



HAL
open science

Experimental study and modeling of the behavior of partially saturated asphalt concrete under freezing condition

van Thang Vu, Olivier Chupin, Jean Michel Piau, Ferhat Hammoum, Stéphane Bouron

► To cite this version:

van Thang Vu, Olivier Chupin, Jean Michel Piau, Ferhat Hammoum, Stéphane Bouron. Experimental study and modeling of the behavior of partially saturated asphalt concrete under freezing condition. *Construction and Building Materials*, 2018, 163, pp.169-178. 10.1016/j.conbuildmat.2017.12.070 . hal-01731346

HAL Id: hal-01731346

<https://hal.science/hal-01731346>

Submitted on 8 Jul 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Experimental study and modeling of the behavior of partially
2 saturated asphalt concrete under freezing condition

3 Van Thang VU, Olivier CHUPIN, Jean-Michel PIAU, Ferhat HAMMOUM,
4 Stéphane BOURON

5 *IFSTTAR, MAST, F-44344 Bouguenais, France*

6

7 **ABSTRACT**

8 Asphalt pavement damaging characterized by series of potholes was recently observed in
9 France and Northern Europe. This type of pavement distress surprisingly occurred in short
10 time laps over large distances during winters and after rainfalls had taken place. Based on
11 these observations, a specific mechanism is suspected to be responsible for such disorders.
12 This mechanism is believed to be related to the behavior under freezing conditions of asphalt
13 concrete (AC) partially saturated with water, which is the focus of the present research. To
14 investigate this behavior two types of experimental test are carried out in the laboratory. One
15 test is performed under free stress condition while the other test is subjected to restrained
16 strain. The experimental results from these two tests show the development of swelling strain
17 and induced stress in the saturated asphalt specimens, respectively. These two effects are
18 attributed to the phase change of pore water from liquid to solid. A constitutive law taking
19 into account viscoelasticity of AC, thermal expansion and swelling induced by frost is
20 elaborated. This law is implemented in a numerical program and validated against the
21 experimental results.

22 **Keywords:** saturated asphalt concrete, freezing, swelling, viscoelasticity, constitutive law.

22 1. INTRODUCTION

23 This research was motivated by field feedbacks showing the apparition of series of potholes
24 taking place in some asphalt pavements in France and other Northern Europe countries. Such
25 degradation occurred almost simultaneously (typically in half a day) over some important part
26 of road sections and under particular weather circumstances combining cold temperatures and
27 rainfall events. Early investigations of these disorders [1][2] have pointed out that a specific
28 mechanism could be at the origin of the problem and that this mechanism was likely related to
29 the mechanical behavior of asphalt concrete (AC) partially saturated with water when
30 subjected to freezing. Traffic and initial damage might represent propitious or aggravating
31 factors to this deterioration mechanism.

32 The mechanical response of partially saturated AC specimens undergoing freezing then
33 started to be studied in the laboratory [3][4]. Experimental tests were performed at the
34 timescale of one (or a few) frost/thaw cycle(s) focusing on the strain evolution during
35 freezing. Results from these studies show that large swelling strain develops in the AC sample
36 during cooling starting at the time at which temperature in the sample reaches some negative
37 value. This swelling strain is attributed to freezing of the pore water occluded in the AC
38 specimen.

39 In this paper, we present additional tests performed on saturated AC to quantify the level of
40 strain but also of stress that can originate from freezing of pore water. The objective is then to
41 use these tests to elaborate a constitutive law dedicated to saturated AC. Two tests are
42 considered. One is run considering traction free boundary condition that let the sample deform
43 freely. The other test is performed under restrained strain and makes thermal stress occur in
44 the sample. The tests performed clearly show the impact of the pore water phase change on
45 the experimental data.

46 It is only recently and following feedbacks from the field that the combined effects of
47 moisture and frost is considered as possibly leading to a frank mechanism of pavement
48 structure deterioration, which often results from fatigue process. This mechanism is not well
49 understood yet and for this reason is investigated in the present work.

50 Note that in the past, moisture susceptibility and moisture damage of AC was studied putting into
51 evidence its impact on the long term on stripping, raveling, shelling and hydraulic scour [5][6][7][8].

52 On the other hand, the impact of frost on pavements was also studied in the laboratory but rather from
53 the sight of the long-term effect of repeated cycles [9][10]. Interestingly, the results from this research
54 shows that the internal structure of AC is modified according to the number of cycles applied,
55 resulting in an increase of void ratio and permeability [11][12] and a decrease of the AC stiffness [13].

56 All these effects can contribute to weaken AC pavements but cannot explain the sudden and
57 simultaneous onset of potholes.

58 This paper is divided into three main sections. First we present the experimental testing of saturated
59 AC materials. Based on the test results, the development of a constitutive law as well as its
60 implementation in a numerical program is presented in a second part. Finally, this law is validated
61 against experimental data.

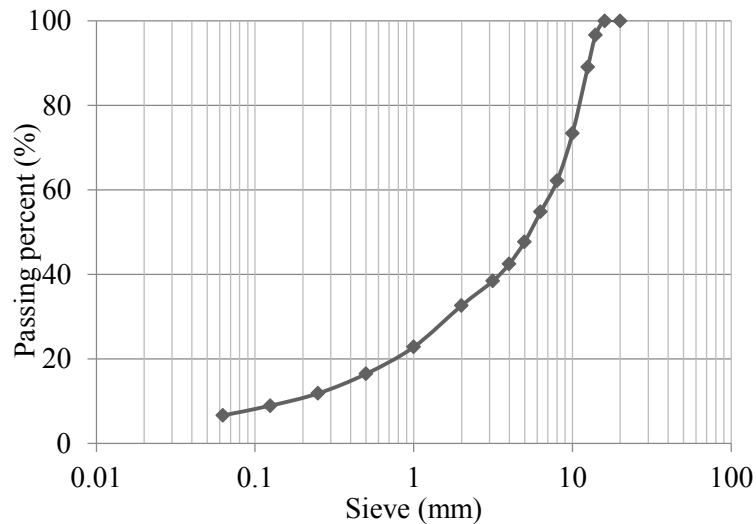
62 **2. EXPERIMENTAL TESTING**

63 Two tests are considered in this section to investigate the behavior of partially saturated AC under
64 freezing. The first test performed according to traction free boundary condition is denoted CTFS
65 which is the acronym for Cooling Test in Free Stress condition. This test is used to evaluate swelling
66 strain that develops in saturated AC under freezing condition. The associated dual variable is the
67 freezing-induced stress which is quantified by means of TSRST which stands for Thermal Stress
68 Restrained of Specimen Test. AC samples are subject to restrained strain during this test.

69 In this section, the AC materials used in the present study and the experimental procedures applicable
70 to each tests are detailed prior to the experimental results are commented.

71 **Material properties and preparation of the AC specimens**

72 The asphalt mixture used in this study is designed according to the French formulation
73 method [14] and is denoted BBSG with a nominal aggregate size of 0/14mm. Its gradation
74 curve is shown in figure 1. A bitumen classified 35/50 with a content of 4.45 ppc was used.



75

76 Figure 1: Grading curve of the aggregates

77

78 The test specimens used in CFTS and TSRST are cored in slabs of BBSG 0/14 that were
79 compacted using the plate-compactor machine. Two series of cylindrical specimens are
80 designed to comply with the geometry required by each test. Dimensions of the specimens
81 used in CFTS are 80 mm in diameter ($\varnothing 80$) and 120 mm in height. All these specimens (6 in
82 total) are cored vertically from the same slab. For use in TSRST, 8 cylindrical specimens of
83 diameter 50 mm ($\varnothing 50$) and of height 160 mm are core-drilled horizontally according to the
84 European standard NF EN 12967-46. Porosity of every specimen is checked by means of the
85 X-ray method [15], which is performed for both dry and partially saturated AC samples.
86 Saturation of an AC specimen is obtained considering the following process: (i) a negative
87 pressure of -86kPa is applied during one hour to the initially dry specimen placed in a tank,

88 (ii) water is slowly added until full immersion of the specimen then maintaining the negative
 89 pressure during three hours. For all the specimens tested, the degree of saturation determined
 90 by weight measurements is found to be around 60% (Table 1).

