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1 Use of Colloidal Thickeners to Inject and Retain Bacterial

2 Growth Media to Repair Cracked Concrete

3

4 I. Feurgard, *^{1, 2, 3} C. Lors, ^{2, 3} R. Gagné, ¹ D. Damidot^{2, 3}

5 ¹ Centre de recherche sur les infrastructures en béton (CRIB), Université de Sherbrooke, 2500 Boulevard de

6 l'Université, J1K2R1 Sherbrooke, Québec, Canada

7 ² IMT Lille Douai, Univ. Lille, EA 4515 - LGCgE – Laboratoire de Génie Civil et Géoenvironnement,

8 département Génie Civil & Environnemental, 941 rue Charles-Bourseul, 59508 Douai, France

9 ivan.feurgard@imt-lille-douai.fr

10

11 Abstract - This study aimed at developing a bacteria-based method to 12 repair cracks in concrete (crack opening < 1 mm) that would be suitable for full-13 scale operations and economically viable. CaCO₃-producing bacteria were 14 injected into calibrated cracks with bioavailable calcium and nutrients in a suspension thickened with a combination of Welan gum and Attagel® 50. These 15 16 thickeners have synergistic effects, enhancing viscosity and shear-thinning 17 behavior. These rheology characteristics made injection without drainage possible 18 for crack widths ranging from 150 to 800 µm. Bacterial growth and the associated 19 CaCO₃ biomineralization were enhanced in the presence of thickeners.

20

21 Keywords: bacteria, cracks, concrete, thixotropy, thickeners, CaCO₃

22 1. Introduction

23 Cementitious materials are prone to developing cracks. Cracks narrower 24 than 100 µm can be closed by natural self-healing, mainly due to the formation of calcium carbonate (CaCO₃) [1]. Larger cracks, however, can dramatically reduce 25 26 the lifespan of a structure by allowing aggressive compounds to penetrate deeper 27 layers of materials and accelerate deterioration. Fine cracks (<1 mm) are currently 28 mostly repaired with synthetic resins, which are easy to use, inexpensive, and 29 watertight. These compounds are, however, pollutants. In addition, the treatment 30 has to be repeated every 10 to 20 years due to chemical degradation of the 31 polymers, resulting in additional costs and emissions [2]-[4]. Supplemental 32 CaCO₃ (mostly calcite) formed through bacterial activity [5] could provide an environmentally friendly alternative to synthetic resins: calcite is stable and long-33 34 lived in most concrete service environments. Consequently, a growing number of 35 studies are focusing on producing self-healing concrete or repairing cementitious 36 structures through biomineralization [6]–[9].

When used as repair agents, calcite-producing bacteria have to be injected into cracks. Maintaining the bacteria alive and able to produce enough calcium carbonate remains a challenge, as cracks are hostile environments. Moreover, conventional liquid bacterial cultures cannot keep bacteria, nutrients, and water inside the cracks. Therefore, a specific growth medium has to be developed. The literature has already reported on several bacteria immobilization techniques already in use, such as polyurethane foam [10], glass beads [11], sand [12], [13],

44 silica gel [14]–[16], and agar gel [17]. Natural colloidal thickeners, however, seem to have the most potential for designing an injectable medium to repair 45 46 cracked concrete. Indeed, these compounds are nonpolluting and inexpensive as 47 well as being well suited for bacterial immobilization [18]. Besides, most 48 colloidal thickeners have highly shear-thinning and/or thixotropic behavior [19], 49 which enhances injection efficiency. Clays, in particular, can entangle bacteria in 50 networks providing protection biofilm-like against protozoa predation, 51 desiccation, and washout [20]-[23]. Used in combination, clays and 52 polysaccharides often show synergistic effects, increasing the stability of the 53 suspension and the effect of both thickeners, making highly shear-thinning and 54 thixotropic suspensions used for various applications [24]–[29].

