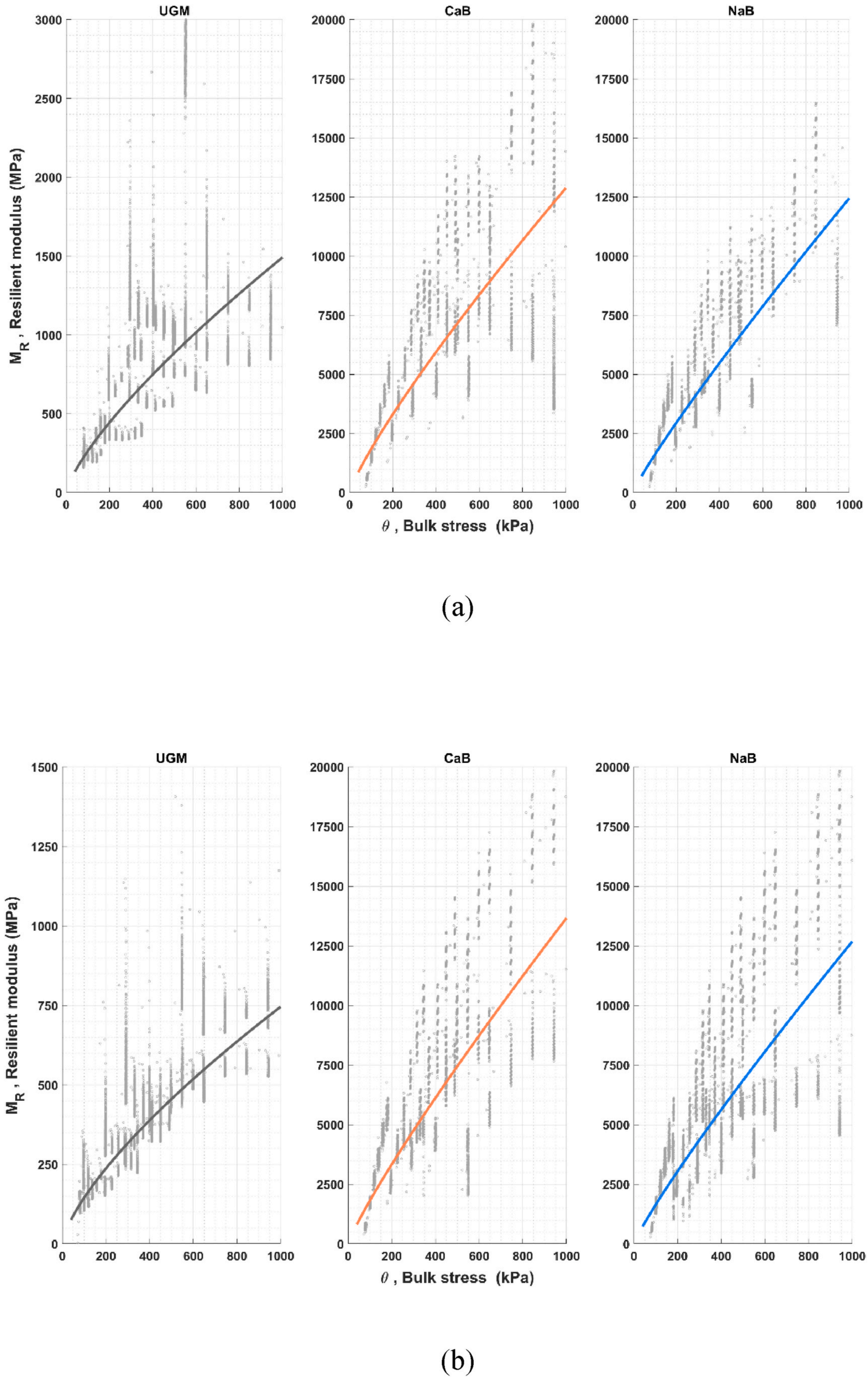
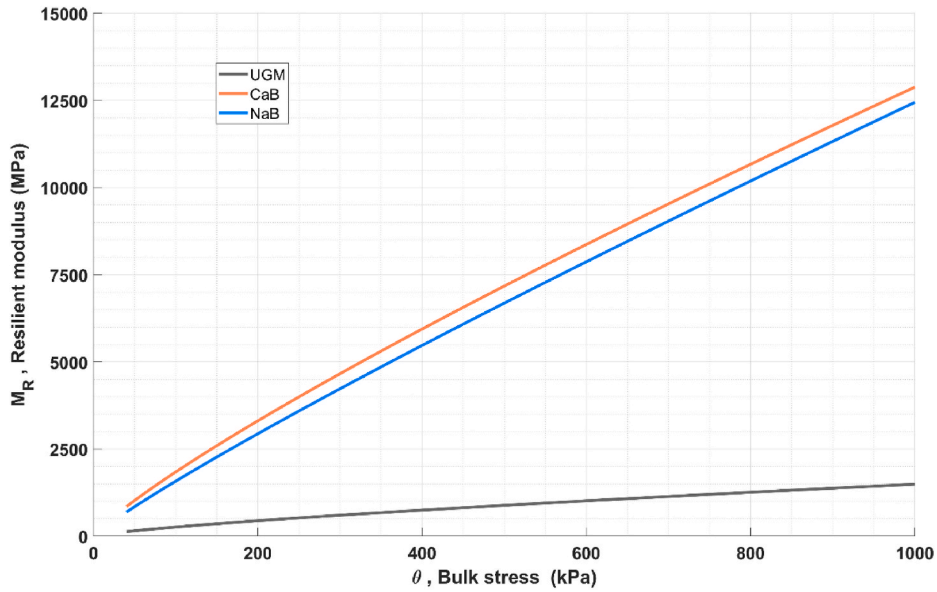
