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1 Comparative study of Stabilization/Solidification of dredged sediments with Ordinary
2 Portland cement and Calcium Sulfo-Aluminate cement in the framework of
3 valorization in road construction material

4

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23 **Abstract**

24 Stabilization/solidification (S/S) of dredged sediments is an environmentally friendly,
25 low-cost and time-efficient way to manage this waste (according to the European
26 waste classification) in the context of valorization as novel resources. In this study,
27 the main objective was to evaluate the efficiency of using a novel and green binder
28 Calcium Sulfo-Aluminate (CSA) cement to solidified Dunkirk sediments. For
29 comparison, the Ordinary Portland Cement (OPC) binder was used as a reference. For
30 this purpose, several tests were performed on samples containing various types and
31 amounts of binders. The experimental program included: modified Proctor
32 compaction test, immediate Californian Bearing Ratio (I-CBR) index test, unconfined
33 compressive strength test, splitting tensile strength test, measurements of elastic and
34 secant modulus, and mineral and micropore structure analysis. It is realistic to
35 conclude that the compaction performance of the CSA-/OPC-solidified sediments is
36 significantly improved. The mechanical performance of compressive, tensile strength
37 and elastic modulus increases with binder content and curing time. The simple model
38 obtained to relate the compressive and tensile strength with elastic modulus allow
39 predicting easily, for a given suitable set of characteristics, the type or the amount of
40 binder needed. This model allows optimizing the amount of binder to reach a given
41 properties of solidified sediments and hence improves the cost of developed material.
42 The results also demonstrate the ability of solidified sediment to be valorized in road
43 construction.

44 **Keywords:** Sediments; Valorization; Ordinary Portland Cement; Calcium

45 Sulfo-Aluminate cement; Mechanical strength; Road material

46 **1. Introduction**

47 To prevent flood risks and ensure a sufficient draft for navigation, regular sediment
48 dredging is carried out every year. However, the dredging process produce a large
49 amount of sediments. In Europe, the annual volume of dredged sediments is estimated
50 at 300 million tons [1]. Fine dredged sediments is regarded as waste with high
51 moisture content, complex components (as contaminants), high organic matter content,
52 high compressibility and low mechanical strength [2], [3], [4], [5]. Conventional
53 management of sediments as ocean dumping, land deposit, and blow-filled piling, are
54 not sustainable and environmentally friendly as it can cause serious secondary
55 pollution [6], [7]. Therefore, try to find an alternative method for sediments
56 management is the core of current research.

57 The valorization of sediments in road construction by stabilization/solidification (S/S)
58 method has received considerable interest in recent years [8], [9], [10], [11], [12].
59 Stabilization/Solidification (S/S) is considered as an environmentally friendly,
60 low-cost and time-efficient way for the treatment of sediments. It can significantly
61 relieve environmental impacts and improve the mechanical properties of sediments
62 [13]. The reuse of S/S treated sediments in the field of construction can be considered
63 as a promising method not only to solve problems related to sediment management
64 but also to provide a new source of construction materials [14], [15]. The traditional
65 binder used for S/S is Ordinary Portland Cement (OPC), and the justification has been
66 proved by efficiency shown over time, low cost, availability and reliability [16], [17].

67 However, the manufacturing process of OPC has significant environmental issues, i.e.,
68 high consumption of energy (5000 MJ/t cement), non-renewable resources (1.5 t
69 limestone and clay/t cement) and high CO₂ emissions (0.95 t CO₂/t cement). OPC
70 manufacturing acts as a significant contributor to anthropogenic CO₂ emission (5-7 %)
71 [18], [19]. Due to the increasing demand for construction, the share of CO₂ emissions
72 attributed to the cement production is predicted to increase from 16 % to 24 % by
73 2050, demonstrating the urgent need to improve its sustainability [20]. Therefore,
74 several research works are undertaken to propose alternative cementitious material
75 with low energy consumption, less pollution or no pollution and excellent durability,
76 such as reactive MgO [21], magnesia–industrial by products [22], [23], [24],
77 Si-modified MgO cement [16], industrial by products–cement [17], calcined dredging
78 sediments–cement [25], basalt fiber–cement [26] uncontaminated sediments–cement
79 [27] and others.

80 The continuous push toward the development of a sustainable cementitious binder has
81 resulted in increased research activity on Calcium Sulfo-Aluminate (CSA) cement in
82 the last few decades. CSA cement is produced by the calcination of gypsum, bauxite,
83 and limestone at ~1250 °C, which is 200 °C lower than the temperature used for
84 Portland cement clinker (~1450 °C) [28]. Moreover, the lower limestone demand (35 %
85 - 40 %) for the manufacture of CSA cement reduces its carbon footprint. The
86 production of 1 t of OPC clinker releases a maximum of 0.95 t of CO₂, whereas the
87 production of 1 t of CSA clinker leads to reduce by one third the CO₂ emissions [29],
88 [30]. The main hydraulic phase of CSA is ye'elite (C₄A₃S), and the secondary

89 phases included belite (C_2S), calcium sulfate, and gehlenite (C_2AS), etc. The
90 hydration of ye'elimite is used to gain early age strength, and the hydration of belite
91 could improve long-term strength [31], [32]. CSA cement exhibits many interesting
92 properties such as short setting time, high early strength, impermeability, sulfate, and
93 chloride corrosion resistance, and low alkalinity [32], [33], [34], [35]. Hence, CSA
94 cement has demonstrated considerable potential in the S/S of hazardous materials,
95 such as low-level radioactive waste, heavy metals waste, sewage sludge, bottom ash,
96 and galvanic sludge [36], [37], [39], [40], [41]. Besides, a few studies use CSA
97 cement in geotechnical applications, especially in ground improvement. For example,
98 it is proved that CSA-treated sand has significantly high initial strength, which
99 powerfully indicates that the use of CSA in geotechnical applications may lead to the
100 reduced construction period and carbon footprint [42], [43], [44], [45]. In fact, to the
101 best of our knowledge, there remain scientific questions as to reused sediments with
102 CSA cement, no research thus far on the use of CSA cement with sediments in road
103 construction. Therefore, this study evaluates the effectiveness of CSA cement on the
104 marine sediment from Dunkirk Port (France) for potential use as road material.

105 In this context, the main objectives of the present research work are: (i) to assess the
106 Proctor compaction properties and immediate Californian Bearing Ratio (I-CBR)
107 index of solidified sediments with the addition of CSA cement; (ii) to validate the
108 efficacy of CSA cement in enhancing the properties (e.g., compressive strength,
109 tensile resistance, and elastic modulus) of solidified sediment and (iii) to demonstrate
110 its ability in comparison to OPC treatment. The results of this paper will contribute to

111 an investigation on the feasibility of using an eco-friendly CSA binder and dredged
112 marine sediments as road material products without complex treatment.

113

114 **2. Experimental materials and methods**

115 **2.1. Raw Materials**

116 The sediments (SD) were dredged from Dunkirk Harbour in the north of France. The
117 basic physical characteristics of sediments are measured according to the standard
118 used in France and/or Europe.

119 - The initial water content is measured according to test standard NF P 94-050
120 [46].

121 - The true density is measured using a helium pycnometer (NF EN ISO 17892-3)
122 [47].

123 - The organic matter is measured by the ignition method at 450 °C (XP P94-047)
124 [48].

125 - The liquid limit and plastic limit, defined by the percussion-cup method and
126 the rolling thread method is measured according to test standard EN ISO
127 17892-12 [49].

128 - The particle size distribution is measured according to test standard EN ISO
129 13320 [50].

130 In terms of binders, Ordinary Portland cement (OPC) with CEM I 52.5 R from
131 LafargeHolcim Saint-Pierre-La-Cour company and calcium sulfoaluminate cement
132 (CSA) from Vicat company were used in this study. The chemical compositions of all

133 these materials were determined by X-ray fluorescence (XRF) analysis with a
134 BRUCKER AXS D8 ADVANCE using cobalt and $k\alpha$ radiation ($k\alpha=1.78 \text{ \AA}$), the
135 results are listed below.

136 **2.2. Methods**

137 In the current study, the mix proportions of different samples are shown in Table 1,
138 which was designed with reference to our previous research [8], [9], [23]. It should be
139 noted that the content of OPC and CSA was determined in percentage by mass of dry
140 sediments. Tap water was used as mixing water.

141 The modified Proctor compaction tests and immediate Californian Bearing Ratio
142 (I-CBR) index tests were carried out according to NF EN 13286-2 [51] and NF EN
143 13286-47 [52], to determine the feasibility of the solidified sediments to be used as a
144 filling material in the road. The test carries out in a Proctor mould with a diameter of
145 150 mm and a height of 120 mm, and the sediment was filled up in five equal layers
146 and 25 strokes were applied to each layer with a 4.5 kg hammer by performing falls
147 from a height of 457 mm. Then test the water content and I-CBR index, in order to
148 determine the maximum dry unit weight, optimum water content and I-CBR index
149 values of the solidified sediments.

150 The unconfined compressive strength was measured by using the INSTRON testing
151 machine according to NF EN 13286-41 [53], as shown in Fig. 1 (a). The cylindrical
152 specimens were prepared by static compression at their respective maximum dry
153 density and optimum water content, according to NF EN 13286-53 [54]. Firstly, the
154 dry sediments and cement were mixed in an electric mixer for 5 min. Then the tap

155 water was added and mixing is performed for another 5 min. Afterwards, the mixtures
156 were transferred into the cylindrical mould with a diameter of 50 mm and a length of
157 100 mm. By using axial compression, the mixtures is compacted to reach the desired
158 height. The compacted specimen was demolded and stored in covered plastic boxes
159 for preventing the moisture losses. The curing is made in a curing room at 20 ± 1 °C
160 for 3 d, 7 d, and 28 d. A group of three same cylindrical specimens was prepared for
161 each mixes, and the results discussed later were the average values measured on three
162 specimens. The unconfined compressive strength is given by the equation (1).