55 The aim of this study was to use the synergistic effect of two colloidal 56 thickeners—Welan gum and Attagel® 50 palygorskite clay—to create a thickened 57 medium suitable for injection into concrete cracks from 150 to 800 µm in width. 58 This study focuses first on the rheological characterization of the thickened 59 growth medium using different Welan and Attagel concentrations to determine the 60 most promising composition. Second, the behavior during injection and 61 subsequent drying of the selected growth medium was tested on calibrated cracks 62 in mortar samples. Lastly, the bacterial activity and the associated amounts of bioprecipitated calcite were assessed. 63

64

65 2. Materials and Methods

66

2.1. Suspension Preparation

All assays were performed in a solution containing 75 g.L⁻¹ calcium Llactate hydrate (Sigma-Aldrich), 47 g.L⁻¹ calcium nitrate tetrahydrate (Fisher Scientific), 20 g.L⁻¹ calcium gluconate (Sigma-Aldrich), and 3 g.L⁻¹ yeast extract (Difco), dissolved in ultrapure water (referred to below as LNG medium).

71 Welan gum (Kelco) and Attagel® 50 (BASF) powders were sterilized 72 separately at 120°C in an autoclave for 15 minutes. Welan or Attagel suspensions 73 were prepared by dispersing the powder at 22°C in the LNG medium, followed by 74 homogenization with a magnetic stirrer at 1000 rpm for 24 hours. To prepare 75 suspensions containing both thickeners, each thickener was separately dispersed 76 in the LNG medium at 22°C at twice the concentration (ensuring better dispersion), then mixed together, and homogenized with a magnetic stirrer at 77 78 1000 rpm for 24 hours. The concentration of Welan and Attagel is expressed as a 79 weight percent of the total weight of the suspension (w:w).

80

81 **2.2.Rheological Assays**

The suspensions were prepared 24 hours before the rheological measurements in order to allow the suspensions to rest after homogenization. Rheological characterizations were carried out with a rheometer with coaxial cylinders (MCR302, Anton Paar) equipped with a CC27/P6 (grooved) inner
cylinder (Anton Paar). After being poured into the cylinder, the suspensions were
allowed to rest for 30 minutes with the inner cylinder in lower position.

88 The first measurement program applied an increasing, then decreasing 89 rotational shear to the fluid. The measuring program set shear rates at 0,1, 1, 10, 50, 100, 250, 500, 250, 100, 50, 10, 1, and 0,1 s⁻¹. Each stage lasted 20 seconds 90 91 and included 50 measurements of shear stress. The second program, starting 92 immediately after the first, was divided in three steps: first, negligible oscillatory 93 shear (oscillation; amplitude: 0,001%; angular frequency: 10 s⁻¹) for 100 seconds, second, high rotational shear at 500 s⁻¹ for 60 seconds; and lastly, negligible 94 95 oscillatory shear (oscillation; amplitude: 0,001%; angular frequency: 10 s⁻¹) for 10 minutes. The negligible oscillatory shear simulates rest in order to characterize the 96 97 thixotropic behavior of the suspension.

98 The rheological characterization of the LNG medium thickened with 99 Welan and Attagel followed a two-step experimental design. A first step was to 100 determine the boundaries of the rheological characterization with a Hadamard 101 matrix (Table 1).

102

2 Table 1. Hadamard matrix for the rheological characterization of the thickened medium

Ν	Welan (% w:w)	Attagel (% w:w)
1	0,2	4
2	0,2	8
3	0,4	4
4	0,4	8

Based on the experimental results, the response of the medium to changes in thickener concentration was determined according to a composite experimental design. This design had two factors—Welan and Attagel concentrations—and three variables for each. As a result, 9 experiments had to be performed (Table 2). Two additional suspensions were characterized to complete the surface graphs: WA34, containing 0,3% Welan and 4% Attagel, and WA38, containing 0,3% and 8% Attagel.