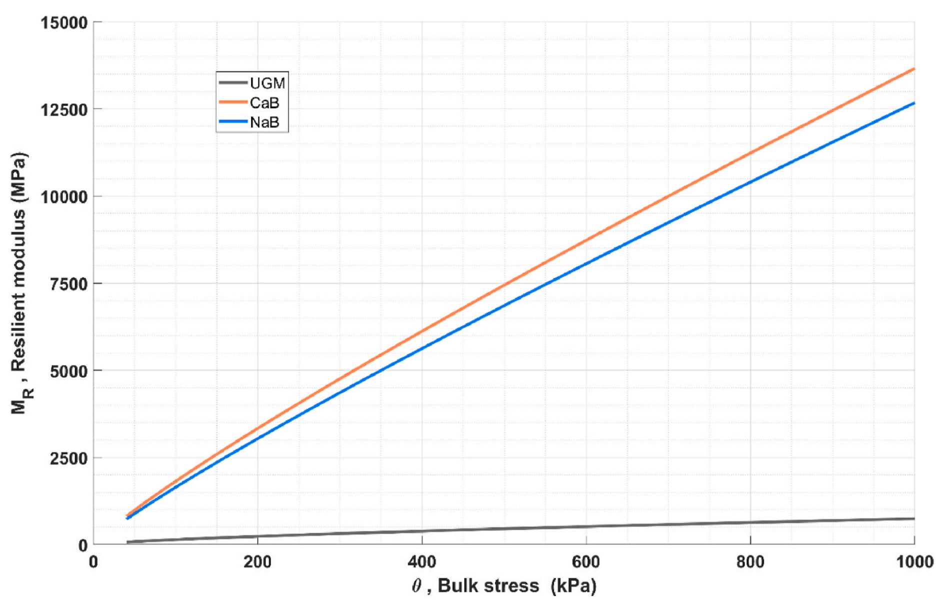