91

Type of test	Number of specimens tested	Specimen dimensions (mm)	Average porosity (%)	Average degree of saturation (%)	Test details
CTFS	6	Ø80 × 120	6.2	63	All specimens are tested successively under dry and wet conditions
TSRST	8	Ø50 × 160	6.5	60	3 specimens are tested under dry conditions and 5 under wet conditions

92

93

Table 1: Summary of the experimental campaign carried out

94

95 **Experimental procedures**

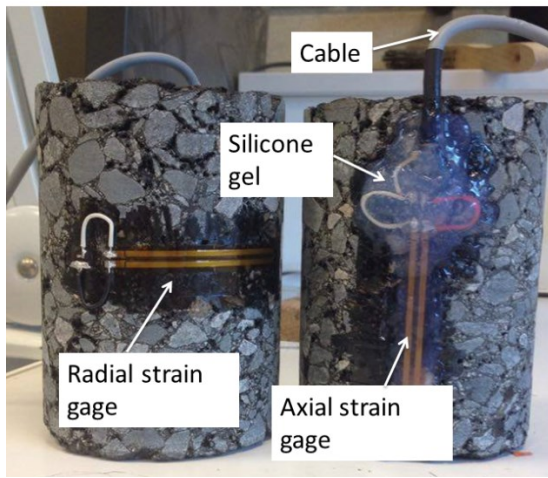
96 The experimental procedures specific to the CFTS and TSRST tests are described in this
 97 section. In particular, instrumentation of the samples is focused on as well as the evolution of
 98 temperature imposed to the samples.

99 *Cooling test in free stress conditions (CTFS)*

100 In this test, the cylindrical AC specimens (Ø80 × 120 mm) are equipped with two strain
 101 gages and a temperature sensor glued on surface of the specimen at mid-height (Fig. 2a). One
 102 of the strain gages is positioned vertically and thus measures the axial strain while the other
 103 placed horizontally measures strain in the (ortho-) radial direction. Both gages are protected
 104 against external temperature and moisture by a silicone coating.

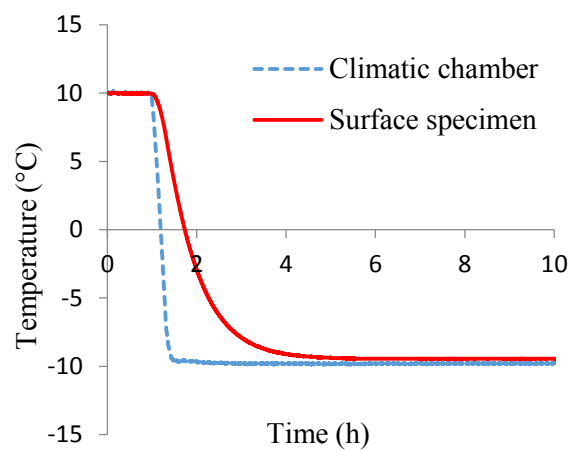
105 The instrumented specimens are tested imposing traction-free boundary condition all over
 106 their outer surface within a climatic chamber. The controlled temperature of the climatic
 107 chamber is varied from 10 °C to -10 °C as shown in figure 2b. The specimens are tested first
 108 under dry conditions and then after partial saturation performed as explained before. The axial
 109 and radial strain evolutions are recorded during cooling of the AC samples which are free to
 110 deform given the mechanical boundary conditions.

111



112

(a)



(b)

113

114 Figure 2: (a) Picture of the instrumented AC specimen. (b) Evolution of the controlled temperature of
 115 the climatic chamber and of the temperature measured at the surface of a dry AC specimen during
 116 CTFS testing.

117

118 Since strain gages are sensitive to temperature, their raw measurement must be corrected to
 119 obtain the correct value of strain under variable temperature. In this study, the correction is
 120 done based on the measurement of a particular gage glued on an invar rod also placed in the
 121 climatic chamber and thus subjected to the same controlled temperature as the AC samples.
 122 Invar is an alloy having a very small coefficient of thermal expansion
 123 ($\alpha_{Invar} \approx 0.03 \mu m/m/^{\circ}C$).

124

125 The strain recorded on the AC sample can be decomposed into the following parts:

126
$$\varepsilon_{AC}^{measure}(t) = \varepsilon_{AC}^{true}(t) + \varepsilon_{gage}^{err}(t) \quad (1)$$

127 And that recorded on the Invar rod as follows:

128
$$\varepsilon_{Invar}^{measure}(t) = \varepsilon_{Invar}^{true}(t) + \varepsilon_{gage}^{err}(t) \quad (2)$$

129 Quantity $\varepsilon_{gage}^{err}(t)$ reflects the measurement bias brought by the gage sensitivity to
130 temperature. However, considering that α_{Invar} is negligible then
131 $\varepsilon_{Invar}^{true}(t) = \alpha_{Invar} \Delta\theta \sim 0$ and the actual (corrected) strain of AC samples is given by:

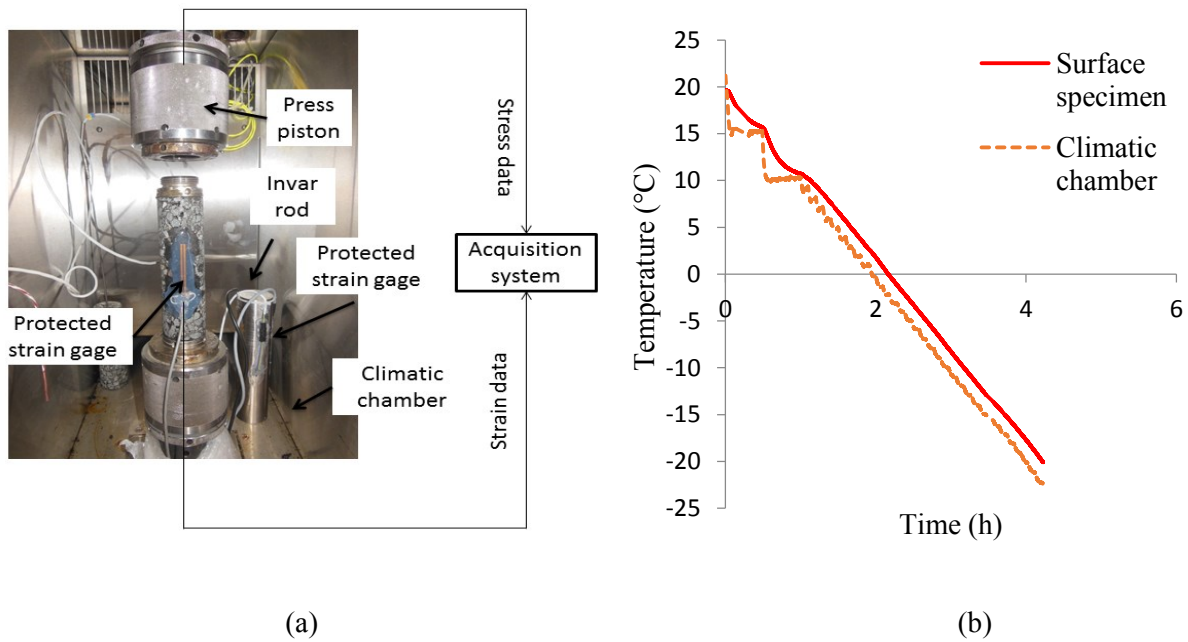
132
$$\varepsilon_{AC}^{true}(t) = \varepsilon_{AC}^{measure}(t) - \varepsilon_{Invar}^{measure}(t) \quad (3)$$

133

134 *Thermal stress restrained specimen test (TSRST)*

135 This test is adapted from the European standard NF EN 12967-46 (TSRST). The cylindrical
136 specimens ($\varnothing 50 \times 160 \text{ mm}$) tested are clamped between two press pistons and placed into a
137 climatic chamber, the controlled temperature of which is decreased at the rate of $10 \text{ }^\circ\text{C/h}$ (Fig
138 3b). The length of the specimen is maintained constant during the test by acting on the force
139 imposed between the two pistons. The value of stress in the AC specimen is inferred from this
140 force that ensures a zero longitudinal strain during testing. This is controlled through the
141 corrected measurement (as described in the previous section) of a strain gage glued to the
142 lateral surface of the AC specimens.

143 The TSRST campaign carried out in this study involves eight AC specimens among which
144 three are tested under dry conditions and five after saturation.



145

146

147 Figure 3: (a) Experimental set-up used in TSRST testing. (b) Evolution of the controlled temperature
 148 of the climatic chamber and of the temperature measured by a sensor glued at the surface of an AC
 149 specimen.

150

151 Note that to avoid variability effect from one sample to another in the comparison between
 152 the two tests considered in this paper, some saturated AC samples are utilized for both CTFS
 153 testing and then TSRST testing after the saturation has been set back to the initial level.