163 The elastic modulus is determined in an unconfined compression test in accordance
164 with NF EN 13286-43 [55], which using the secant slope at 30% of peak compressive
165 strength. Firstly, the maximum compression strength of the specimen is measured (for
166 a given mix). Then the elastic modulus is measured on another sample. As shown in
167 Fig. 1 (b), to measure the elastic modulus, an extensometer with three displacement
168 sensors were used. During the elastic modulus measurement, the compressive
169 maximum effort applied corresponds to 30% of the maximum compression strength.

170 The elastic modulus is determined according to equation (2).

171 The indirect tensile strength test was chosen so as to obtain the splitting tensile
172 strength, which determined in accordance with NF EN 13286-42 [56]. For the indirect
173 tensile test, the same specimens (ϕ 50 mm \times h 100 mm) as those in the unconfined
174 compressive strength test were used. The specimen was placed horizontally between
175 two-plywood band, and a compressive force applied perpendicularly to the axis of
176 symmetry of the cylinder specimen, as shown in Fig. 1 (c)-(d). The splitting tensile

177 strength is calculated by the following equation (3).

$$178 \quad q_c = \frac{4F_c}{\pi D^2} \quad (1)$$

$$179 \quad E = \frac{1.2F_c}{\varepsilon_E \pi D^2} \quad (2)$$

$$180 \quad q_{it} = \frac{2F_{it}}{\pi HD} \quad (3)$$

181 where q_c is the unconfined compressive strength; q_{it} is the splitting tensile strength;

182 F_c is the maximum force of compressive test; F_{it} is the maximum force of tensile test;

183 H and D are the length and diameter of the specimens; ε_E is the longitudinal strain of

184 the specimen, when $F = 0.3 F_c$.

185 The crystallographic composition and microstructural properties of typical samples

186 were investigated by X-ray diffraction (XRD) and mercury intrusion porosimetry

187 (MIP) tests. Fragments taken from the broken samples after compressive strength tests

188 were dried at 40 °C for at least 48 h. The XRD analysis was determined by the

189 BRUCKER AXS D8 ADVANCE X-ray diffractometer with a Co K α radiation source.

190 The micropore structure analysis was defined by the MIP tests with a Micromeritics

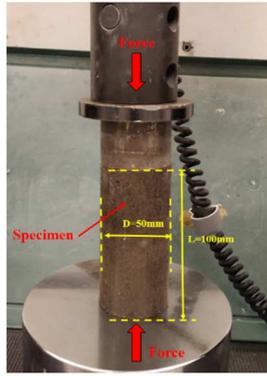
191 Autopore V porosimeter.

192

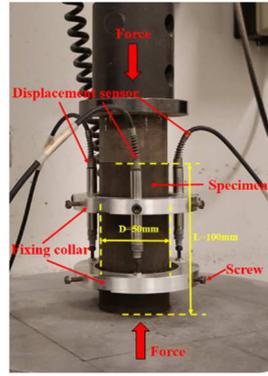
193 **Table 1** Mix proportions of different samples.

Samples	OPC (%)	CSA (%)	SD (%)	Curing time (d)
SD	0	0	100	3, 7, 28
SD2OPC	2	-	98	3, 7, 28
SD4OPC	4	-	96	3, 7, 28
SD6OPC	6	-	94	3, 7, 28
SD2CSA	-	2	98	3, 7, 28
SD4CSA	-	4	96	3, 7, 28
SD6CSA	-	6	94	3, 7, 28

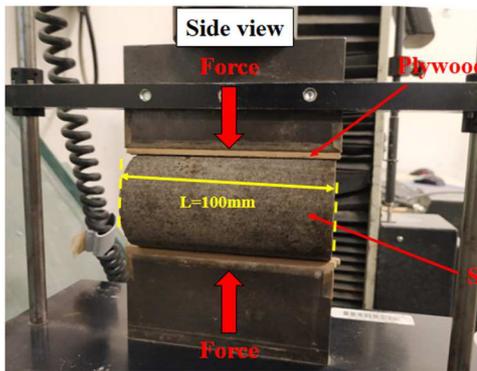
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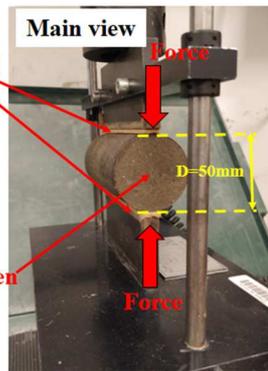
(a)



(b)



(c)



(d)

Fig. 1 A view of the (a) unconfined compressive strength and (b) elastic modulus test; (c) The side view and (d) the main view of indirect tensile strength test.

3. Results and discussion

3.1. Physical and chemical characteristics

The basic physical characteristics of sediments are shown in Table 2. The initial water content measured is about 5.20 %. It is worth to note that this value is related to the water content of the sediments after 3 months of natural drying. After dredging this later value can exceed 100 %. The true density, measured using a helium pycnometer is about 2.58 g/cm³. The organic matter measured by the ignition method is about 7.67 %. The low value of the true density could be explained by the high amount of

210 organic matter content measured. The liquid limit and plastic limit, defined by the
 211 percussion-cup method and the rolling thread method are respectively 39.5 % and
 212 28.0 %. The test results induce a plasticity index of 11.5 %. This result is typical of
 213 previous studies on sediments dredged in the north part of France. The results for the
 214 particle size distribution show that the sediments are composed of 6.97 % clay, 39.48 %
 215 silt and 53.55 % sand. The low proportion of clays particle combined with the high
 216 amount of organics matter content could explain the obtained value of liquid limit and
 217 plastic limit.

218 For Ordinary Portland Cement (OPC), Calcium Sulfo-Aluminate cement (CSA) and
 219 sediments used in this study, the chemical compositions are listed in Table 3.

220 **Table 2** Basic physical characteristics of sediments.

Parameter	Value	Test standard
Initial water content (%)	5.20	NF P 94-050
Density (g/cm ³)	2.58	NF EN ISO 17892-3
Organic contents (%)	7.67	XP P94-047
Atterberg limit tests		EN ISO 17892-12
Liquid limit (%)	39.5	
Plastic limit (%)	28.0	
Plasticity index (%)	11.5	
Particle size distribution		EN ISO 13320
Clay fraction (% < 2 μm)	6.97	
Silt fraction (2 μm < % < 63 μm)	39.48	
Sand fraction (% > 63 μm)	53.55	

221

222 **Table 3** Chemical composition of the materials. (wt %)

Components	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	TiO ₂	Fe ₂ O ₃
SD	1.5	5.4	51.4	traces	1.2	12.1	0.3	4.9
OPC	1.0	4.8	19.9	3.3	1.0	64.1	0.3	2.6
CSA	1.1	17.4	8.5	13.7	0.3	40.5	0.9	7.3

223

224 **3.2. Compaction properties and I-CBR Index**

225 The effects of CSA and OPC binders on the compaction curves under the modified
226 Proctor compaction test are shown in Fig. 2. The saturation degree curves for $S_r = 80\%$
227 and $S_r = 100\%$ are also presented in Fig. 2.

228 According to European standard NF EN 13286-2 [51], we can easily get the values of
229 maximum dry density and optimum moisture from the Proctor curve, which
230 corresponding to the coordinate of maximum position on the Proctor curve. It can be
231 seen from Fig. 2 that for the raw sediments, the maximum dry density is 1.641 g/cm^3 ,
232 and the corresponding optimum moisture content is 21.8% . For solidified sediments
233 with OPC, the maximum dry density is highly reduced after 2% addition of OPC
234 whereas for 4% and 6% addition the changes of dry density are less important
235 (decrease of maximum dry density from 1.578 g/cm^3 to 1.574 g/cm^3). At the same
236 time with the decrease in the maximum dry density, the optimal moisture content
237 increases in the same way. For solidified sediments with CSA, as for OPC addition,
238 the maximum dry density is highly reduced after 2% addition of CSA and at the same
239 time, the optimal moisture content is increased. However, with an addition of 4% and
240 6% of CSA in the mixture, the maximum dry density seems to increase again and the
241 optimal water content decreases (an increase of maximum dry density from 1.575
242 g/cm^3 to 1.615 g/cm^3 and a decrease of optimal moisture content from 23.5% to
243 20.2%). These results are well highlighted in Fig. 4 (a)-(c).