Fig. 6. Experimental and modelled M_R of RLTT specimens according. to Hicks & Monismith formulation for CRA (a) and NGA (b).



(a)

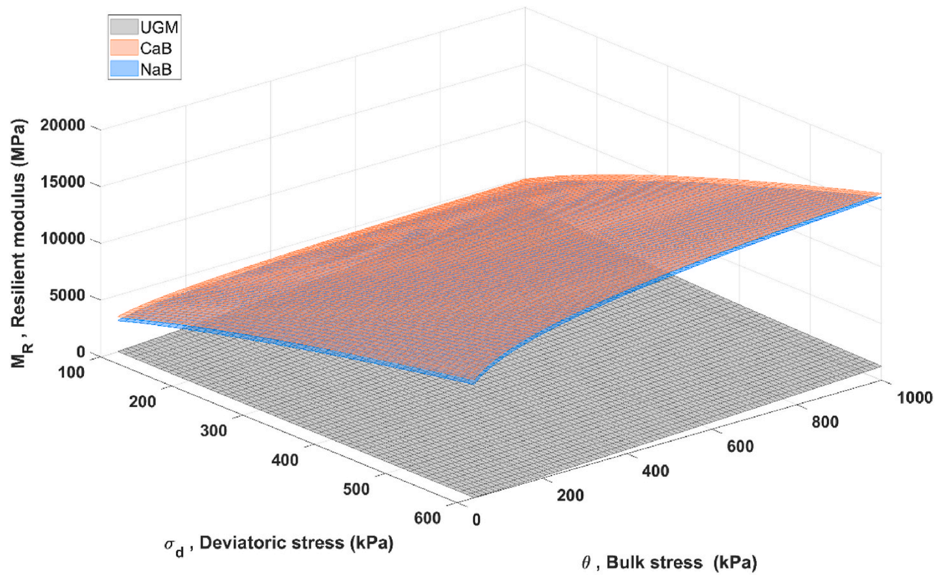


(b)

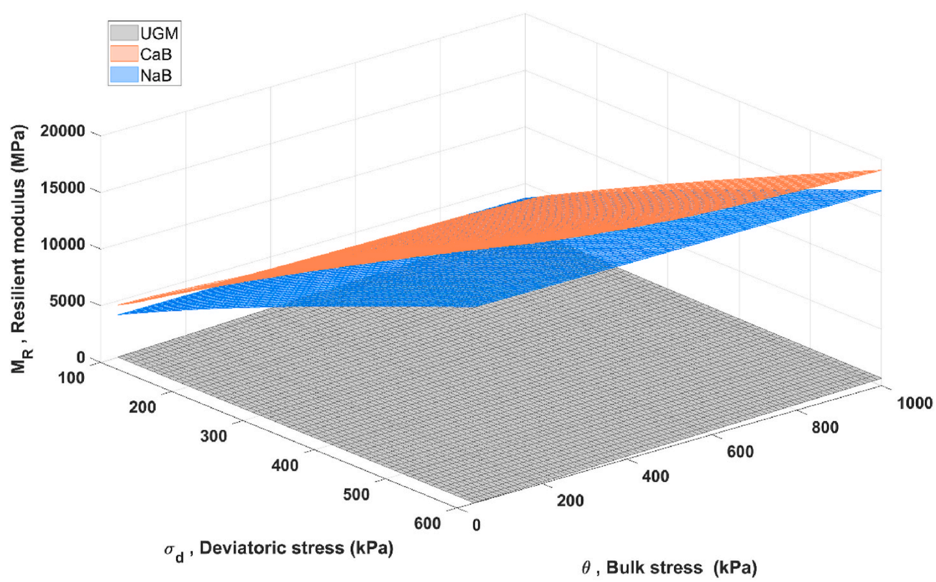
Fig. 7. Comparison between the trends of resilient moduli M_R. evaluated according to Hicks & Monismith model for CRA (a) and NGA (b).

document the enhancement in the material performance and this improvement occurs for both the considered aggregates types (CRA and NGA) and for both the investigated bentonite types (CaB and NaB). To some extent, these outcomes can be related with the positive results found in a previous investigation led by Li (Li et al., 2019). Anyway, some relevant discrepancies exist as Li's field test applied sodic bentonite at a much higher rate (5%) to stabilize finer geomaterials (silty sand) also in combination with geosynthetics (geotextile). Table 6 details the regression parameters of Hicks & Monismith and Uzan formulations; it can be clearly seen that the values found by using the least-squares method between model trend and experimental data are largely positive.