154

155 **Results and discussions**

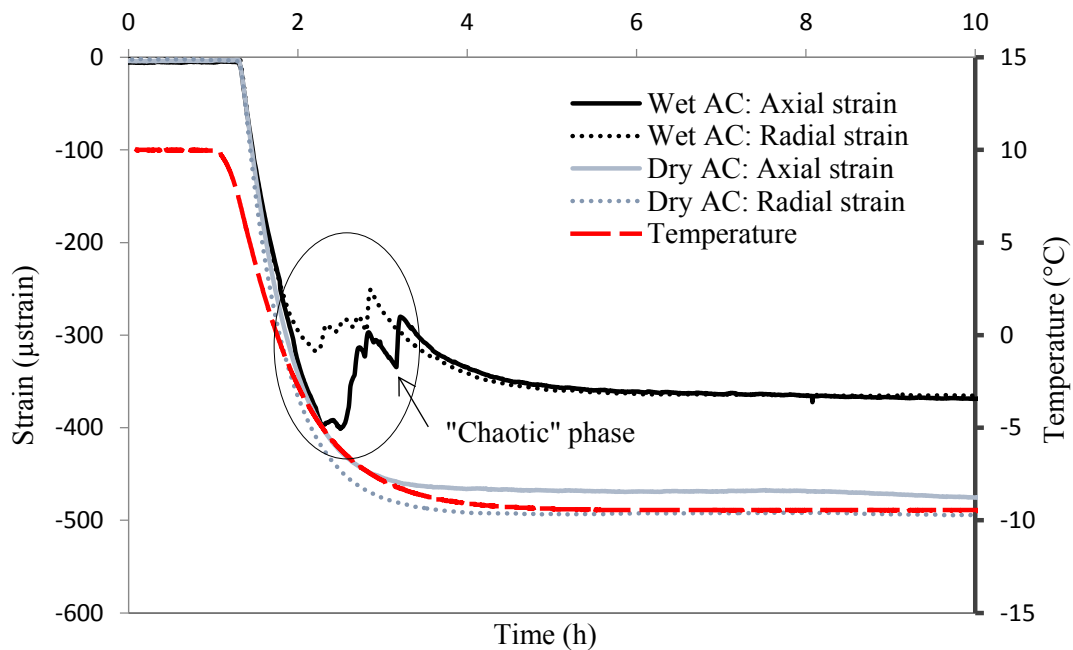
156 *Effect of water phase change on the measured strain evolution during CTFS testing*

157 Some typical experimental results from CTFS testing are presented below showing the
 158 corrected strain evolution with respect to time. In particular, figure 4 displays the comparison
 159 between the radial and the axial strain obtained for the same AC sample tested under dry and
 160 wet conditions. The AC specimen under consideration has a porosity of 7.7% ($n = 7.7\%$) and
 161 a degree of saturation equal to 65% ($S_r = 65\%$).

162 As expected during cooling, the radial and the axial strain curves show an isotropic thermal
 163 contraction under dry condition. In this case, the change in strain for a temperature variation
 164 of $-20\text{ }^{\circ}\text{C}$ ($\Delta\theta = -20\text{ }^{\circ}\text{C}$) is about $-500\text{ }\mu\text{strain}$ reflecting a coefficient of thermal expansion
 165 equal to $25\text{ }\mu\text{m}/\text{m}/^{\circ}\text{C}$, which is typical of AC materials.

166 Concerning the saturated specimen, the evolution of the axial and the radial strain is similar at
 167 the beginning to that obtained under dry condition. However, it exhibits for a while afterwards
 168 a “chaotic” phase composed of several peaks oriented opposite to the strain direction
 169 observed until that moment during cooling. Once this phase is over, the strain evolution
 170 becomes smooth again till the end of the test and is homothetic to the temperature curve
 171 whose decrease is ending at this time to eventually reach a plateau. During the “chaotic”
 172 phase, the evolution of the axial strain is not exactly similar to that of the radial strain but the
 173 two curves are superimposed again during the last part of the test.

174

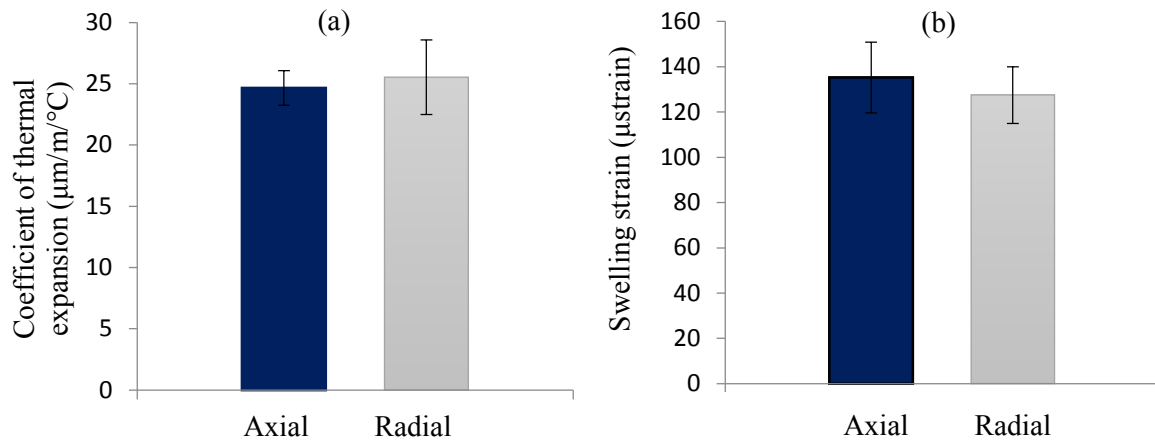


175

176 Figure 4: Corrected measurements of the axial and the radial strain recorded for an AC sample tested
 177 under dry and wet conditions ($n = 7.7\%$ and $S_r = 65\%$) and temperature evolution measured on the
 178 outer surface of the dry specimen during CTFS testing.

179 The comparison between the strain plateaus obtained for the dry and the wet specimens at the
180 end of the test at a temperature of $-10\text{ }^{\circ}\text{C}$ shows a positive difference (swelling) of about
181 $130\text{ }\mu\text{strain}$ and $110\text{ }\mu\text{strain}$ in the radial and the axial direction, respectively. This difference
182 clearly results from the “chaotic phase” which undoubtedly can be associated to the water
183 phase change from liquid to ice within the whole sample. Indeed solidification is known to
184 induce an increase of 9% in volume in the case of free water. For the six tests of the CTFS
185 campaign, the swelling (“chaotic”) phase starts as the external temperature is below $-2\text{ }^{\circ}\text{C}$
186 instead of $0\text{ }^{\circ}\text{C}$ probably due to several physical phenomena taking place in the AC samples.
187 These phenomena can be related to capillary forces, stagnancy of pore water and super
188 cooling effect, the chemical change of pore water at contact with the aggregates, etc.

189 Figure 5 shows a summary of the results obtained in this campaign. As displayed in figure 5a
190 on the left, the coefficients of thermal expansion calculated for the dry specimens in the axial
191 and the radial directions can be considered similar; the relative difference between them is
192 lower than 3%. On the other hand, figure 5b shows that the relative difference in terms of
193 swelling strain obtained in the two directions is also very small and of the order of 6%.
194 Consequently, the behavior of the AC specimens (dry or saturated) can be assumed as
195 isotropic.



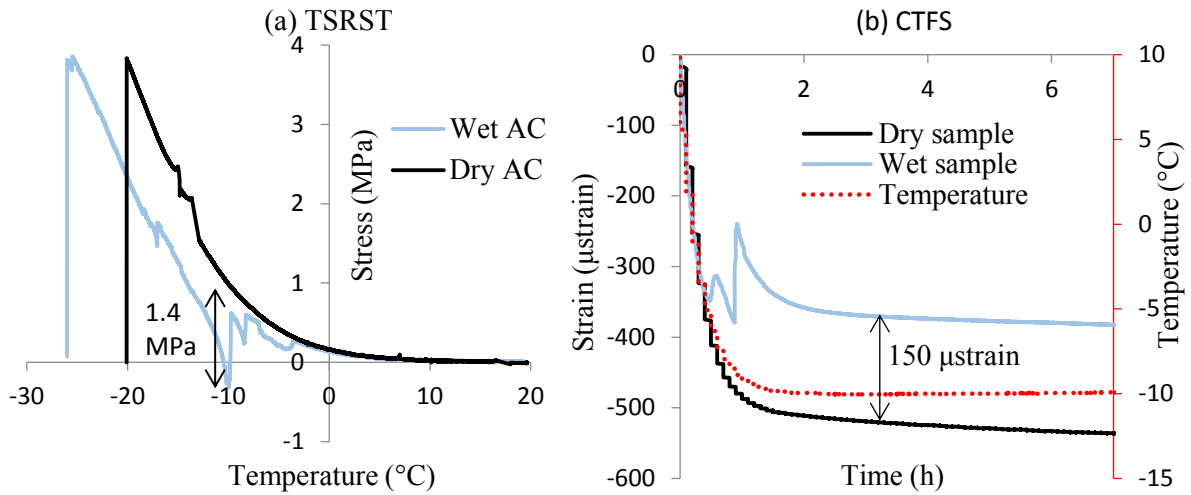
196

197 Figure 5: Comparison between the corrected measurements recorded in the axial and the radial
 198 directions: (a) Coefficients of thermal expansion for the dry specimens. (b) Swelling strains in the case
 199 of saturated specimens. (Error bars show the standard deviation of the measurements performed on 6
 200 samples).