111Table 2. Extended experimental design for the rheological characterization of the thickened112suspensions

N	We	lan	Attagel				
	Factor value	% (w:w)	Factor value	% (w:w)			
1	-1	0,2	-1	5			
2	0	0,3	-1	6			
3	+1	0,4	-1	7			
4	-1	0,2	0	5			
5	0	0,3	0	6			
6	+1	0,4	0	7			
7	-1	0,2	+1	5			
8	0	0,3	+1	6			
9	+1	0.4	+1	7			

113

114 **2.3. Study of Pseudoplastic Behavior**

115 The pseudoplastic behavior of each suspension was quantified with the116 Ostwald-deWaele law for viscoelastic fluids, also referred to as the power law:

117
$$\eta = K \dot{\gamma}^{n-1} \tag{1}$$

118 where η = viscosity, K = consistency index, $\dot{\gamma}$ = shear rate, and n = power-law 119 index.

120 The power-law index is defined by the shear-thinning behavior of the suspension. 121 It is equal to 1 for Newtonian fluids and decreases as the shear-thinning behavior 122 increases. The consistency index K defines the overall viscosity and is equal to the 123 viscosity of the fluid at 1 s⁻¹. In this study, a custom indicator—the "viscosity drop 124 factor"—was used to illustrate the power-law index. This factor is equal to the 125 viscosity at 0,1 s⁻¹ divided by the viscosity at 500 s⁻¹. It represents the loss of 126 viscosity of the suspension under shear.

127

128 **2.4. Injection Assays**

129 Injection assays were performed on annular cracked mortar samples made 130 as described by Ducasse-Lapeyrusse [30] (height: 50 mm, outer diameter: 131 150 mm, inner diameter: 55 mm, reinforced with a 95 mm steel ring). Mortars 132 were cast according to ASTM C109M [31] with a water/cement ratio of 0,485 and 133 a sand/cement ratio of 2,75 with standard pure silica Ottawa sand and ordinary Canadian Portland cement (GU, Blaine fineness 381 m².kg⁻¹), Curing lasted for 134 28 days at 23°C and 100% RH. Crack openings between 150 and 500 µm were 135 136 made by forcing a steel expansive core inside the mortar, as described by Gagné 137 and Argouges [1]. Samples were then carbonated for one month at 4% CO₂, 20°C, 138 40% RH, allowing crack self-healing. Crack openings were measured with a 139 videomicroscope on 24 points evenly distributed on both sides of the mortar. 140 Crack width was determined with air permeability measurements according to the
141 method described by Gagné and Argouges [1]. The samples were dried at ambient
142 temperature for 48 hours before the air permeability measurements.

143 For the injection tests, 10 mL of suspension were injected inside the cracks 144 at low pressure with a custom injection device (Fig. 1). The suspension was 145 slowly injected inside the crack, then the injection device was removed and the 146 excess levelled off. If the crack had not been completely filled, the suspension 147 was considered to be too thick. Conversely, the suspension was too fluid if 148 drainage was observed after injection. In total, 52 cracks were tested for injection 149 of thickened suspensions, including 18 with the WA36 suspension to take crack 150 diversity into account. Six cracks were selected to test repeated injections of 151 WA36.



153 Fig. 1. From left to right – cross-sectional view of the injection device setup on a mortar sample;
154 upper side view; cracked mortar sample after injection of a colored solution

155

152

After injection, the sample was dried at ambient temperature for 48 hours,and then sawn to observe the cross section of the crack under scanning electron

microscopy (SEM) and energy dispersive spectroscopy (EDS) analysis. A small part of the inner surface of each crack was directly observed, and referred to as the "raw surface." All samples were metallized with carbon thread prior to observation.

162

2.5. Bacterial Growth Assays

In order to assess the effect of the thickeners on the production of calcium carbonate by the bacteria, the bacterial strain *Bacillus pseudofirmus* (DMS 2516, issued by DSMZ) was cultivated at 20°C in LNG medium versus in thickened LNG (referred to as LNGW) medium (Table 3).