Focusing on the stabilization extent attained by the two bentonite clays, M_R related to CaB is slightly higher than the one related to NaB and this finding is consistent for both the aggregate types. To some extent, this result could be related to the outcome of a previous research comparing sodic and calcic bentonites to be mixed with sand, where it was found that the shear strength of calcium bentonite was higher than the shear strength of sodium bentonite (Gleason et al., 1997). The small difference in M_R assessed in this study can be ascribed to the peculiar chemical compositions of the bentonite clays as reported in subsection 2.1. Comparing CaB with NaB, the chemical compounds that display the largest different amounts are SiO_2 (+6.7%), CaO (−4.7%), Fe_2O_3 (+3.6%) and Al_2O_3 (−2.8%). The small gap in the M_R values is however



(a)



(b)

Fig. 8. Comparison between the trends of resilient moduli M_R. evaluated according to Uzan model for CRA (a) and NGA (b).

Table 6
Regression parameters for Hicks & Monismith and Uzan models.

Specimen	Hicks & Monismith		Uzan		
	$k_{1,HM}$ (−)	$k_{2,HM}$ (−)	$k_{1,UZ}$ (−)	$k_{2,UZ}$ (−)	$k_{3,UZ}$ (−)
CRA-UGM	2 637	0.753	1 576	1.297	−0.519
CRA-CaB	18 448	0.844	35 296	0.142	0.677
CRA-NaB	15 803	0.896	31 633	0.149	0.718
NGA-UGM	1 450	0.711	1 050	1.048	−0.320
NGA-CaB	18 192	0.876	43 364	−0.070	0.915
NGA-NaB	16 472	0.886	37 435	−0.002	0.854

negligible from a road engineering standpoint; in fact, the reduced thickness of a stabilized base layer calculated according to the Norwegian pavement design guide considering M_R for θ=200 kPa would be practically the same for both CaB and NaB (NPRA, 2018, 2014).

3.2. Resistance to permanent deformation

The trend of the development of permanent deformation is interpreted according to the Coulomb approach as depicted in Fig. 9a and Fig. 9b for CRA and NGA, respectively. Compared to the untreated aggregates, the presence of bentonite significantly reduces the development of permanent deformation. Compounding this finding with the increase in resilient modulus presented in the previous subsection, the use of bentonite clay does apport a beneficial contribution when it comes to stabilize roads unbound thanks to the physical bonding created with the aggregate particles (Tingle et al., 2007). The values of the elastic limit angles ρ and the failure limit angles φ are reported in Table 7. The improvement related to the elastic limit angle (average