201

202 *Effect of water phase change on the measured stress evolution during TSRST testing*

203 Representative results from TSRST testing are shown in figure 6a which displays the stress
 204 evolution obtained for dry and wet specimens when temperature is decreased from 20 °C to
 205 -30 °C. The dry and the saturated AC samples have a porosity of 5.9% and 5.1%,
 206 respectively. The saturated sample was first subjected to CTFS testing and then to TSRST
 207 testing once saturation has been refilled to the initial level of 60%. The swelling strain for the
 208 saturated AC specimen is inferred from the difference between the final plateaus resulting
 209 from CTFS testing (Fig. 6b); a value of 150 μstrain is obtained (axial direction).



210

211 Figure 6: Comparison between the mechanical responses in terms of stress and strain obtained for the
 212 dry and wet AC samples: (a) TSRST, (b) CTFS

213 Concerning stress evolution, the dry AC sample exhibits the characteristic response of asphalt
 214 concrete materials tested according to the TSRST protocol (Fig 6a); the axial tensile stress
 215 increases as temperature decreases to compensate thermal contraction. Due to hardening of
 216 the AC material with temperature (loss of relaxation capability), the tensile stress increases
 217 more and more as temperature diminishes. The tests stops brutally at failure of the specimen
 218 (*i.e.* 4 MPa at -21 °C), as illustrated by the drop of the stress curve in figure 6a.

219 At the beginning of the test and as long as temperature is higher than the freezing point of
 220 pore water detected at around -5°C, the saturated sample exhibits a quite similar response as
 221 the dry sample. For temperature variations from -5 °C to -10 °C, a decrease of the stress
 222 magnitude is then observed, even leading to slight compression at -10 °C. Afterward, the
 223 stress curve for the wet AC becomes similar again to that of the dry AC, remaining parallel to
 224 it but below. Failure of the (partially) saturated specimen is reached for the same stress value
 225 as the dry specimen (\approx 4 MPa) but at a lower temperature (-26 °C instead of -21 °C).

226 Basically, the shift between the two curves can be interpreted by a compressive stress of
 227 magnitude 1.4 MPa developing in the specimen during the phase change of water into ice.

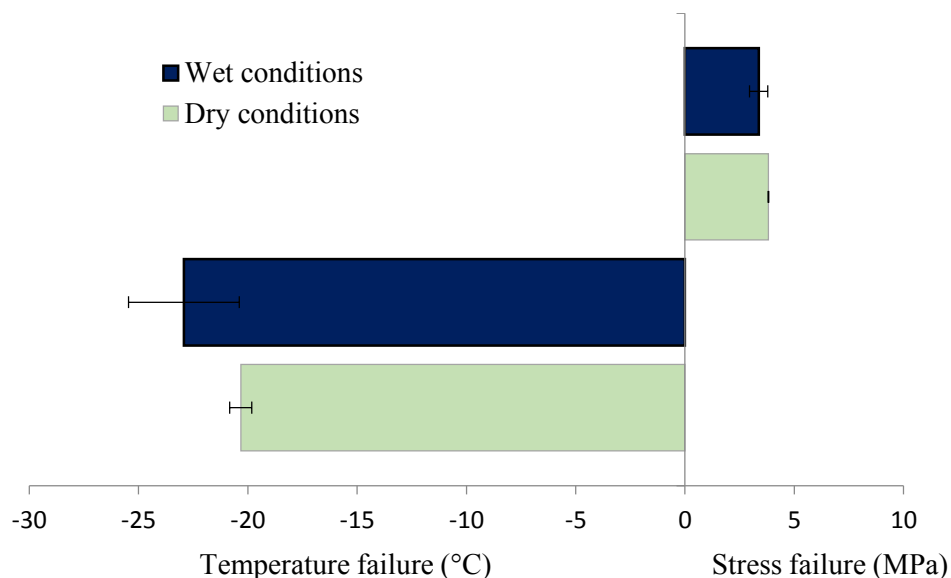
228 Comparison of the CTFS and the TSRST results for this saturated specimen indicates that the

229 1.4 MPa “swelling stress” can be considered roughly as the counterbalance effect of the
230 150×10^{-6} “swelling strain” through a secant modulus of 10,000 MPa during the water
231 phase change.

232 The trend observed for this particular sample is confirmed by the rest of the TSRST
233 campaign. The average temperature at failure is lower for the saturated than for the dry
234 specimens. The values obtained are $-23 \pm 2.5^\circ\text{C}$ and $-20.3 \pm 0.5^\circ\text{C}$, respectively (Fig 7). On the
235 other hand, the average critical stress value at material failure seems to be slightly higher for
236 dry than for saturated specimens with values equal to $3.8 \pm 0.01 \text{ MPa}$ and $3.37 \pm 0.4 \text{ MPa}$,
237 respectively (Fig 7).

238 However, note that the lower temperature obtained at failure for the saturated specimens must
239 not be interpreted as an improvement of mechanical performance of the material in presence
240 of water. TSRST test rather shows that a frost front propagating into saturated AC layers of
241 pavements can develop unexpected internal stress field which effects need to be further
242 investigated.

243



244

245 Figure 7: Comparison between the dry and the saturated AC specimens in terms of temperature and
246 critical stress obtained at failure (averaged over all the samples of the TSRST campaign and error bars
247 show the standard deviation of the measurements performed on 3 dry and 5 saturated samples).

249 The impact of the phase change of pore water into ice on the creep function was studied in
250 [16] on the basis of complex modulus test campaigns performed on the same AC sample in
251 dry and saturated conditions. For temperatures above the freezing point of pore water no
252 difference is observed between these two conditions, whereas ice formation is found to
253 increase the stiffness of saturated AC specimens. However, the increase is less than 10 % and
254 is not considered in the following.

255 **3. CONSTITUTIVE MODEL DEDICATED TO THE BEHAVIOR OF SATURATED** 256 **AC EXPOSED TO FREEZING**

257 The experimental results presented earlier in this paper are used here to develop a constitutive
258 law for the modeling of the thermo-mechanical behavior of partially saturated AC materials
259 exposed to freezing. As well known, bituminous mixes are thermo-sensitive materials
260 exhibiting viscoelastic properties which are accurately captured by the Huet model [17].
261 Consequently, the developed law is based on this model and extends its scope to taking into
262 account variable temperature condition, thermal expansion and swelling effects due to phase
263 change of pore water.

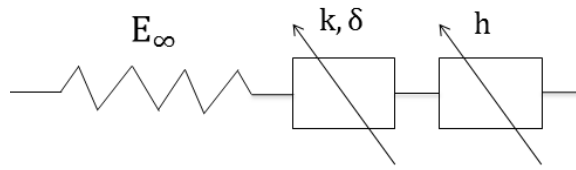
264 The development of the constitutive law is presented step-by-step in this section, going from
265 the unidimensional behavior of AC under isothermal condition to the full tridimensional
266 expression including all the aforementioned physical phenomena, especially frost effects. The
267 developed constitutive law is then discretized in time and implemented in a numerical
268 program. Finally this law is used to model the CTFS and the TSRST tests and is validated
269 against the experimental data.

270 **The Huet model under isothermal condition**

271 *Rheological model and strain as a convolution integral (1D)*

272 The Huet model is a viscoelastic model composed of a linear elastic spring of modulus E_∞
 273 connected in series with two parabolic dashpots of exponent k and h (Fig 8). The creep
 274 function for this model depends on time, t , and temperature, θ , and reads:

275



276

277 Figure 8: The Huet rheological model.

278

279
$$J_H(t, \theta) = J_{h,k} \left(\frac{t}{a(\theta)} \right) \quad (4)$$

280 With

281
$$J_{h,k}(u) = \frac{1}{E_\infty} \left(1 + \frac{u^h}{\Gamma(h+1)} + \delta \frac{u^k}{\Gamma(k+1)} \right) \quad (5)$$

282 in which $\Gamma(\cdot)$ stands for the gamma function and δ is a weight parameter associated to the
 283 dashpot of exponent k .