244 Fig. 3 shows the I-CBR index curves of the raw sediments and OPC/CSA-solidified
245 sediments. The measured I-CBR index values at the optimal moisture contents for all

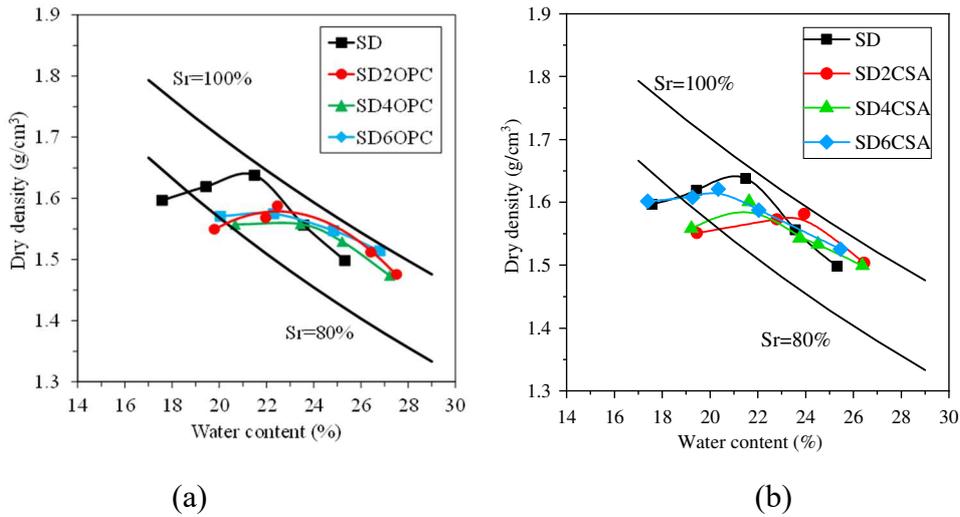
246 the mixtures are shown in Fig. 4 (c). The I-CBR index value of raw sediments is about
247 15 % at the optimum moisture content. This value is lower than that for a sub-layer
248 material ($I\text{-CBR} \geq 25 \%$) according to the specifications in French standards [57]. The
249 addition of CSA to dredged sediments leads to an increase linearly of the I-CBR index
250 with the increase in the CSA content. After the addition of 2 % of CSA, the I-CBR
251 index value reach 20 % at the optimum moisture content and then increases to 30 %
252 and 40 % as the CSA content increases to 4 % and 6 %. From this result, it could be
253 reasonable to predict that the treatment of sediments by 3 % of CSA could be
254 sufficient to reach an I-CBR index value of 25 % with is the due value to be used in
255 sub-layer material ($I\text{-CBR} \geq 25 \%$). To be used in the foundation layer ($I\text{-CBR} \geq$
256 35 %), treatment with 5 % CSA could be a reasonable value according to the
257 specifications in French standards [57].

258 For the OPC-solidified sediments, its I-CBR index values increase from 30 % to 45 %
259 with the increase of the OPC content from 2 % to 6 %. From this result, it could be
260 also reasonable to predict that the I-CBR index value of treated sediments with 1.5 %
261 OPC could be sufficient to reach 25 %, which is the due value to be used in sub-layer
262 material ($I\text{-CBR} \geq 25 \%$). To be used in the foundation layer ($I\text{-CBR} \geq 35 \%$),
263 treatment with 4 % OPC could be a reasonable content.

264 It appears from these results that some of the solidified sediment specimens (include
265 SD2OPC, SD4OPC, SD6OPC, SD4CSA and SD6CSA) present adequate properties
266 for use as road material. However, the results of modified Proctor and I-CBR index
267 tests reflect the behavior of solidified sediment in a short time (curing for less than 1

268 hour). To examine the mechanical behavior of solidified sediment in the long term
 269 (curing for several days or even longer periods), it is necessary to measure the
 270 mechanical characteristics in terms of compressive strength and/or tensile strength
 271 and elastic modulus at long terms.

272

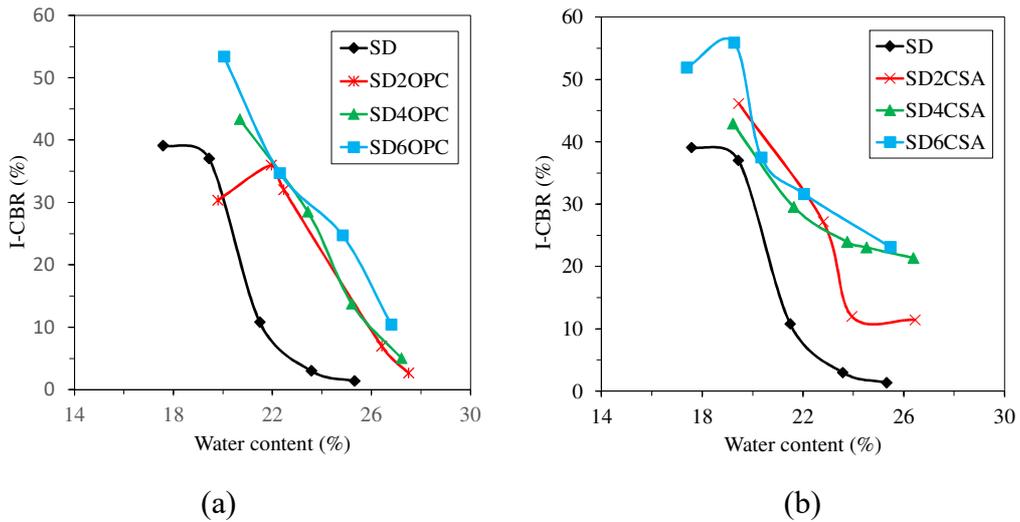


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274

275 **Fig. 2.** Compaction curves of solidified sediments with (a) OPC; (b) CSA.

276

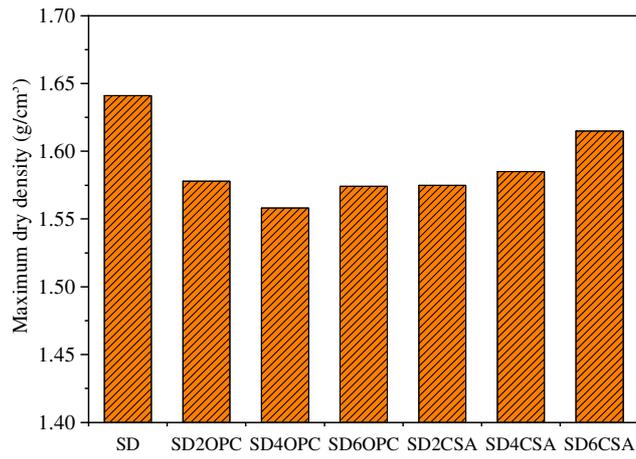


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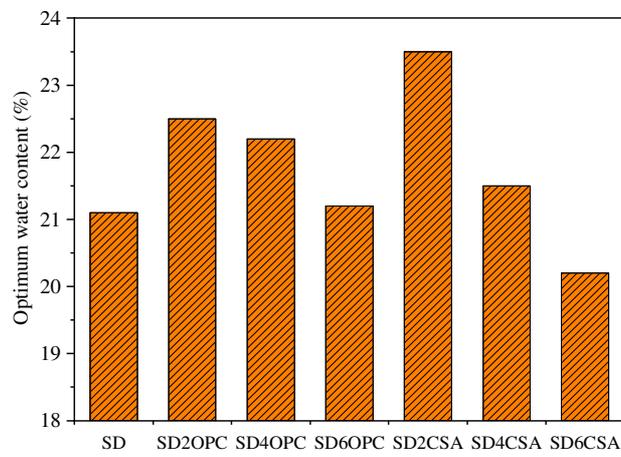
278

279 **Fig. 3.** I-CBR index curves of solidified sediments with (a) OPC; (b) CSA.

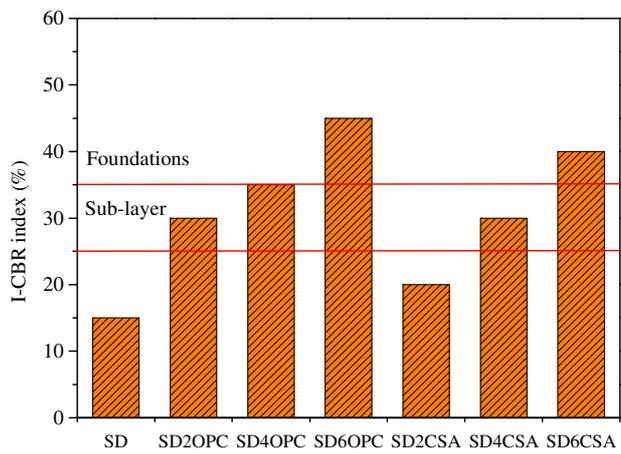
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(a)



(b)



(c)

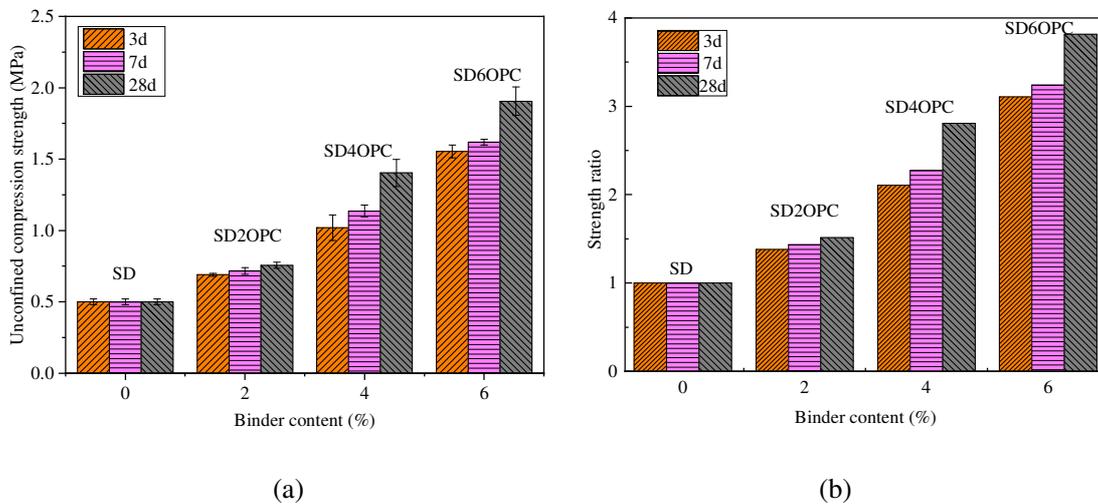
Fig. 4. (a) Maximum dry density; (b) Optimal moisture content; (c) I-CBR index of different samples.