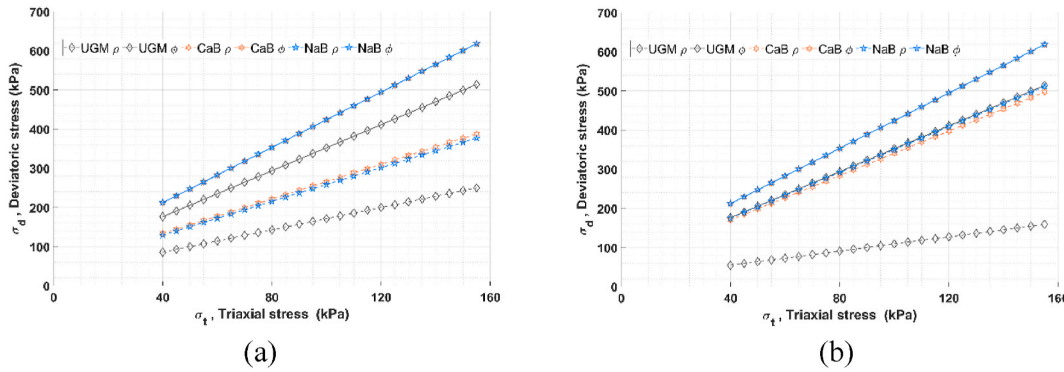


Fig. 9. Elastic limit angle ρ and failure limit angle φ for CRA (a) and NGA (b).

Table 7
Values of elastic limit angle ρ and failure limit angle φ.

Specimen	Limit angles	
	ρ (°)	φ (°)
CRA-UGM	55.0	71.2
CRA-CaB	65.7	74.2
CRA-NaB	65.1	74.2
NGA-UGM	42.3	71.2
NGA-CaB	70.6	74.2
NGA-NaB	71.1	74.2

equal to +10.4° for CRA and +28.6° for NGA) is higher than the enhancement of the failure limit angle (average equal to +3.0° for both CRA and NGA).

The significant gap between the elastic limit angles ρ of CRA-UGM and NGA-UGM can be correlated to the remarkable differences also observed in the other measured properties (Los Angeles value, micro-Deval value and resilient modulus). The discrepancies between the mechanical response of the untreated aggregates CRA and NGA can be ascribed to their distinct chemical compositions (e.g., noticeably different amount of SiO_2) as reported in subsection 2.1. CaB led to a slightly higher resilient modulus than NaB. However, no significant differences were registered for the resistance to permanent deformation. In this regard, more research is needed to corroborate these findings considering other aggregate types with different geological origins.

4. Conclusions and recommendations

Bentonite is a clay rock used in different fields including civil engineering. This study focused on the application of two types of bentonites, namely calcium bentonite (CaB) and sodium bentonite (NaB), to stabilize the unbound layers of road pavements. Given the huge extent of the global road network and the large associated amount of maintenance operations, any solution that can improve the mechanical performance of road infrastructures is of sure engineering interest. In particular, Low Volume Roads (LVRs) are entirely made of unbound aggregates and may require even more frequent maintenance. In this context, bentonite represents a resource that is readily available and environmentally sound, its application requires common blading and mixing equipment.

The study has shed light on the use of CaB and NaB as potential binders applied to two different aggregate types, namely crushed rock and natural gravel. A laboratory investigation has been performed by means of Repeated Load Triaxial Tests (RLTTs), which have assessed the mechanical properties of both treated and untreated dry aggregates. The results are synthetically reported in Table 8 in terms of resilient modulus M_R, elastic limit angle ρ and failure limit angle φ; M_R is evaluated for an average bulk stress θ=200 kPa as a representative condition (NPRA, 2018, 2014). Based on the experimental investigation, the following conclusions can be drawn:

(1) The use of bentonite clay is an effective solution to stabilize unbound granular materials by significantly increasing the resilient modulus as found by evaluating the experimental data using both Hicks & Monismith model and Uzan model.

Table 8
Values of resilient modulus M_R, elastic limit angle ρ and failure limit angle φ; Crushed Rock Aggregate (CRA), Natural Gravel Aggregate (NGA), Unbound Granular Material (UGM), Calcium Bentonite (CaB) and Sodium Bentonite (NaB).

		Resilient modulus	**Elastic limit angle**	**Failure limit angle**
		M_R (MPa)*	**ρ (°)**	**φ (°)**
CRA	**UGM**	444	55.0	71.2
	CaB	3 312	65.7	74.2
	NaB	2 941	65.1	74.2
NGA	**UGM**	237	42.3	71.2
	CaB	3 338	70.6	74.2
	NaB	3 045	71.1	74.2

(2) All the specimens stabilized with bentonite clays have attained smaller permanent deformations than untreated rock aggregates with significant increase in the values of elastic limit angle and failure limit angle.
(3) In terms of enhancing the resilient modulus, CaB has showed a slightly higher performance when compared to NaB. Anyway, the difference is negligible from a road engineering standpoint. The performance of CaB and NaB have been similar in terms of reducing permanent deformation.