284 The creep function is written with respect to the single scalar variable $\frac{t}{a(\theta)}$ by virtue of the
 285 time-temperature equivalence principle applying for asphalt materials. $a(\theta)$ denotes the time-
 286 temperature shift factor, which in this work is expressed as follows:

287

288
$$a(\theta) = \exp(A_0 + A_1\theta + A_2\theta^2) \quad (6)$$

289

290 where A_0, A_1 and A_2 are constant parameters of the model.

291 The Huet model parameters can be identified using experimental data stemming from
 292 complex modulus tests performed in the frequency domain.

293 The constitutive law is then provided by the mathematical relationship below (of type Stieltjes
 294 convolution integral), which expresses the strain response (ε) to the stress history function σ :

295

$$296 \quad \varepsilon(t) = J_H(t, \theta) \otimes \dot{\sigma}(t) = \int_{-\infty}^{\infty} J_H(t - \tau, \theta) \frac{d}{dt} \sigma(\tau) dt \quad (7)$$

297

298 *Tridimensional strain response in the time domain*

299 For an isotropic material, the above constitutive equation (Eq. 7) can be extended to the
 300 tridimensional case by considering the deviatoric and the volumetric components of strain and
 301 stress tensors and introducing the creep function for each of them. In this paper, Poisson's
 302 ratio is assumed real and constant leading to the following Hooke type constitutive
 303 relationship:

304

$$305 \quad \boldsymbol{\varepsilon}(t) = J_H(t, \theta) \otimes [(1 + \nu)\dot{\boldsymbol{\sigma}}(t) - \nu \operatorname{tr}(\dot{\boldsymbol{\sigma}}(t)) \mathbf{I}] = \int_0^t J_H(t - \tau, \theta) \frac{d}{dt} [(1 + \nu)\dot{\boldsymbol{\sigma}}(\tau) -$$

$$306 \quad \nu \operatorname{tr}(\dot{\boldsymbol{\sigma}}(\tau)) \mathbf{I}] dt \quad (8)$$

307

308 where $\boldsymbol{\varepsilon}$, $\boldsymbol{\sigma}$ are tensors of strain and stress, respectively and \mathbf{I} is the unit 3×3 tensor

309 **Constitutive law for asphalt materials under variable temperature condition**

310 Temperature variation has two significant effects to be considered on the behavior of dry
311 asphalt materials: (i) thermal expansion, (ii) change of creep function. Considering the case of
312 saturated AC material, a third effect due to swelling has to be added as shown by the
313 experimental findings presented before.

314

315 *Model for the case of dry AC material*

316 The thermal expansion is accounted for through the classical relationship:

317
$$\boldsymbol{\varepsilon}^{th}(\theta) = \alpha \Delta\theta \mathbf{I} \quad (9)$$

318 in which α is the coefficient of thermal expansion ($\mu\text{m}/\text{m}/^\circ\text{C}$) and $\Delta\theta(t) = \theta(t) - \theta_o$ is the
319 difference between the temperature at time t and that of the reference state denoted θ_o .

320 On the other hand, the computation of the mechanical strain under variable temperature can
321 be achieved using the concept of “equivalent time” defined by [18]:

322
$$t_e(t) = \int_0^t \frac{d\tau}{a(\theta(\tau))} \quad (10)$$

323 This expression can be easily derived for a Kelvin-Voigt model which viscosity is
324 proportional to $a(\theta)$. Using the time t_e instead of t makes it possible to express this model as
325 a Kelvin Voigt constitutive law but with constant viscosity and independently of the
326 temperature. This property extends to the Huet model using the spectral decomposition of its
327 creep function as an infinite series of Kelvin Voigt elements which viscosity depends for all
328 of them upon the same $a(\theta)$ function.

329 Considering only on the mechanical strain, the Stieltjes integral then writes:

330

331
$$\boldsymbol{\varepsilon}(t_e) = \int_0^{t_e} J_{h,k}(t_e - \tau_e) \left[(1 + \nu) \frac{d\boldsymbol{\sigma}}{dt_e}(\tau_e) - \nu \operatorname{tr} \frac{d\boldsymbol{\sigma}}{dt_e}(\tau_e) \mathbf{I} \right] d\tau_e \quad (11)$$

332 That is, coming back to time t and taking also the thermal strain part, the viscoelastic law
 333 under variable temperature:

334
$$\boldsymbol{\varepsilon}(t) = \int_0^t J_{h,k}(t_e(t) - t_e(\tau)) [(1 + \nu)\dot{\boldsymbol{\sigma}}(\tau) - \nu \operatorname{tr} \dot{\boldsymbol{\sigma}}(\tau) \mathbf{I}] d\tau + \boldsymbol{\varepsilon}^{th}(\theta(t)) \quad (12)$$

335 *Model for the case of partially saturated AC material*

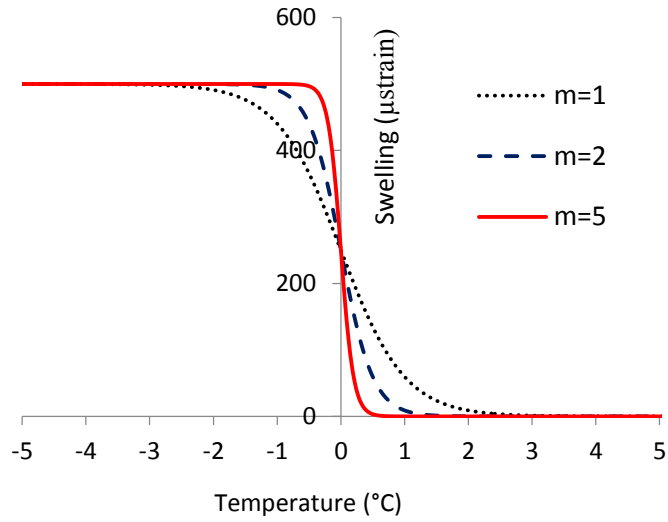
336 In addition to thermal expansion and change in the creep (resp. relaxation) capability and as
 337 evidenced by the experimental tests presented in section 2, saturated AC exhibits swelling
 338 effects when temperature is varied passing through the freezing point of pore water.

339 With regards to CTFS test, here we suggest to model the swelling effects by adding a strain
 340 component $\boldsymbol{\varepsilon}_f$ to the constitutive law (Eq. 12). This one is assumed isotropic and depending
 341 on the difference between the temperature of the material and that of the freezing point of
 342 pore water θ_f . As already mentioned, θ_f may depend on several physical phenomena taking
 343 place in the porous asphalt and not considered in the model. From the macroscopic point of
 344 view of the present approach, θ_f is set according to the temperature at which the behavior of
 345 the saturated AC sample departs from that of the dry sample in the experimental tests. Thus,
 346 the swelling strain is defined as:

347
$$\boldsymbol{\varepsilon}_f(\theta(t)) = \varepsilon_{f0} \frac{1 - \tanh[m(\theta(t) - \theta_f)]}{2} \mathbf{I} \quad (13)$$

348 where m is a parameter that allows us to adjust the temperature range (centered in θ_f) for
 349 which most of the swelling deformation occurs (Figure 9). This parameter is used to calibrate
 350 the transition of ε_f from zero prior to freezing to ε_{f0} after full completion of the phase change
 351 of pore water. Depending on the value of m , this transition can go from quite smooth to sharp.