- 167
- 168

Table 3. Composition of the different media used for bacterial growth

Name	Composition
NBN medium	11,8 g/L calcium nitrate (Sigma-Aldrich) 8 g/L nutrient broth (Difco)
LNG medium	 75 g/L calcium lactate (Sigma-Aldrich) 20 g/L calcium gluconate (Sigma-Aldrich) 47 g/L calcium nitrate (Fisher) 3 g/L yeast extract (Difco)
LNGW medium	LNG 0,3% Welan (w/w) 6% Attagel (w/w)

170 Stock bacteria were stored at -85°C in cryotubes containing 1 mL of 171 bacteria in NBN medium (Table 3) and 0,5 mL glycerol (30%) at a bacterial 172 concentration of 5.10⁹ to 1.10¹⁰ bacteria/mL. During the pre-culture, the bacteria 173 were cultivated for 30 hours in NBN medium at 30°C on an orbital shaker 174 (150 rpm). After 30 hours, the pre-culture was centrifuged at 4000 rpm for 175 20 minutes at 20°C. One pellet from 100 mL of pre-culture was used to inoculate 176 each 100 mL batch of the growth assay.

177 The growth assays were performed in 250 mL Erlenmeyer flasks 178 containing 100 mL LNG or LNGW medium (Table 3). Each condition was 179 performed in triplicate. The bacteria were cultivated for 35 days at 20°C on an 180 orbital shaker (150 rpm). Three milliliters of bacterial suspension were periodically sampled in order to monitor pH (Sensitix 41 probe, WTW), bacterial 181 182 concentration, and lactate concentration during the assay. After 35 days, the assay 183 was stopped and the cultures were centrifuged at 4000 g for 20 minutes at 20°C, 184 rinsed twice with 40 mL ultrapure water, then dried at 40°C and weighed to determine the concentration of solids. A fraction of the dry pellet was used to 185 186 determine the calcium carbonate concentration by TGA (Jupiter STA 449 F3, 187 Netzch). To monitor bacterial concentration, the samples were diluted in saline suspension ($c = 9 \text{ g.L}^{-1}$), stained with acridine orange (Sigma-Aldrich), and fixed 188 189 on nuclepore filters (Whatman). The bacterial cells were then counted under an 190 epifluorescence microscope (Leica, France) at 490 nm. Lactate concentration was 191 measured by ion chromatography (ICS-3000, Dionex).

192

193 3. Results and Discussion

194 **3.1. Rheological Assays**

195 3.1.1. <u>Characterization of Shear-Thinning Behavior</u> 196 <u>and Viscosity</u>

First, suspensions defined by the Hadamard matrix were studied (Table 4). LNG medium containing 4% of Attagel did not show a strong viscosity recovery at rest. These suspensions were stable and presented no segregation or loss of consistency after being stored for three days at ambient temperature. The LNG medium containing 8% Attagel, however, was prone to segregation. The optimal range of concentration of Attagel was higher than 4% to ensure a significant effect of the thickener, but lower than 8% to prevent its destabilization.

204 Welan did not have a strong impact on the stability or on the thixotropic 205 behavior of the suspension, but did affect viscosity. Indeed, suspensions 206 containing 0,2% Welan had low viscosity and might therefore be prone to 207 drainage after injection into cracks. Increasing the Welan concentration to 0,4% 208 dramatically increased the viscosity of the studied suspensions. This concentration 209 was sufficient to avoid post-injection drainage at any Attagel concentration. 210 Indeed, suspension WA48, containing 0,4% Welan and 8% Attagel, was paste-211 like under high shear and formed a weak gel after 4 hours at rest.