290 **3.3. Unconfined compressive strength**

291 Fig. 5 shows the variation of unconfined compressive strength (q_c) and unconfined
 292 compressive strength ratio (η_c , defined as the ration of unconfined compressive
 293 strength of solidified sediments q_{cn} to the unconfined compressive strength of raw
 294 sediments q_{c0} as in equation (4)) with the amount of treatment with OPC.

295
$$\eta_c = \frac{q_{cn}}{q_{c0}} \quad (4)$$

296 For instance, under the condition of 28 d curing, the raw sediments (SD) display the
 297 lowest q_c value (0.50 MPa), and the q_c of solidified sediments with 2 %, 4 % and 6 %
 298 OPC inclusion increases to 0.76 MPa (SD2OPC), 1.40 MPa (SD4OPC) and 1.91 MPa
 299 (SD6OPC). Meanwhile, the η_c correspondingly increases to 1.52 (SD2OPC), 2.80
 300 (SD4OPC) and 3.82 (SD6OPC) as compared with that of SD (1.00). In addition,
 301 under the condition of the 4 % OPC content, the q_c of solidified sediments (SD4OPC)
 302 is respectively 1.05 MPa, 1.14 MPa and 1.40 MPa at 3 d, 7 d and 28 d, while the
 303 corresponding η_c changes from 2.10 to 2.28 and 2.80. This experimental result is
 304 consistent with the previous study performed [9], [11].



305

306

307 **Fig. 5.** (a) Unconfined compressive strength and (b) strength ratio of solidified

308 sediments with OPC.

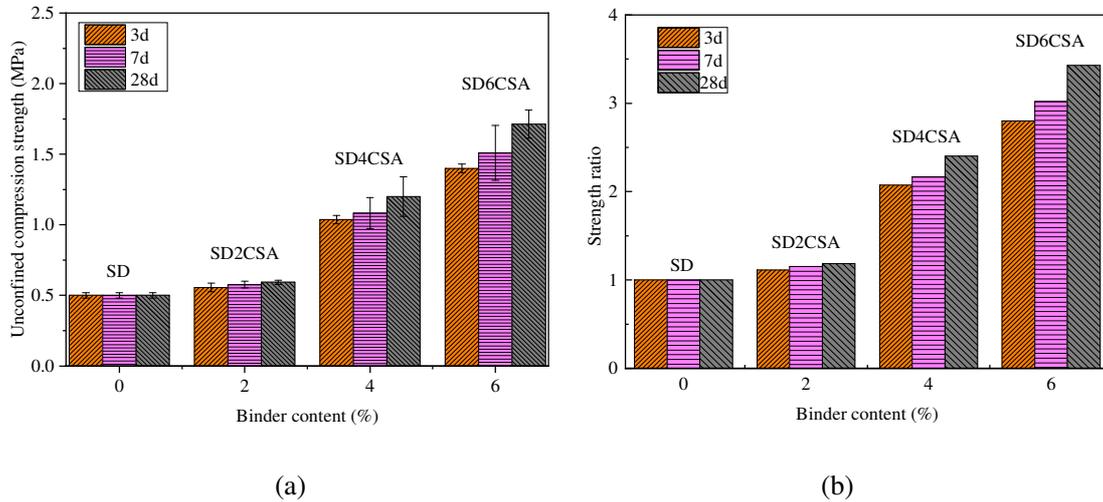
309

310 For CSA-solidified sediments specimens, the q_c and η_c are reported in Fig. 6. It is
311 similar to OPC-solidified sediments specimens, both CSA content and curing time
312 lead to possibly changing trend of the q_c and η_c . After the same curing time of 28 d,
313 the q_c of CSA-solidified sediments specimens increases from 0.50 MPa (SD) to 0.59
314 MPa (SD2CSA), 1.20 MPa (SD4CSA) and 1.71 MPa (SD6CSA) with the increase of
315 CSA content from 0 % to 6 %, the η_c correspondingly increases from 1.00 (SD) to
316 1.18 (SD2OPC), 2.40 (SD4OPC) and 3.42 (SD6OPC). Under the condition of 4 %
317 CSA inclusion, the q_c of SD4CSA specimens is 1.04 MPa (3 d), 1.08 MPa (7 d) and
318 1.20 MPa (28 d) with the curing time changes from 3 d to 28 d, while the
319 corresponding η_c is 2.07 (3 d), 2.17 (7 d) and 2.40 (28 d), respectively.

320 However, for solidification of sediments as road material, comparing the effects of
321 OPC and CSA treatment under the same condition (binder content and curing time), it
322 can be seen that the CSA performs a little worse than OPC from the point of view of
323 engineering performance capacity. The CSA did not show its high early strength
324 property for solidification of sediments in this study. This may be due to the organic
325 matter and/or metallic pollution in the sediment, which could influence the hydration
326 reaction of CSA [58]. Even the type of CSA cement may decide its different strength
327 performance [44]. Indeed, the compressive strength of solidified sediments with CSA
328 still can be reached to 78.41 - 98.42 % that of using OPC in this study. Thus,
329 considering the main advantages of CSA - green, low carbon, environmentally

330 friendly, and energy saving, we still consider CSA as an effective alternative for
 331 solidification of sediments to replace traditional binder OPC.

332



333

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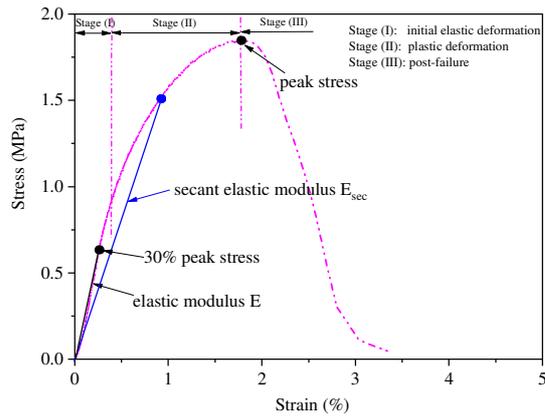
335 **Fig. 6.** (a) Unconfined compressive strength and (b) strength ratio of solidified
 336 sediments with CSA.

337

338 3.4. Elastic modulus and secant modulus

339 Elastic modulus is an important characteristic to evaluate the ability of solidified
 340 sediments to resist deformation. As illustrated in Fig. 7, a typical stress-strain curve
 341 showing how to determine elastic modulus. It is evident that this typical stress-strain
 342 curve can be divided into three stages: (I): initial elastic deformation stage; (II):
 343 plastic deformation stage; (III): post-failure stage. The elastic modulus (E) can be
 344 obtained from the linear portion (stage I) of the stress-strain curves at 30% of peak
 345 stress [55]. Each result consisted of three measurements.

346



347

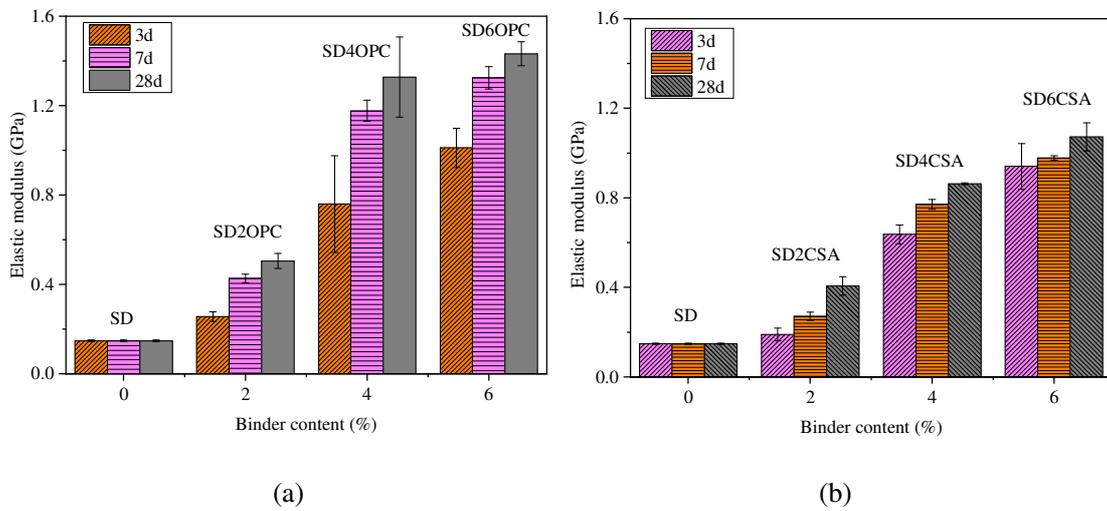
348 **Fig. 7.** A determined example of elastic modulus and secant modulus in a typical
 349 stress-strain curve.