352



353

354 Figure 9: Swelling strain as a function of temperature for different values of parameter m and

355 $\theta_f = 0^\circ C$

356

357 Finally, the constitutive law developed to represent the thermo-mechanical behavior of AC

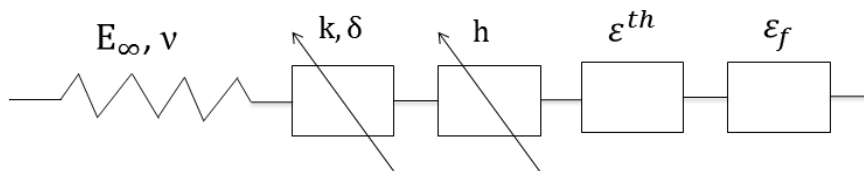
358 partially saturated with water can be schematized by the rheological model shown in figure

359 10. Considering a constant Poisson's ratio, the three dimensional expression of this law (for

360 variable temperature) is given by:

361
$$\boldsymbol{\varepsilon}(t) = \int_0^t J_{h,k}(t_e(t) - t_e(\tau)) [(1 + \nu)\dot{\boldsymbol{\sigma}}(\tau) - \nu \text{tr } \dot{\boldsymbol{\sigma}}(\tau) \mathbf{I}] d\tau + \boldsymbol{\varepsilon}^{th}(\theta(t)) + \boldsymbol{\varepsilon}_f(\theta(t)) \quad (14)$$

362



363

364 Figure 10: Sketch of the rheological model developed to model saturated AC materials.

365

366 **Time discretization of the three-dimensional constitutive law**

367 As shown by Eq. (14) the developed constitutive law is complex and its use requires
368 numerical computation. In this section, we present the time discretization of this law for
369 isothermal and variable temperature conditions. For both cases, expression of the strain tensor
370 at time t_n for a given stress history function is derived as well as the dual expression of the
371 stress tensor in response to a given strain history function.

372 *Constitutive law in isothermal condition*

373 Under this condition, the θ variable is omitted in the following equations. Using the Euler
374 method and considering the time interval $[t_i, t_{i+1}]$, we approximate the time derivative of the
375 stress tensor in Eq. (12) by the following finite difference: $\dot{\sigma}(t) \approx \frac{\sigma_{i+1} - \sigma_i}{\Delta t}$, where $\Delta t =$
376 $t_{i+1} - t_i$ is the time step assumed constant. At first, we focus on the assessment of $\epsilon(t_n)$ at
377 the different times $t_0, t_1, \dots, t_i, \dots, t_N$ resulting from the following implicit calculation of
378 Eq. (12):

379
$$\epsilon(t_n) \approx \sum_{i=0}^{n-1} \int_{t_i}^{t_{i+1}} J_H(t_n - \tau) d\tau \frac{(1+\nu)[\sigma_{i+1} - \sigma_i] - \nu \text{tr}(\sigma_{i+1} - \sigma_i) \mathbf{I}}{\Delta t} \quad (15)$$

380 Here we assume that at step n all strain and stress quantities ϵ_i, σ_i for $0 \leq i \leq n - 1$ have
381 already been computed and are known.

382 The definite integral of the creep function at each time step is computed according to the
383 trapezoidal rule, which for only one interval between t_i and t_{i+1} leads to:

384
$$\epsilon(t_n) \approx \sum_{i=0}^{n-1} \frac{J_H(t_n - t_{i+1}) + J_H(t_n - t_i)}{2} \Delta t \times \frac{(1+\nu)[\sigma_{i+1} - \sigma_i] - \nu \text{tr}(\sigma_{i+1} - \sigma_i) \mathbf{I}}{\Delta t} \quad (16)$$

385 For the sake of simplification, we denote by $\bar{\chi}$ the tensor of all the known values from t_0 to
 386 t_{n-1} related to history of the stress tensor. $\bar{\chi}$ is defined by:

387

$$388 \quad \bar{\chi} = J_{H_{n,n}} [(1 + \nu) \boldsymbol{\sigma}(t_{n-1}) - \nu \operatorname{tr}(\boldsymbol{\sigma}(t_{n-1})) \mathbf{I}] - \sum_{i=0}^{n-2} J_{H_{n,i+1}} [(1 + \nu) \boldsymbol{\sigma}(t_{i+1}) - \\ 389 \quad \nu \operatorname{tr} \boldsymbol{\sigma}(t_{i+1}) \mathbf{I}] - [(1 + \nu) \boldsymbol{\sigma}(t_i) - \nu \operatorname{tr} \boldsymbol{\sigma}(t_i) \mathbf{I}] \quad (17)$$

390

391 in which:

$$392 \quad J_{H_{n,i+1}} = \frac{J_H(t_n - t_{i+1}) + J_H(t_n - t_i)}{2} \quad (18)$$

393 Using this notation, Eq. (17) simply reads:

$$394 \quad \boldsymbol{\varepsilon}(t_n) = J_{H_{n,n}} [(1 + \nu) \boldsymbol{\sigma}(t_n) - \nu \operatorname{tr}(\boldsymbol{\sigma}(t_n)) \mathbf{I}] - \bar{\chi} \quad (19)$$

395 Eq. (19) can be used to compute the response in terms of strain at time t_n to a prescribed
 396 stress history function. To obtain the response in terms of stress to an imposed strain history
 397 function, Eq. (19) must be reversed. To accomplish this, we first notice from Eq. (19) that:

$$398 \quad \operatorname{tr} \boldsymbol{\sigma}(t_n) = \frac{1}{(1-2\nu)J_{H_{n,n}}} [\operatorname{tr} \boldsymbol{\varepsilon}(t_n) + \operatorname{tr}(\bar{\chi})] \quad (20)$$

399 Substituting Eq. (20) into Eq. (19) leads to:

$$400 \quad \boldsymbol{\sigma}(t_n) = \frac{1}{(1+\nu)J_{H_{n,n}}} [\boldsymbol{\varepsilon}(t_n) + \bar{\chi}] + \frac{\nu}{(1+\nu)(1-2\nu)J_{H_{n,n}}} [\operatorname{tr} \boldsymbol{\varepsilon}(t_n) + \operatorname{tr} \bar{\chi}] \mathbf{I} \quad (21)$$

401 With:

$$402 \quad \lambda_n = \frac{\nu}{(1-2\nu)(1+\nu)J_{H_{n,n}}}, \text{ and } \mu_n = \frac{1}{2(1+\nu)J_{H_{n,n}}} \quad (22)$$

403 the expression of the stress tensor at the time t_n is finally given by:

404

405
$$\boldsymbol{\sigma}(t_n) = 2\mu_n \boldsymbol{\varepsilon}(t_n) + \lambda_n \text{tr} \boldsymbol{\varepsilon}(t_n) \mathbf{I} + 2\mu_n \bar{\boldsymbol{\chi}} + \lambda_n \text{tr} \bar{\boldsymbol{\chi}} \mathbf{I} \quad (23)$$

406

407 This equation at time t_n is similar to Hooke's law with "initial" stress.

408

409 *Constitutive law for variable temperature condition*

410 In the case of a partially saturated AC subjected to variable temperature condition the
 411 constitutive law is given by Eq (14). Its discretized expression is derived in a similar way as
 412 that of the isothermal case adding the concept of equivalent time, thermal expansion and the
 413 swelling strain. The discretized form at time t_n reads:

414
$$\boldsymbol{\varepsilon}(t_n) = \tilde{J}_{H_{n,n}} [(1 + \nu) \boldsymbol{\sigma}(t_n) - \nu \text{tr} (\boldsymbol{\sigma}(t_n)) \mathbf{I}] - \bar{\boldsymbol{\chi}}' + \boldsymbol{\varepsilon}^{th}(\theta(t_n)) + \boldsymbol{\varepsilon}_f(\theta(t_n)) \quad (24)$$

415 where the quantities

416
$$\tilde{J}_{H_{n,i+1}} = \frac{J_H(t_e(t_n) - t_e(t_{i+1})) + J_H(t_e(t_n) - t_e(t_i))}{2} \quad (25)$$

417 are now computed considering the equivalent time evaluated as:

418
$$t_e(t_n) = \int_0^{t_n} \frac{d\tau}{a(\theta(\tau))} = \sum_{i=0}^{n-1} \frac{\Delta t}{2} \left[\frac{1}{a(\theta(t_{i+1}))} + \frac{1}{a(\theta(t_i))} \right] \quad (26)$$

419 The tensor $\bar{\boldsymbol{\chi}}'$ refers to quantities evaluated for past times (from t_0 to t_{n-1}) and is given by:

420
$$\bar{\boldsymbol{\chi}}' = \tilde{J}_{H_{n,n}} [(1 + \nu) \boldsymbol{\sigma}(t_{n-1}) - \nu \text{tr} (\boldsymbol{\sigma}(t_{n-1})) \mathbf{I}] - \sum_{i=0}^{n-2} \tilde{J}_{H_{n,i+1}} [(1 + \nu) \boldsymbol{\sigma}(t_{i+1}) -$$

 421
$$\nu \text{tr} \boldsymbol{\sigma}(t_{i+1}) \mathbf{I}] - [(1 + \nu) \boldsymbol{\sigma}(t_i) - \nu \text{tr} \boldsymbol{\sigma}(t_i) \mathbf{I}] \quad (27)$$