212 Table 4. Hadamard matrix and rheological characterization of the thickened suspensions

	0,2% Welan	0,4% Welan
4% Attagel	Too fluid Slightly thixotropic Viscosity at 1 s ⁻¹ : 2,3 Pa.s	Correct viscosity Slightly thixotropic Viscosity at 1 s ⁻¹ : 4,9 Pa.s
8% Attagel	Correct viscosity Slight tendency to segregate Viscosity at 1 s ⁻¹ : 12,1 Pa.s	Excessive viscosity Slight tendency to segregate Viscosity at 1 s ⁻¹ : 15,3 Pa.s

213

The nine suspensions in the experimental design described in Table 2 yielded flow curves accurately fitting the Ostwald law ($R^2 > 0,99$) and had strong shear-thinning behavior, with power-law indexes lower than three (Table 5). *Table 5. Fitting of suspensions containing Welan gum and Attagel with Ostwald law for viscoelastic fluids*

Sample	Welan (%) Attagel (%)		К	n	Viscosity Drop Factor	R ²
WA24	0,2	4	2,33	0,235	633	0,997
WA25	0,2	5	3,93	0,204	829	0,998
WA26	0,2	6	5,82	0,185	933	0,998
WA27	0,2	7	8,57	0,173	1038	0,999
WA28	0,2	8	11,9	0,164	1175	0,999
WA34	0,3	4	3,22	0,239	651	0,999
WA35	0,3	5	4,94	0,211	810	0,999
WA36	0,3	6	7,31	0,191	958	0,999
WA37	0,3	7	10,9	0,175	1093	0,999
WA38	0,3	8	14,8	0,164	1134	0,999
WA44	0,4	4	4,18	0,247	664	0,999
WA45	0,4	5	6,34	0,214	833	0,999
WA46	0,4	6	8,99	0,194	979	0,999
WA47	0,4	7	12,5	0,177	1105	0,999
WA48	0,4	8	16,7	0,171	1147	0,999

Figure 2 provides the effect of each thickener on the consistency index K. Both thickeners increased the value of K and, therefore, the viscosity of the suspensions proportionally to their concentrations.



Fig. 2. Evolution of the consistency index of the studied suspensions as a function of Welan and
 Attagel contents

226

223

Figure 3 displays the power-law index "n" as a function of Welan and Attagel concentrations. The value of "n" decreased as Attagel concentration increased, but it was not affected by the Welan concentration. Therefore, in this range of concentrations, only the Attagel concentration played a role in reducing the value of "n" and increasing the shear-thinning behavior of the suspensions.





Fig. 3. Evolution of the power law index of the studied suspensions as function of Welan and
 Attagel contents

In all samples, when shear stress is displayed as a function of time, the modification of shear rate was followed by a progressive response of shear stress (Fig. 4: for clarity, only one sample (WA36) is displayed as an example). The suspensions therefore have short-term thixotropic behavior. The time needed for viscosity stabilization after a change in shear is approximately of 15 seconds, which is similar for destructuration (following an increase in shear rate) and recovery (following a drop in shear rate).



Fig. 4. Flow curve of suspension WA36 containing 0,3% Welan and 6% Attagel, displayed as
shear stress / shear rate as a function of time

248 Moreover, the complex viscosity and storage modulus of all the samples 249 progressively increased when subjected to 10 minutes of oscillatory measurements, following destructuration at 500 s⁻¹ (Fig. 5). The Welan-Attagel 250 251 suspensions therefore had long-term thixotropic behavior. After 10 minutes, the 252 complex viscosity of the suspension was still increasing, suggesting a greater 253 buildup in viscosity. The most concentrated suspensions (WA46, WA37, WA38, 254 and WA48; see Table 5) were able to form weak gels after 6 hours at rest, which 255 confirms that viscosity recovery continued to greatly increase viscosity.