350

351 The variations of elastic modulus E and their error bars of solidified sediments with
 352 different binder contents and curing time are plotted in Fig. 8. The results presented
 353 indicate that the variation in the elastic modulus has an upward trend as the increase
 354 of binder content and the curing time. After 28 d of curing, the elastic modulus of
 355 OPC-solidified sediments increases by 2.33 times (0.50 GPa), 7.87 times (1.33 GPa)
 356 and 8.53 times (1.43 GPa) as compared with raw sediment (0.15 GPa), with
 357 increasing OPC content from 2 % to 6 %. Additionally, the SD4OPC specimen has a
 358 higher E values after 7 d and 28 d curing than that at 3 d curing time, E changed from
 359 0.76 GPa (3 d) to 1.18 GPa (7 d) and 1.33 GPa (28 d). A similar conclusion can be
 360 observed for CSA-solidified sediment specimens, and both CSA content and curing
 361 time had a great influence on the elastic modulus. Higher CSA content and longer
 362 curing time benefit for the developing of elastic modulus, such as the specimens cured
 363 28 d, they achieved the higher E values of 0.41 GPa (SD2CSA), 0.86 GPa (SD4CSA)
 364 and 1.07 GPa (SD6CSA) when the CSA contents were 2 %, 4 % and 6 %, respectively,

365 while the E values was only 0.15 GPa for SD. Besides, with the curing time increase
 366 from 3 d to 28 d, the E values of CSA-solidified sediment samples were increases
 367 significantly, the E values of SD4CSA still as high as 0.64 GPa (3 d), 0.77 GPa (7 d)
 368 and 0.86 GPa (28 d). Achour et al. [59] also reported similar conclusions, elastic
 369 modulus increases with the increase of binder content and curing time.

370



371

372

373 **Fig. 8.** Elastic modulus of solidified sediments with (a) OPC; (b) CSA.

374

375 As showed in Fig. 7, the secant modulus (E_{sec}) was determined from the slope of the
 376 lines, which were drawn from the starting point, up to every point of the stress-strain
 377 curves [60], [61]. Fig. 9 (a)-(b) shows the secant modulus E_{sec} -strain curves of OPC
 378 and CSA-solidified sediments after 28 d cured, respectively. The E_{sec} -strain curves of
 379 SD4OPC and SD4CSA at 3 d, 7 d and 28 d are shown in Fig. 9 (c)-(d). From the
 380 obtained results, the dominant trend observed of all specimens goes through three
 381 stages, which corresponding to the three stages of the stress-strain curves.

382 (i) Stage I, which corresponding to the initial elastic deformation stage of stress-strain

383 curves, E_{sec} increases a little at low strains in this stage. It is worth to note that E_{sec}
384 should be constant in this stage due to the stress increases linearly with the strain in
385 the initial elastic deformation stage, theoretically. However, because of the contact
386 between specimen and press machine is incomplete at the initial stage, resulting in the
387 stress increases approximately linear with the strain in the experiment, this is the
388 reason that E_{sec} increases a little at low strains in this stage.

389 (ii) Stage II, E_{sec} decreases by the increases of axial strain until the point that
390 corresponding to the peak stress point of stress-strain curves, therefore, it was
391 considered corresponding to the plastic deformation stage of stress-strain curves.

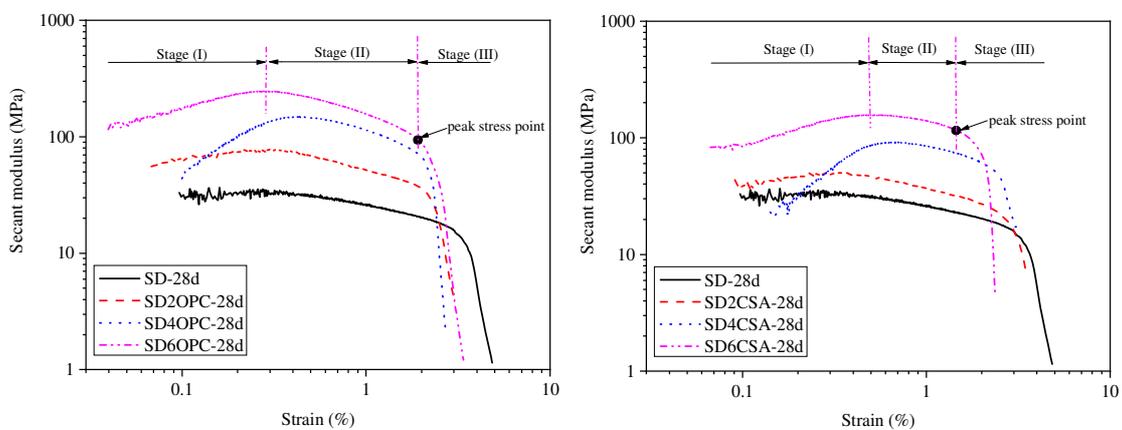
392 (iii) Stage III, which means the post-failure stage of stress-strain curves, E_{sec} sudden
393 decrease significantly with increases of the strain.

394 However, E_{sec} becomes larger for solidified sediments with binder than raw sediments,
395 the higher the binder amount and curing time, the higher the E_{sec} at the same strain.
396 The reason for this event can be explained as the hydration reaction of binder, as the
397 reaction goes on with more binder amount and curing time, the systems produced a
398 large number of hydration products, include the sample particles interact with each
399 other, increase the E_{sec} .

400 It should be noted that the values of elastic modulus and secant modulus differ by an
401 order of magnitude (GPa and MPa). This is because the axial deformation data of the
402 elastic modulus tests comes from three displacement sensors, which were stuck on to
403 the specimens to record the true axial deformation of the specimens. However, the
404 axial deformation data used for the calculation of the secant modulus tests comes

405 from the press machine; the measured axial deformation of the top and bottom
 406 surfaces is greater than the actual axial deformation of the specimen, lead to measured
 407 secant modulus much smaller than the true elastic modulus of the specimen. This is
 408 also why European standard NF EN 13286-43 [55] recommends this method to
 409 measure the true elastic modulus of the specimen.

410

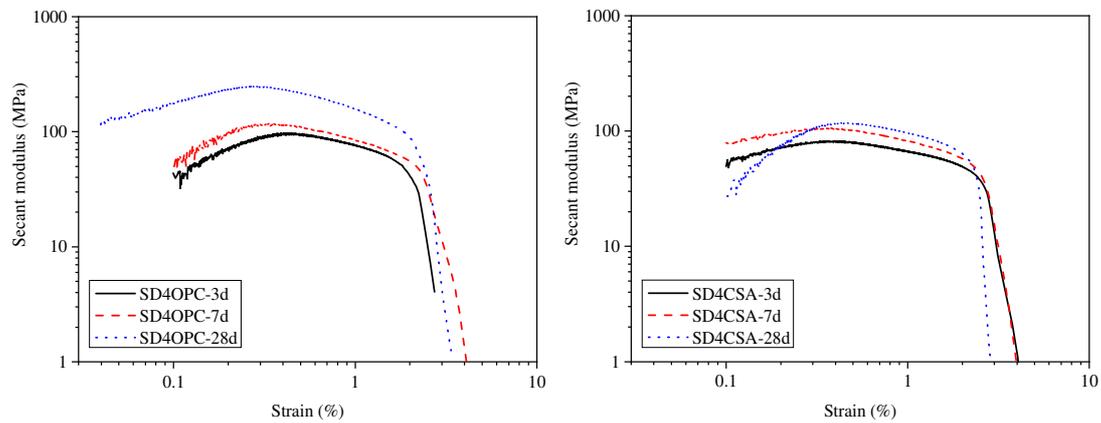


411

(a)

(b)

412



413

(c)

(d)

414

415 **Fig. 9.** Secant modulus curves of solidified sediments (a) Sediments with OPC cured
 416 28 d; (b) Sediments with CSA cured 28 d; (c) SD4OPC cured for 3 d, 7 d, and 28 d; (d)
 417 SD4CSA cured for 3 d, 7 d, and 28 d.

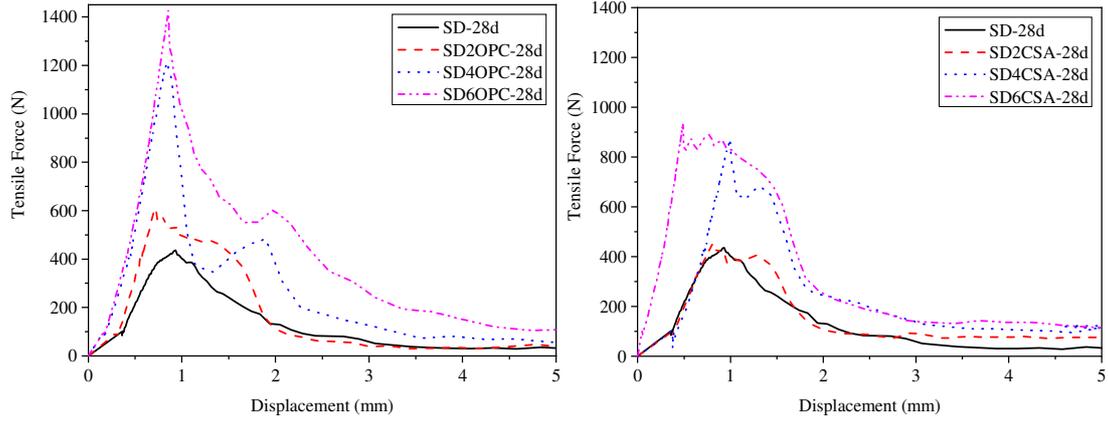
418

419 **3.5. Splitting tensile strength**

420 Fig. 10 summarizes the effect of binder content and curing time in terms of the
421 splitting tensile force-displacement behavior of solidified sediments. In general, the
422 results reveal some common features: all the curves indicate a brittle behavior, no
423 matter of raw sediment or solidified sediments; the force increases immediately with
424 increasing displacement until reaching the peak splitting tensile force value, then
425 reduce immediately followed by an increase of the displacement.