422

423 The thermal expansion and freezing strain at time t_n are computed using the following
 424 expressions:

425
$$\boldsymbol{\varepsilon}^{th}(\theta(t_n)) = \alpha (\theta(t_n) - \theta(t_0)) \mathbf{I} \quad (28)$$

426 and

427
$$\boldsymbol{\varepsilon}_f(\theta(t_n)) = \varepsilon_{f0} \frac{1 - \tanh[m(\theta(t_n) - \theta_f)]}{2} \mathbf{I} \quad (29)$$

428

429 $\boldsymbol{\varepsilon}(t_n)$ can be computed from Eq. (24) when $\boldsymbol{\sigma}(t_n)$ is given. Conversely, Eq. (30) provides the
 430 stress tensor at time t_n as a function of strain and quantities related to the loading history of
 431 the material:

432
$$\boldsymbol{\sigma}(t_n) = 2\tilde{\mu}_n \boldsymbol{\varepsilon}(t_n) + \tilde{\lambda}_n \text{tr}(\boldsymbol{\varepsilon}(t_n)) \mathbf{I} + \mathbf{Y}_n \quad (30)$$

433 With

434
$$\mathbf{Y}_n = 2\tilde{\mu}_n [\bar{\boldsymbol{\chi}}' - \boldsymbol{\varepsilon}^{th}(\theta(t_n)) - \boldsymbol{\varepsilon}_f(\theta(t_n))] + \tilde{\lambda}_n \text{tr}[\bar{\boldsymbol{\chi}}' - \boldsymbol{\varepsilon}^{th}(\theta(t_n)) - \boldsymbol{\varepsilon}_f(\theta(t_n))] \mathbf{I} \quad (31)$$

435

436 and

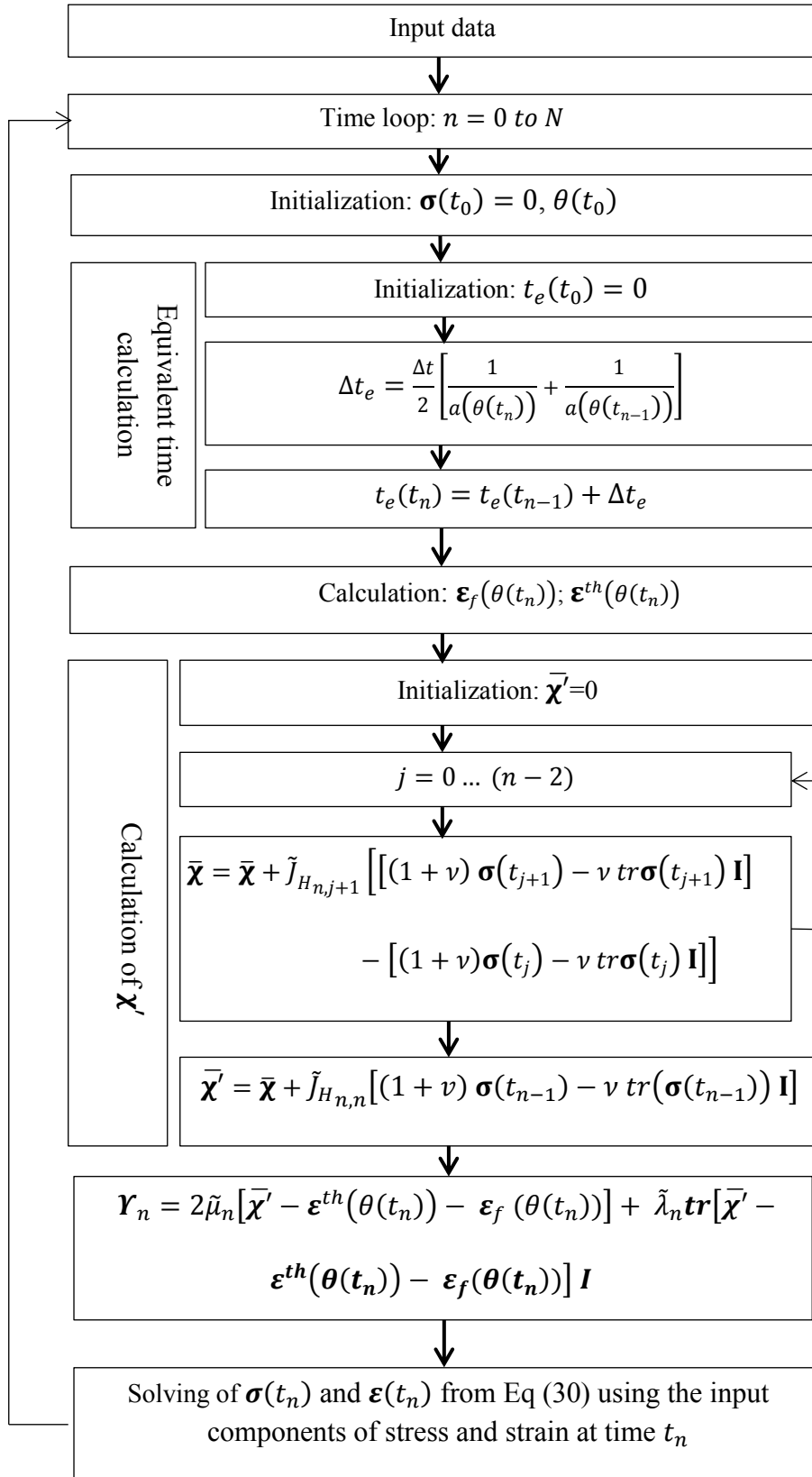
437
$$\tilde{\lambda}_n = \frac{\nu}{(1-2\nu)(1+\nu)\tilde{J}_{n,n}}, \quad \text{and} \quad \tilde{\mu}_n = \frac{1}{2(1+\nu)\tilde{J}_{n,n}} \quad (32)$$

438

439 Eq (30) also reads like Hooke's law with "initial" stress \mathbf{Y}_n .

440 *Algorithm for the computation of the mechanical response*

441 The equations above are implemented in a numerical program. Figure 11 shows the different
 442 steps of the algorithm utilized to compute the whole set of strain and stress tensor components
 443 in response to the given ones considering variable temperature, thermal expansion and
 444 swelling strain. The developed program is used in the next section to model the behavior of
 445 dry and saturated AC during CTFS and TSRST testing.



446

447 Figure 11: Algorithm for evaluation of the constitutive law under variable temperature

448 **4. MODELING OF CTFS AND TSRST WITH THE DEVELOPED CONSTITUTIVE**
 449 **LAW**

450 The developed constitutive relationship can be used now to simulate the transient response of
 451 AC samples in the CTFS and TSRST tests, assuming homogeneous temperature, strain and
 452 stress within the samples over the all duration of the tests. The numerical results are compared
 453 with the experimental data presented in section 2 obtained with the same specimen submitted
 454 to the two tests. The viscoelastic properties of the AC material are characterized from
 455 complex modulus tests [19] for the dry AC sample and the use of software Viscoanalyse to
 456 determine the Huet parameters. The values obtained are shown in Table 2. Poisson’s ratio is
 457 set to 0.28. The other material parameters related to thermal expansion and freezing are
 458 inferred from the CTFS and TSRST testing (Table 2).

459 The input temperature for the simulations is that measured by the sensor placed at the surface
 460 of the dry specimen.

461

Huet model parameters	Thermal expansion coefficient ($\mu m/m/^{\circ}C$)	Swelling strain coefficients
$E_{\infty} = 34862 MPa; h = 0.57;$ $k = 0.21; \delta = 1.96; \nu = 0.28$	$\alpha = 25$	$m = 5; \varepsilon_{f0} = 150 \mu strain; \theta_f =$ $-6^{\circ}C$ for CTFS and $\theta_f = -10^{\circ}C$ for TSRST

462 Table 2: Properties of the used AC materials

463

464 **CTFS test modeling**

465 In this test, stress free boundary condition applies on the outer surface of the specimen

466 $\sigma(t) = 0$. The components of the strain tensor in cylindrical coordinates check:

467 $\varepsilon_{rr}(t) = \varepsilon_{\theta\theta}(t) = \varepsilon_{zz}(t)$ and $\varepsilon_{rz}(t) = \varepsilon_{r\theta}(t) = 0$.