For future research, it is suggested to evaluate the mechanical properties after the exposure to wet-dry or freeze-thaw cycles. Performing a full-scale field test would be beneficial to attain a more thorough characterization of the stabilization potential of bentonite. Furthermore, it may be relevant to compare the stabilization effects attained by calcic and sodic bentonites on more aggregate types to confirm whether the small differences in the elastic stiffness observed in this study can be consistently found.

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. **Pengxiang Zhao:** Writing – review & editing, Visualization. **Shazim Ali Memon:** 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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References

Adomako, S., Engelsen, C.J., Thorstensen, R.T., Barbieri, D.M., 2021. Review of the relationship between aggregates geology and Los Angeles and micro-Deval tests. Bull. Eng. Geol. Environ. https://doi.org/10.1007/s10064-020-02097-y.

Arulrajah, A., Piratheepan, J., Disfani, M.M., Bo, M.W., 2013. Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. J. Mater. Civ. Eng. 25, 1077–1088. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000652.

ASTM International, 2019. D5890 - 19 Standard test method for swell index of clay mineral component of geosynthetic clay liners. USA. https://doi.org/10.1520/D5890-19.2.

ASTM International, 2016. D4644 - 16 Standard test method for slake durability of shales and other similar weak rocks. USA. https://doi.org/10.1520/D4644-16.2.

Barati, S., Tabatabaie Shourijeh, P., Samani, N., Asadi, S., 2020. Stabilization of iron ore tailings with cement and bentonite: a case study on Golgohar mine. Bull. Eng. Geol. Environ. 79, 4151–4166. https://doi.org/10.1007/s10064-020-01843-6.

Barbieri, D.M., Dorval, J.-G., Lou, B., Chen, H., Shu, B., Wang, F., Hoff, I., 2021a. Dataset regarding the mechanical characterization of sedimentary rocks derived from Svalbard for possible use in local road constructions. Data Brief 34, 106735. https://doi.org/10.1016/j.dib.2021.106735.

Barbieri, D.M., Hoff, I., Ho, C.-H., 2021b. Crushed rocks stabilized with organosilane and lignosulfonate in pavement unbound layers: repeated load triaxial tests. Front. Struct. Civ. Eng. https://doi.org/10.1007/s11709-021-0700-5.

Barbieri, D.M., Hoff, I., Mork, H., 2017. Laboratory investigation on unbound materials used in a highway with premature damage. In: 10th International Conference on the Bearing Capacity of Roads, Railways and Airfields.

Barbieri, D.M., Hoff, I., Mørk, M.B.E., 2019. Mechanical assessment of crushed rocks derived from tunnelling operations. In: Cheng, W.-C., Yang, J., Wang, J. (Eds.), 5th GeoChina International Conference 2018. Springer, pp. 225–241. https://doi.org/10.1007/978-3-319-95783-8_19.

Barbieri, D.M., Lou, B., Dyke, R.J., Chen, H., Zhao, P., Memon, S.A., Hoff, I., n.d. Dataset regarding calcium bentonite and sodium bentonite as stabilizers for roads unbound. Data Brief.

Barbieri, D.M., Lou, B., Wang, F., Hoff, I., Wu, S., Li, J., Vignisdottir, H.R., Bohne, R.A., Anastasio, S., Kristensen, T., 2021c. Assessment of carbon dioxide emissions during production, construction and use stages of asphalt pavements. Transp. Res. Interdiscip. Perspect. 11 https://doi.org/10.1016/j.trip.2021.100436.

CEN, 2018. ISO 17892-12 Determination of Liquid and Plastic Limits (Belgium).