426 Indeed the peak tensile force and stiffness increase significantly with the increase of
427 binder content and curing time. For 28 d curing specimens, the peak tensile force of
428 SD is 436.54 N, the peak tensile force of solidified sediments increase to 610.41 N
429 (SD2OPC), 1214.26 N (SD4OPC) and 1427.41 N (SD6OPC), due to the addition of
430 2 %, 4 % and 6 % OPC binder. Moreover, the addition of 2 %, 4 % and 6 % CSA
431 binder to the sediments increases the peak tensile force to 453.01 N (SD2CSA),
432 869.69 N (SD4CSA) and 934.21 N (SD6CSA) in relation to the raw sediments after
433 28 d curing. For SD4OPC (Fig. 10c) and SD4CSA (Fig. 10d), it seems that the peak
434 tensile force increase significantly with curing time increase from 3 d to 28 d. The
435 peak tensile force increases to 482.39 N (3 d), 558.00 N (7 d) and 1200.82 N (28 d)
436 for SD4OPC and to 651.08 N (3 d), 786.05 N (7 d) and 914.69 N (28 d) for SD4CSA.

437

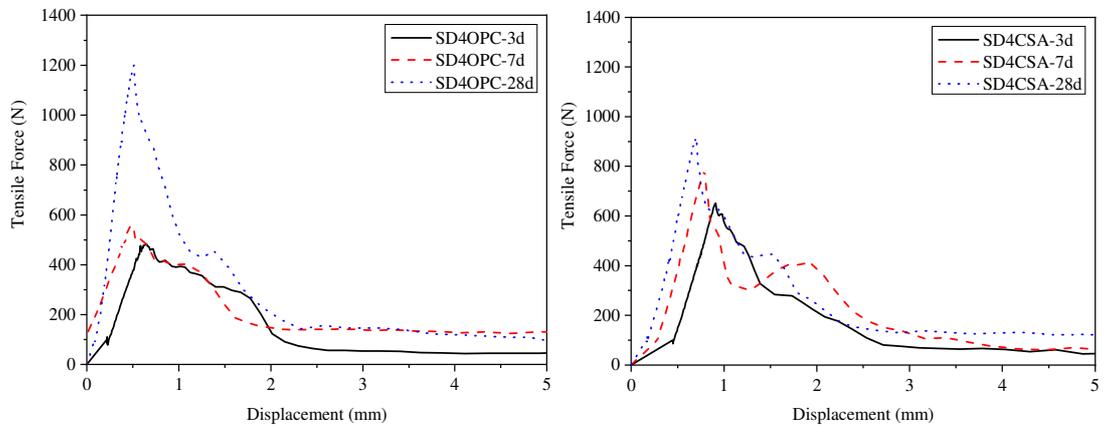


438

439

(a)

(b)



440

441

(c)

(d)

442 **Fig. 10.** Splitting tensile force-displacement curves of solidified sediments (a)

443 Sediments with OPC cured 28 d; (b) Sediments with CSA cured 28 d; (c) SD4OPC

444 cured for 3 d, 7 d, and 28 d; (d) SD4CSA cured for 3 d, 7 d, and 28 d.

445

446 Fig. 11 shows the variation of the splitting tensile strength (q_{it}) and the tensile

447 strength ratio (η_{it} , defined as the ratio splitting tensile strength of solidified sediment

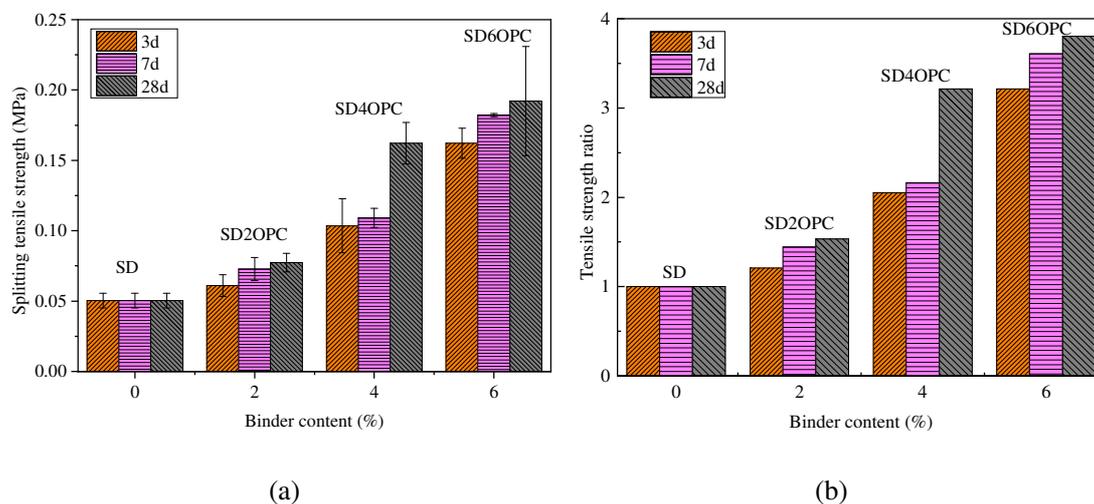
448 q_{itm} to the splitting tensile strength of raw sediment q_{it0} as shown on Equation (5)) with

449 the amount of binder treatment and curing time.

450
$$\eta_{it} = \frac{q_{itm}}{q_{it0}} \quad (5)$$

451 It can be observed that the OPC inclusion contributes to the enhancement of the
 452 splitting tensile strength of solidified sediments. In the same curing time of 28 d, the
 453 splitting tensile strength q_{it} increases from 0.050 MPa (SD) to 0.077 MPa (SD2OPC),
 454 0.162 MPa (SD4OPC) and 0.192 MPa (SD6OPC) with the increase of OPC content
 455 from 0 % to 6 %, the η_{it} correspondingly increases to 1.54 (SD2OPC), 3.24 (SD4OPC)
 456 and 3.84 (SD6OPC) as compared with that of SD (1.00). Moreover, the increase of
 457 curing time can effectively improve the q_{it} and η_{it} of the solidified sediments with
 458 OPC. The splitting tensile strength of SD4OPC specimen increases to 0.109 MPa (7 d)
 459 and 0.162 MPa (28 d) as compared with that at 3 d (0.104 MPa), meanwhile, the
 460 corresponding η_{it} changes to 2.18 and 3.24 as compared with that of SD4OPC
 461 specimen at 3 d (2.08).

462



463

464

465 **Fig. 11.** (a) Splitting tensile strength and (b) tensile strength ratio of solidified
 466 sediments with OPC.

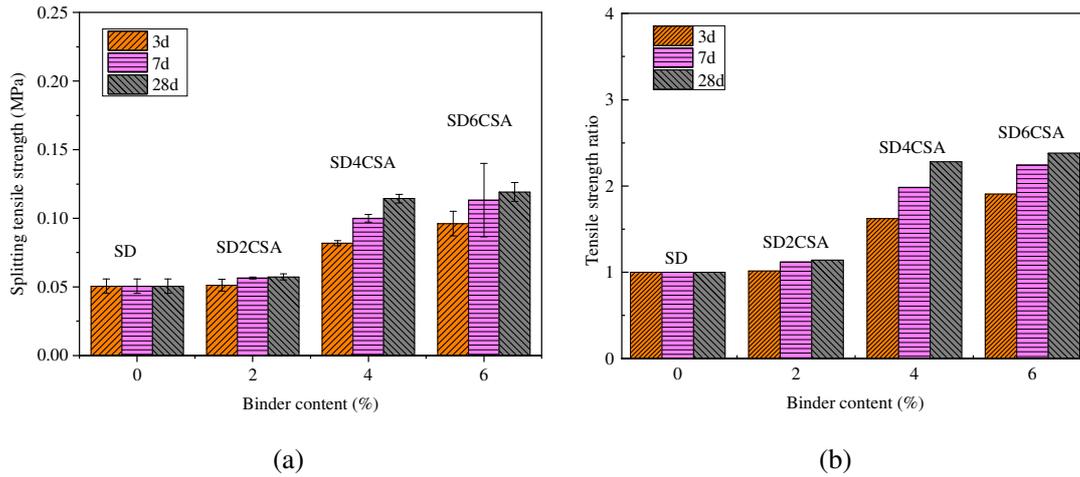
467

468 Fig. 12 shows the splitting tensile strength values and tensile strength ratio of

469 CSA-solidified sediments specimens cured for 3 d, 7 d and 28 d. As expected, the
470 CSA has an obviously positive effect on the tensile strength during all times. This is
471 because the CSA with water systems produced a large number of hydration products,
472 which are formed filled pores to give a higher strength.
473 Especially for the specimens with 2, 4 and 6 % CSA at 28 d, which had the higher
474 tensile strength of 0.057 MPa, 0.114 MPa and 0.119 MPa than that of SD (0.050 MPa),
475 and the η_{it} correspondingly is 1.14 (SD2OPC), 2.28 (SD4OPC), 2.38 (SD6OPC) and
476 1.00 (SD). This indicated that the addition of CSA could significantly improve the
477 tensile strength of the solidified sediments. As the reaction proceeds, there was an
478 increase in tensile strength for SD4CSA specimens after cured, and the tensile
479 strength achieved the most about 0.082 MPa, 0.100 MPa and 0.114 MPa at 3 d, 7 d
480 and 28 d, respectively, while the η_{it} correspondingly is 1.64 (3 d), 2.00 (7 d) and 2.28
481 (28 d). According to the research of Zhang et al. [62], the ettringite is the main
482 hydration product and plays a significant role in improving the strength of CSA
483 treated specimens, and ettringite continues to increase with curing time and CSA
484 content. Thus, this is the reason that the splitting tensile strength of CSA-solidified
485 sediment specimens increases with the increasing of curing time and CSA content.