Fig. 5 (A) complex viscosity and (B) dynamic modulus of the suspension WA36 containing 0,3%
Welan and 6% Attagel under oscillatory shear after 30 s., stirring at 500 s⁻¹

261 Combining Welan and Attagel yields shear-thinning, thixotropic, and 262 settling-resistant suspensions for injection into cracked mortar. The rest of the 263 experiments using thickened solutions were performed with suspension WA36, 264 which contained 0,3% Welan and 6% Attagel dispersed in the LNG medium 265 (referred to hereafter as LNGW).

3.2

3.2. Injection Assays with the LNGW Suspension

The LNGW suspension was successfully injected into all the cracks (150
to 500 μm) and filled at least 80% of the cracks with no post-injection drainage.

Additional injections into cracks up to 800 µm filled cracks to 100% without postinjection drainage, which suggests a wider injection range. This versatility is due to the shear-thinning and thixotropic behavior of the suspension: viscosity can be strongly lowered by shaking to facilitate injection, while recovery prevents postinjection drainage.

Upon drying, the thickened suspension formed a thin film covering most of the inner surface of the crack, with a network of crests almost joining both sides of the crack (Figs. 6 and 7). The film deposited on the inner surface of the crack was irregular and less than 50 μm thick on most of the surface.



279 Fig. 6. Film formed inside a 800 µm crack by the thickened suspension (LNGW) after injection

280

278



and drying

281

Fig. 7 Cross-sectional SEM observation of a 580 µm crack after injection of the thickened
 suspension (LNGW)

284

The film was made of interlaced 5 μ m long needles with some particles, such as dolomite cubes, mortar debris, and precipitates (Fig. 8). This observation is similar to SEM observations of Attagel described in the literature [32], showing that the film is mainly composed of clay. Indeed, the composition of the solid deposit, as determined by EDS analysis (Table 6), was close to the composition of 290 the Attagel as provided by the supplier [32], although SiO₂ concentrations varied

in the sample.



293 Fig. 8. SEM observations of the inner surface of a crack after injection of thickened suspension.

294	(A) dolomite cube covered with clay needles; (B) clay deposit
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295

292

296Table 6: Average measured composition of the solid deposit and commercial Attagel297composition [32]

Mineral (as element)	Average Measured Value (mass%)	Attagel Concentration (mass%)			
SiO2	77,7 (+/- 9,0)	65,2			
Al ₂ O ₃	11,7 (+/- 1,2)	12,7			
MgO	11,1 (+/- 0,9)	12,3			
CaO	5,6 (+/- 3,2)	3,9			
Fe ₂ O ₃	4,5 (+/- 1,0)	3,5			

298

A comparison of six mortars with different crack widths (225–350 μ m) shows that the deposit of clay polymer film in the crack significantly reduced the air permeability (Fig. 9). This led to a reduction in the apparent width of the crack by more than 50 μ m after each injection of thickened suspension. The fact that the film itself was mostly thinner than 50 μ m confirms the important role of the crest network in air permeability reduction. Repeated injections led to an accumulation
of layers, producing a proportional reduction of the apparent crack width up to
200 µm.



307

Fig. 9 Apparent width of cracks in six mortar samples, initially and after repeated injections of
 the LNGW medium

310

311 **3.3.** Bacterial Growth Assays with the LNGW Suspension

Figure 10 shows the evolution of the bacterial population during the 312 313 growth assay. As concentrated inoculum was used, the initial population already ranged between 3.10⁹ and 4.10⁹ bacteria/mL at day 0. In the non-thickened 314 315 medium (LNG), the bacterial population rapidly increased and stabilized at 1.10^{10} bacteria/mL during the rest of the assay. The bacteria were in the form of 316 317 small cocci, mostly assembled in tetrads or small clusters (Fig. 11). In the 318 thickened medium (LNGW), the bacterial population also initially increased, but to a lesser extent than in LNG. Then, the bacterial population decreased slightly 319

during the assay, but this might be attributed counting bias. Indeed, the coccitended to form massive clusters with time, hampering counting accuracy.