CEN, 2011. ISO 1097-1 Tests for Mechanical and Physical Properties of Aggregates. Part 1: Determination of the Resistance to Wear (Micro-deval) (Belgium).

CEN, 2010. ISO 1097-2 Tests for Mechanical and Physical Properties of Aggregates. Part 2: Methods for the Determination of Resistance to Fragmentation (Belgium).

CEN, 2004. ISO 13286-7 Cyclic Load Triaxial Test for Unbound Mixtures (Belgium).

CEN, 2003. ISO 13286-4 Test Methods for Laboratory Reference Density and Water Content - Vibrating Hammer (Belgium).

Dananaj, I., Frankovská, J., Janotka, I., 2005. The influence of smectite content on microstructure and geotechnical properties of calcium and sodium bentonites. Appl. Clay Sci. 28, 223–232. https://doi.org/10.1016/j.clay.2004.02.006.

Dias Filho, J.L.E., Santos, V.G.P., Maia, P.C.A., Xavier, G., de, C., 2015. Study of relationship between wear tests on rocks by slake durability, micro-Deval and Los Angeles abrasion tests. In: Rocca, R.J., Flores, R.D.V., Sfriso, A.O. (Eds.), Integrating Innovations of Rock Mechanics: Proceedings of the 8th South American Congress on Rock Mechanics. IOS Press, Buenos Aires, pp. 225–230.

Douglas, R.A., 2016. Low-volume Road Engineering. CRC Press, Boca Raton.

Gleason, M.H., Daniel, D.E., Eykholt, G.R., 1997. Calcium and sodium bentonite for hydraulic containment applications. J. Geotech. Geoenviron. Eng. 123, 438–445. https://doi.org/10.1061/(asce)1090-0241 (1997)123:5(438).

Gomes Correia, A., Winter, M.G., Puppala, A.J., 2016. A review of sustainable approaches in transport infrastructure geotechnics. Transp. Geotech. 7, 21–28. https://doi.org/10.1016/j.trgeo.2016.03.003.

Grim, R.E., 1953. In: Clay Mineralogy, first ed. McGraw-Hill, London.

Hewett, D.F., 1917. The origin of bentonite. J. Wash. Acad. Sci. 7, 196–198.

Hicks, R.G., Monismith, C.L., 1971. Factors influencing the resilient properties of granular materials. In: Highway Research Record, pp. 15–31.

Hoff, I., Bakløkk, L.J., Aurstad, J., 2003. Influence of laboratory compaction method on unbound granular materials. In: 6th International Symposium on Pavements Unbound.

Huang, Y.H., 2004. In: Pavement Analysis and Design, second. (Upper Saddle River).

Jones, D., 2017. Guidelines for the Selection, Specification, and Application of Chemical Dust Control and Stabilization Treatments on Unpaved Roads.

Kunz, B.K., Little, E.E., Barandino, V.L., 2021. Aquatic toxicity of chemical road dust suppressants to freshwater organisms. Arch. Environ. Contam. Toxicol. 2 https://doi.org/10.1007/s00244-020-00806-y.

Lekarp, F., Isacsson, U., Dawson, A., 2000a. State of the art. I: resilient response of unbound aggregates. J. Transport. Eng. 126, 66–75. https://doi.org/10.1061/(ASCE)0733-947X (2000)126:1(66).

Lekarp, F., Isacsson, U., Dawson, A., 2000b. State of the art. II: permanent strain response of unbound aggregates. J. Transport. Eng. 126, 76–83. https://doi.org/10.1061/(ASCE)0733-947X (2000)126:1(76).

Li, C., Ashlock, J.C., White, D.J., Vennapusa, P.K.R., 2019. Mechanistic-based comparisons of stabilised base and granular surface layers of low-volume roads. Int. J. Pavement Eng. 20, 112–124. https://doi.org/10.1080/10298436.2017.1321417.