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Fig. 12. (a) Splitting tensile strength and (b) tensile strength ratio of solidified sediments with CSA.

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$$q_c = 9.5q_{it} \quad (6)$$

502

$$q_c = 12.2q_{it} \quad (7)$$

503

504

505

These equations are plotted in Fig. 13 (a) with the experimental data. It can be seen that the regression lines from equations (6)-(7) showed a relatively good relationship between the compressive and splitting strength. The coefficient of determination (R^2),

506 which indicates how much of the total variation in the dependent variable can be
507 accounted for by the regression equation, was obtained as 0.99 and 0.98 for equations
508 (6)-(7) in this study, respectively. In particular, it is found that a unified equation (8)
509 with $R^2 = 0.97$ can satisfactorily describe the correlation between q_c and q_{it} on all
510 solidified sediment specimens. Therefore, the derived linear equations may
511 successfully be used to represent the relationship between the compressive and
512 splitting strength of solidified sediments.

$$513 \quad q_c = 10.4q_{it} \quad (8)$$

514 Fig 13 (b)-(c) show the variation of compressive strength q_c versus elastic modulus E
515 and splitting tensile strength q_{it} versus elastic modulus E , respectively. It is observed
516 that both q_c and q_{it} have a trend to increase with the increasing E according to the
517 obtained test data points. In this study, the simple exponential model was used for
518 describing the relationship between the strength and elastic modulus. The model
519 results between q_c and E of OPC- and CSA-solidified sediments are reflected in
520 equation (9) and (10) with the coefficient of determination $R^2 = 0.93$ and 0.98 ,
521 respectively. The unified equation (11) with $R^2 = 0.92$ can explain how compressive
522 strength is related to the elastic modulus of solidified sediment specimens.

$$523 \quad q_c = 0.471e^{0.931E} \quad (9)$$

$$524 \quad q_c = 0.407e^{1.313E} \quad (10)$$

$$525 \quad q_c = 0.454e^{1.040E} \quad (11)$$

526 Equation (12) and (13) with $R^2 = 0.94$ and 0.95 , respectively, are derived from the
527 regression analysis to express quantitatively the correlation of q_{it} and E of OPC- and

528 CSA-solidified sediments. A unified equation can be expressed by equation (14) with
529 $R^2 = 0.94$, which can be acceptable to describe approximately the changing trend of
530 splitting strength with elastic modulus on the designed materials.

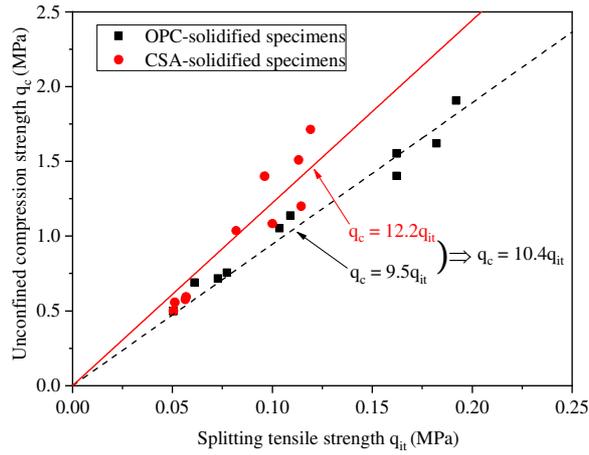
$$531 \quad q_{it} = 0.046e^{0.997E} \quad (12)$$

$$532 \quad q_{it} = 0.043e^{0.990E} \quad (13)$$

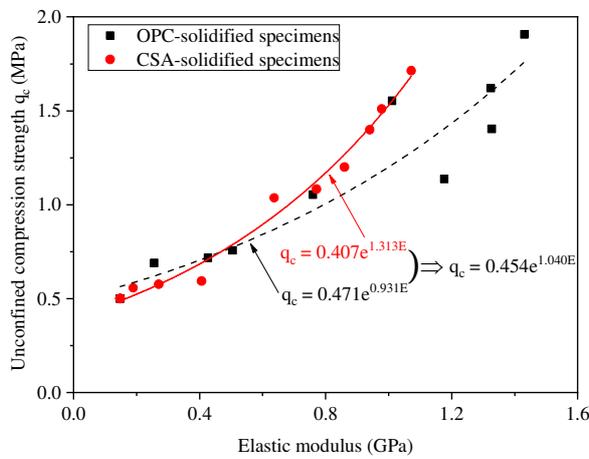
$$533 \quad q_{it} = 0.044e^{1.011E} \quad (14)$$

534 In general, equation (8), (11) and (14) demonstrates the relationships among the
535 compressive strength, tensile strength and elastic modulus, this is to say, these
536 equations provide an alternative approach to predict the approximate value of other
537 two parameters if one parameter is given. By example, this leads to help to predict the
538 tensile strength and the elastic modulus from the compression strength. This later test
539 is easier to perform, cheaper and quicker to carry out in comparison to the tensile
540 strength and the elastic modulus measurements. Moreover, in the stage of designing a
541 new formulation, this procedure could save time, reduce the number of samples and
542 hence save the materials. Even if the ratio of 10 between the compressive strength
543 over the tensile strength is commonly encountered for OPC treated materials, the
544 relation between the tensile strength or the compressive strength with the young
545 modulus has to be specific to a given material (in our case to treated sediments).

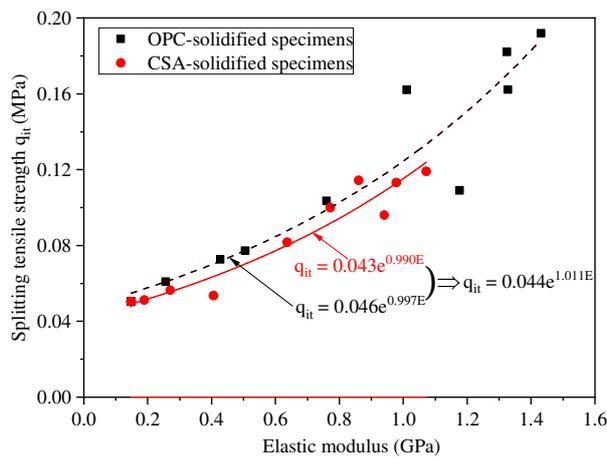
546



(a)



(b)



(c)

Fig. 13. Relationship of (a) compression and splitting tensile strength; (b) compression strength and elastic modulus; (c) splitting tensile strength and elastic modulus.

556

557 **3.7 Evaluation of solidified sediments as road materials**

558 Fig. 14 assess the suitability of solidified dredged sediments as road materials
559 according to European standard NF EN 14227-15 [63], using the mechanical
560 characteristics of the direct tensile strength (q_t) and elastic modulus (E) at 360 d of the
561 solidified dredged sediments.

562 It is noted that the direct tensile strength q_t shall be derived from q_{it} using the
563 Equations (15) [56] [63]. The estimated values at 360 d for solidified sediments with
564 cement should be calculated from the measured values at the curing period of 28 d,
565 according to Equations (16) and (17) [8] [59]. In the absence of specific data, the
566 coefficients 0.6 and 0.65 are assumed to remain valid for solidified sediments. The
567 use of this extrapolation was confirmed in the literature. The results from Wang et al.
568 [8] and Achour et al. [59] confirmed this extrapolation.

$$569 \quad q_t = 0.8q_{it} \quad (15).$$

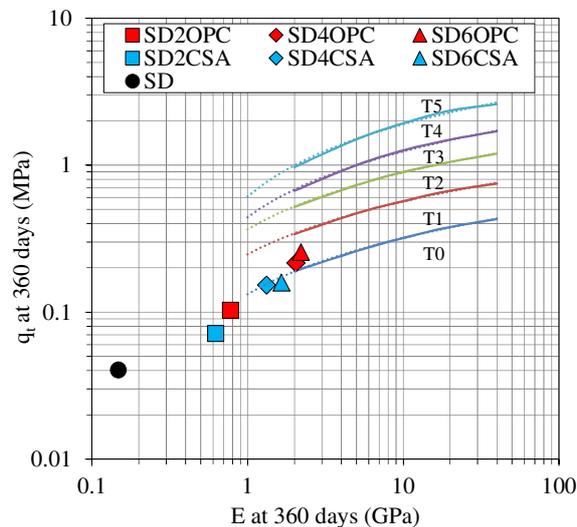
$$570 \quad \frac{q_t-28d}{q_t-360d} = 0.6 \quad (16)$$

$$571 \quad \frac{E-28d}{E-360d} = 0.65 \quad (17)$$

572 However, a great improvement of material classification can be observed, compared
573 with raw sediments. This proves the beneficial effects of OPC and CSA treatment to
574 increase the mechanical properties of raw sediments. It should be noted that the
575 minimum class required for potential use as a sub-base material in class T2. Hence,
576 this means that no samples in this study can be used as a sub-base or base course
577 material for a large class of traffic intensities. The samples of SD4OPC and SD6OPC,

578 which belong to the class T1 might be possibly reused as roadbed filling materials for
 579 roads of low traffic intensity. This conclusion is consistent with the previous study [8].
 580 If the need arises to enhance the material classification to Class T2 for high traffic
 581 intensity, the effective way may be to increase the amount of binder and/or to explore
 582 the combined effect of OPC and CSA, finally to combine the present sediments with
 583 coarser materials to improve its mechanical properties. This work will be carried out
 584 in a next stage.