322 The pH progressively increased during the assay both in the LNG and in 323 LNGW media. After 35 days, the pH increased roughly 1 point, reaching a final 324 value of approximately 7,5 at the end of the assay, with or without thickeners. 325 Without thickeners, there was a steady decrease of lactate concentration in the LNG medium (Fig. 12), stopping after 20 days and leading to the consumption of 326 80% of the lactate. Lactate consumption was quicker in the LNGW medium, 327 328 leading to complete consumption after 20 days. Thus, the presence of thickeners 329 did not hinder the bacterial activity and even seemed to be beneficial.

330



Fig. 10, Evolution of bacterial population (A) and pH (B) in the LNG and LNGW suspensions
at 20°C. Experiment performed in triplicate



336Fig. 11. Bacterial cells after 10 days in the LNG bacterial suspension at 20°C, after337acridine orange staining, observed by epifluorescence

338



339

Fig. 12. Evolution of lactate concentration in the LNG and LNGW bacterial suspensions.
 Experiment performed in triplicate

342

In the LNG medium, the average CaCO₃ production (Table 7) was 17,0 344 g/L (+/- 0,9 g/L) after 35 days. In the LNGW medium, the average CaCO₃ 345 production after 35 days was 25,1 g/L (+/- 3,0 g/L). The production of calcium carbonate was therefore more important in the thickened medium, which is
consistent with the greater lactate consumption. The presence of thickeners also
contributed to increasing the total dry weight at the end of the assay, as Attagel
added 60 g/L to the final solid composition in the samples.

350 Moreover, the protective effect of clays on bacteria have been largely 351 documented [20-23], and might constitute a major advantage as maintaining 352 bacterial survival and activity is a major challenge for outdoor bioprocesses. As 353 for the scope of crack sealing, the combination of biomineralization and clay 354 deposit is particularly interesting as both factors help reduce crack permeability. 355 Moreover, the clay deposit might serve as a scaffold for calcium carbonate 356 crystals, improving their durability inside the crack. Additionally, this growth medium shows interesting properties for a pilot-scale test: 357

- It is nonpolluting and nontoxic, and involves inexpensive materials.

- Its rheological properties make it suitable for various sizes of cracks.

- 360 It can be prepared by simple dispersion of dry powders and does not
 361 require complex protocols or specific precautions.
- 362 It forms a washout-resistant film inside the crack, contributing its
 363 sealing.
- 364
- 365 Table 7. Dry weight and calcium carbonate production after 35 days in the LNG and LNGW
 366 suspensions

Sample LNG- LNG- LNG- Average LNGW- LNGW- LNGW- Average

	1	2	3		1	2	3	
Dry weight (g/L)	19,7	21,2	20,3	20,4	94,3	88,3	88,5	90,3
				(+/- 0,8)				(+/- 3,4)
CaCO₃ in dry	83%	84%	85%	84	38%	34%	35%	36
residue (%)				(+/- 1)				(+/- 2)
CaCO ₃ production	16,4	17,7	17,2	17,1	28,5	23,2	23,6	25,1
(g/L)				(+/- 0,7)				(+/- 3,0)

368

369 4. Conclusion

370 Adding polysaccharide gum (Welan) and a palygorskite clay (Attagel) to 371 growth medium made it possible to design stable suspensions with strong shear-372 thinning and thixotropic behavior. The thickened suspension was efficiently 373 injected into cracks ranging from 150 to 800 µm. Cultivated in a growth medium 374 containing 0,3% Welan and 6% Attagel, Bacillus pseudofirmus was able to grow 375 and precipitate larger amounts of calcium carbonate than in the non-thickened 376 growth medium. Future studies will aim at confirming the healing potential of the 377 thickened medium developed in this study by testing it on an outdoor pilot scale 378 or on real-scale concrete structures.

379

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Bacillus pseudofirmus calcite-forming bacteria



Attagel clay and Welan gum



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