Luckham, P.F., Rossi, S., 1999. Colloidal and rheological properties of bentonite suspensions. Adv. Colloid Interface Sci. 82, 43–92. https://doi.org/10.1016/S0001-8686(99)00005-6.

Meijer, J.R., Huijbregts, M.A.J., Schotten, K.C.G.J., Schipper, A.M., 2018. Global patterns of current and future road infrastructure. Environ. Res. Lett. 13 https://doi.org/10.1088/1748-9326/aabd42.

NPRA, 2018. Håndbok N200 Vegbygging. Vegdirektoratet, Norway.

NPRA, 2014. Håndbok N200 Vegbygging. Vegdirektoratet, Norway.

Parsakhoo, A., Hosseini, S.A., Lotfalian, M., Salarijazi, M., 2020. Effects of molasses, polyacrylamide and bentonite on dust control in forest roads. J. For. Sci. 218–225.

Petkovic, G., Engelsen, C.J., Håøya, A.O., Breedveld, G., 2004. Environmental impact from the use of recycled materials in road construction: method for decision-making

in Norway. Resour. Conserv. Recycl. 42, 249–264. https://doi.org/10.1016/j.resconrec.2004.04.004.
Plati, C., 2019. Sustainability factors in pavement materials, design, and preservation strategies: a literature review. Construct. Build. Mater. 211, 539–555. https://doi.org/10.1016/j.conbuildmat.2019.03.242.
Praticò, F., Saride, S., Puppala, A., 2011. Comprehensive life-cycle cost analysis for selection of stabilization alternatives for better performance of low-volume roads. Transport. Res. Rec. 120–129. https://doi.org/10.3141/2204-16.
Pusch, R., 2015. In: Bentonite Clay: Environmental Properties and Applications, first ed. CRC Press, Boca Raton.
Spagnoli, G., Sridharan, A., Oreste, P., Bellato, D., Di Matteo, L., 2018. Statistical variability of the correlation plasticity index versus liquid limit for smectite and kaolinite. Appl. Clay Sci. 156, 152–159. https://doi.org/10.1016/j.clay.2018.02.001.
Spaulding, C., Masse, F., LaBrozzi, J., 2008. Ground improvement technologies for a sustainable world. Civ. Eng. Mag. 78, 54–59. https://doi.org/10.1061/ciegag.0000168.
Sun, W., Wang, L., Wang, Y., 2017. Mechanical properties of rock materials with related to mineralogical characteristics and grain size through experimental investigation: a comprehensive review. Front. Struct. Civ. Eng. 11, 322–328. https://doi.org/10.1007/s11709-017-0387-9.
Tan, E.H., Zahran, E.M.M., Tan, S.J., 2020. A review of chemical stabilisation in road construction. IOP Conf. Ser. Mater. Sci. Eng. 943 https://doi.org/10.1088/1757-899X/943/1/012005.
Tingle, J.S., Newman, J.K., Larson, S.L., Weiss, C.A., Rushing, J.F., 2007. Stabilization mechanisms of nontraditional additives. Transport. Res. Rec. 2, 59–67. https://doi.org/10.3141/1989-49.
Uzan, J., 1985. Characterization of granular material. Transport. Res. Rec. 52–59.
Van Der Merwe Steyn, W.J., Visser, A.T., 2011. Evaluation of sustainability of low-volume roads treated with nontraditional stabilizers. Transport. Res. Rec. 186–193. https://doi.org/10.3141/2204-24.
Werkmeister, S., Dawson, A., Wellner, F., 2005. Permanent deformation behavior of granular materials and the shakedown concept. Transport. Res. Rec. 1757, 75–81. https://doi.org/10.3141/1757-09.
Zhang, T., Yang, Y.L., Liu, S.Y., 2020. Application of biomass by-product lignin stabilized soils as sustainable geomaterials: a review. Sci. Total Environ. 728 https://doi.org/10.1016/j.scitotenv.2020.138830.