585



586

587 **Fig. 14.** Classification of solidified sediments with OPC and CSA.

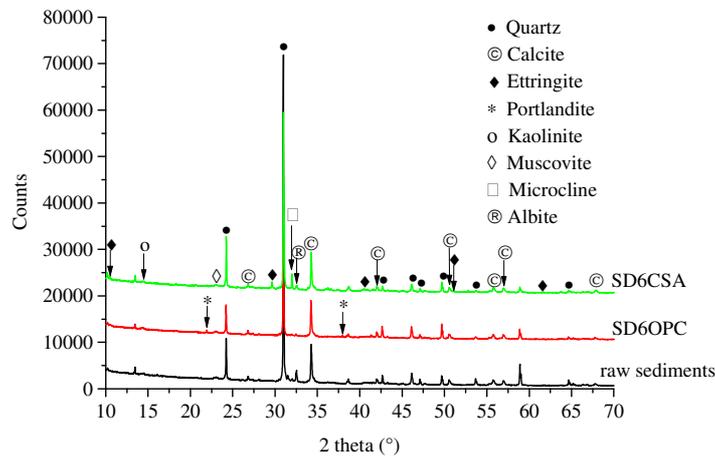
588

589 3.8 X-ray diffraction analysis

590 X-ray diffraction (XRD) analysis was used to determine the mineralogical
 591 composition of raw and OPC/CSA-solidified sediments at 7d, and the representative
 592 results are given in Fig. 15. For raw sediments, quartz (SiO_2) and calcite (CaCO_3)
 593 were observed as the main phases, the result also indicated some minor phases such as
 594 gypsum (CaSO_4), kaolinite, muscovite, microcline, and albite. The main hydration

595 phases observed of OPC-solidified sediments (SD6OPC) are portlandite (CaOH_2) and
 596 a little of ettringite ($\text{Ca}_6\text{Al}_2\text{S}_3\text{O}_{50}\text{H}_{64}$), however, calcium silicate, calcium aluminate
 597 and aluminosilicate phases were not detected. XRD results reveal that the ettringite
 598 ($\text{Ca}_6\text{Al}_2\text{S}_3\text{O}_{50}\text{H}_{64}$) is the main hydration product in CSA-solidified sediments
 599 (SD6CSA). The XRD results show the different main hydration product for OPC and
 600 CSA-solidified sediments, lead to the different mechanical strength of solidified
 601 sediments.

602



603

604 **Fig. 15.** XRD traces of raw sediments, OPC-solidified sediments and CSA-solidified
 605 sediments specimens.

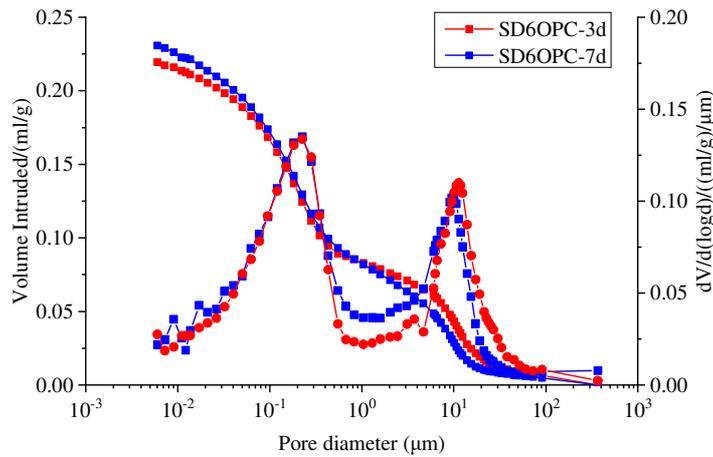
606

607 3.9 Micropore structure analysis

608 The micropore structure of the solidified sediments was investigated and the results is
 609 shown in Fig. 16 and Table 4. It's easily observed that the four typical samples
 610 showed approximately the same pattern with apparent diameters of pores in the range
 611 of 0.006-400 μm , and all the pore size distributions model are bimodal. Indeed, the
 612 main pores of all the samples distributed in the range of 0.01–1.0 μm and 1.0–40 μm .

613 According to previous research [64], the pore structure can be divided into four major
 614 ranges: $<0.01 \mu\text{m}$, $0.01\text{-}1 \mu\text{m}$, $1\text{-}40 \mu\text{m}$ and $>40 \mu\text{m}$, as presented in Table 4. With the
 615 curing time increase from 3 d to 7 d, the pores volume percentage of larger pores in
 616 the range of $1\text{-}40 \mu\text{m}$ and $>40 \mu\text{m}$ shows a decreasing trend, while the pores volume
 617 percentage of the smaller pores in the range of $<0.01\mu\text{m}$ and $0.01\text{-}1 \mu\text{m}$ shows an
 618 increasing trend. This is due probably to the progress of hydration of binders, which
 619 causes that the larger pores ($1\text{-}40 \mu\text{m}$ and $>40 \mu\text{m}$) transform to smaller pores
 620 ($<0.01\mu\text{m}$ and $0.01\text{-}1\mu\text{m}$), which induces that the pores of the solidified sediments
 621 became finer and denser.

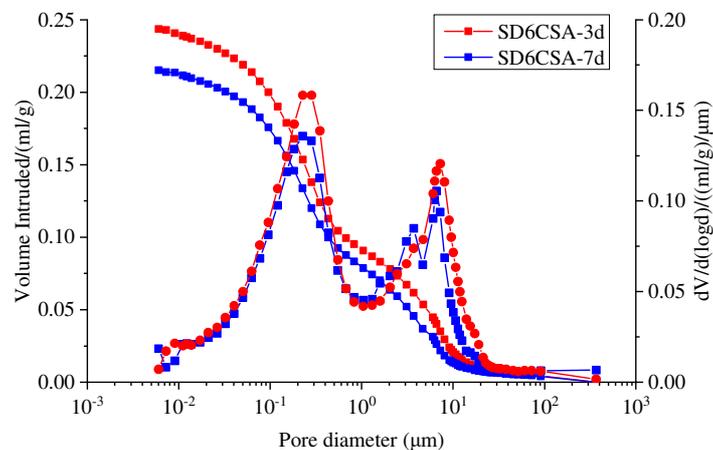
622



623

624

(a)



625

626

(b)

627 **Fig. 16.** Micropore structure analysis of (a) OPC-solidified sediments and (b) and
628 CSA-solidified sediments.

629

630 **Table 4** Pore size distribution of the solidified sediments

Pore size (μm)	Pore size distribution (%)			
	SD6CSA-3d	SD6CSA-7d	SD6OPC-3d	SD6OPC-7d
>40	2.80	2.72	4.72	3.18
1-40	34.51	33.88	33.12	32.30
0.01-1	60.78	61.82	59.53	61.06
<0.01	1.91	1.57	2.63	3.45
Total	100	100	100	100

631

632 **4. Conclusion**

633 In this study, a series of experiments were performed to clarify the feasibility of
634 recycling dredged marine sediments with novel eco-binder CSA cement as road
635 construction materials. The results are compared with the OPC treated sediments.

636 Based on the obtained results, the following conclusions can be drawn:

637 (1) Compared with the raw sediments, the compaction performance of the solidified
638 sediments is significantly improved, which reflects the behavior improvement of
639 solidified sediment in a short time that curing for less than 1 hour. The increase in the
640 I-CBR index value is almost linear with the increase of the binder content (at least in
641 the range of binder content studied in this work). In terms of maximum dry density
642 and the optimum moisture of solidified sediment:

643 a. For OPC treatment, the maximum dry density is decreased

644 accompanied by increasing optimal water content.

645 b. For CSA treatment, after the first decrease of the treatment with 2 %
646 CSA, an increase in maximum dry density is observed for higher
647 treatment content. In the same way, after an increase in the optimal
648 water content of the treatment with 2 % CSA, a decrease is observed
649 for higher treatment content.

650 (2) The incorporation of binder in raw sediments is effective for the improvement in
651 mechanic behavior of solidified sediment in the long term that curing for several days
652 or even longer periods, includes compressive strength, tensile strength and elastic
653 modulus, and these mechanical parameters increase with binder content and curing
654 time.

655 (3) A relative evaluation of the effectiveness of treatment with OPC and CSA has
656 revealed that CSA increases relatively the mechanical properties of solidified
657 sediments in the early stage (during the first three days). Whereas OPC shows a
658 marked increase between 3 d and 28 d.

659 (4) The simple model can satisfactorily describe, respectively, the relationships among
660 the compressive strength, tensile strength and elastic modulus; these equations
661 provide an alternative approach to predict the approximate value of two parameters if
662 the one parameter is given. Which leads to reduce the number and time of the
663 experiments. It is to note that the relation between the strength and the elastic
664 modulus is material dependent.

665 (5) The microstructure induced by OPC treatment and CSA treatment seems to be

666 comparable. The pore size distribution induced is of type bimodal.

667 (6) The evaluation of solidified sediment classification confirms that valorization
668 sediment in road materials is entirely possible.

669

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674 Douai.

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