468 Figure 12 shows the computed strain for the dry and saturated conditions as well as the

469 comparison with the experimental data. The model accuracy for the dry condition is

470 satisfying; a thermal expansion coefficient of $25 \mu\text{strain}/^\circ\text{C}$ leading to a thermal strain

471 approximately equal to $500 \mu\text{strain}$ for $\Delta\theta = -20^\circ\text{C}$. On the other hand, the numerical

472 curve obtained for the saturated condition exhibits globally a similar evolution as the

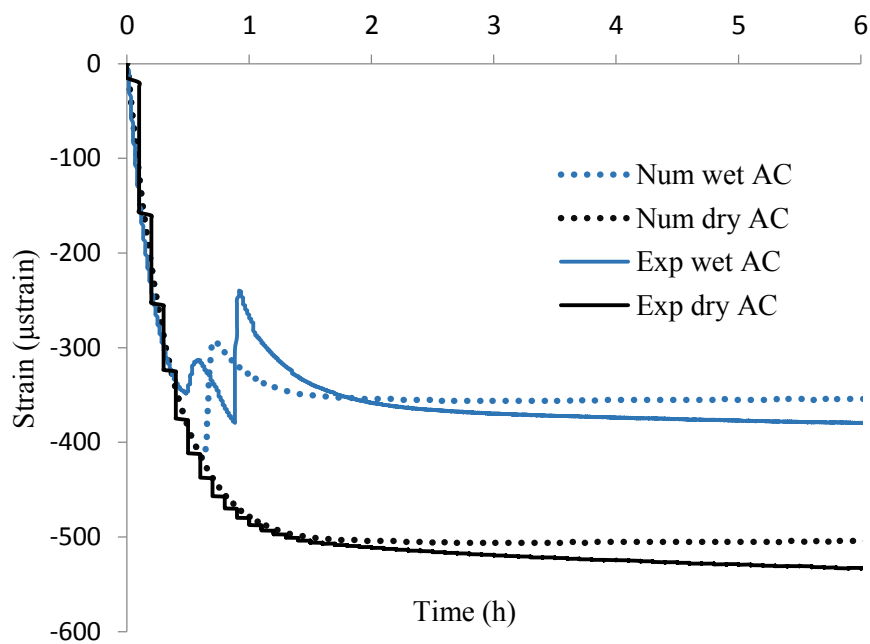
473 experimental curve. However, in accordance to the modeling approach considered here only

474 one single peak is observed during the phase change time period. The model performs

475 relatively well though, when ε_{f0} is determined as the difference of strain between the plateaus

476 obtained for the dry and the saturated conditions at the end of testing.

477



478

479 Figure 12: Comparison between the numerical results and experimental data obtained for CTFS under

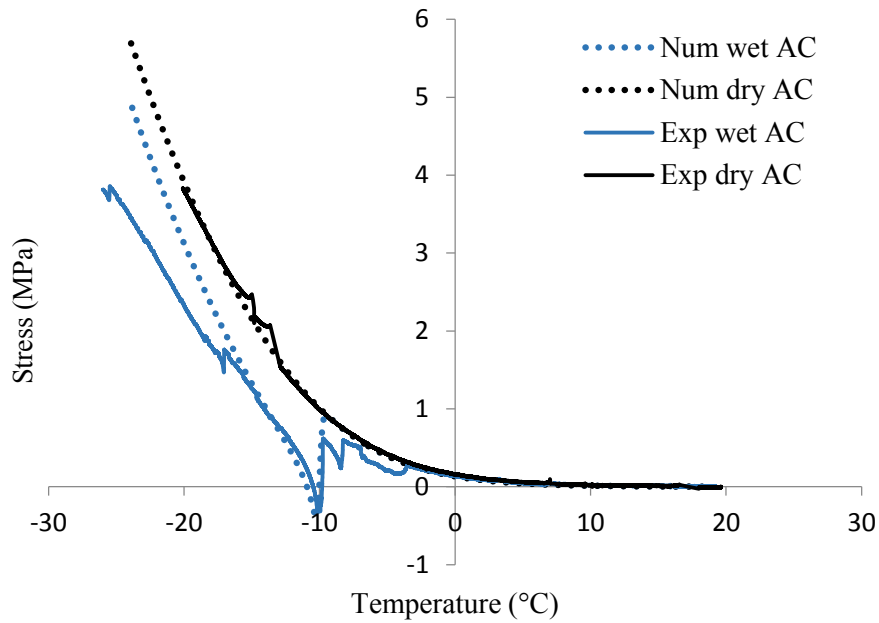
480 dry and wet conditions.

481 **TSRST test modeling**

482 In that case, the two unknowns are the axial stress $\sigma_{zz}(t)$ due to the force applied by the
483 piston to ensure zero deformation of the specimen in the axial direction and the resulting
484 radial strain $\varepsilon_{rr}(t)$. The other strain and stress components are assumed zero.

485 Figure 13 shows the comparison between the curves of experimental and computed axial
486 stress obtained for dry and wet conditions. Obviously the specimen rupture observed at the
487 end of the test (Figure 6a) cannot be reproduced since not accounted for in the model. In the
488 simulations, ε_{f0} is set to zero and $150 \mu\text{strain}$ (according to CTFS testing results) for the dry
489 and saturated conditions, respectively. As shown in Figure 13, a good agreement is obtained
490 for the dry condition revealing the relevance of the concept of equivalent time. The results
491 obtained for the saturated case are also fairly good overall. As long as temperature is greater
492 than $\theta_f = -10^\circ\text{C}$, the stress evolution is superimposed with that of the dry AC. For
493 temperature around θ_f , the axial stress shows an abrupt decrease and even enter the
494 compressive domain. This phase coincides in the model with the occurrence of the peak due
495 to ε_f . This drop in the axial stress is well captured by the model as the counterpart of the
496 swelling effect modeled through ε_f . Afterwards the curve evolves similarly again to that of
497 the dry specimen but is shifted due to the drop undergone at freezing.

498



499

500 Figure 13: Comparison between TSRST experimental data and the simulated axial stress obtained for
 501 the dry and partially saturated conditions

502

503 Finally, the agreement of the simulations with the experimental data is fairly good for both
 504 tests what validates the developed model incorporating thermal expansion and swelling strain
 505 and relying on the concept of equivalent time. It is shown that the calibration of the swelling
 506 strain can be performed according to CTFS testing once full solidification of pore water has
 507 taken place. Then the model makes it possible to simulate accurately the complex evolution of
 508 the axial stress observed during TSRST testing of the saturated AC specimens.

509 **5. CONCLUSION**

510 The purpose of the present research was to study the thermo-mechanical behavior of partially
 511 saturated asphalt concrete (AC) materials subjected to freezing. This research program was
 512 initiated following the sudden damaging of asphalt pavements observed during recent winters
 513 in France and Northern Europe countries.

514 Two types of experimental tests were carried out in this study; CTFS and TSRST testing were
515 performed on dry and partially saturated samples to evaluate the impact of freezing pore water
516 on the behavior of saturated AC. The test results have revealed a significant effect with
517 prominent and brutal changes of the mechanical response in terms of strain (swelling) or
518 stress of the specimens tested. In addition, these tests have indicated that deformation due to
519 thermal expansion and swelling was quite isotropic. Concerning TSRST testing, the
520 (negative) temperature at which failure occurs was found to be 12% lower for the saturated
521 specimens than for the dry ones. In that case, the critical stress at failure was also slightly
522 smaller.

523 In parallel, a tridimensional constitutive model dedicated to saturated AC materials was
524 developed on the basis of experimental results. The development of this model has taken into
525 account the following characteristics of AC: viscoelasticity, thermal expansion and swelling
526 effect under variable temperature. Discretization of this law was implemented in a numerical
527 program and was validated through simulation of the CTFS and TSRST testing.

528 It is believed that the significant frost effects observed during CTFS and TSRST transposed to
529 a pavement structure could lead to the issue mentioned above. Further steps in this research
530 will thus include testing on pavement structures and implementation of the developed
531 constitutive law in a finite element (FE) code coupling the mechanical problem to the heat
532 equation with phase change. These simulations will be used to investigate the impact of
533 swelling and self-stress effects developing at the frost front.

534 **ACKNOWLEDGMENT**

535 The authors gratefully acknowledge LHOIST Southern Europe for the financial support to
536 this work. Experimental tests in the laboratory were carried out at IFSTTAR Nantes.

537 **REFERENCES**

- 538 [1] Vulcano- GN, Kerzreho JP, Mauduit V, and Chabot A, “Stripping phenomenon of top layers of
539 thick pavements,” presented at the 11th International Conference on Asphalt Pavements, France,
540 2010.
- 541 [2] V. Mauduit *et al.*, “Dégradation subite des enrobés bitumineux par période de gel/dégel: Analyse
542 de cas de terrain et recherche exploratoire en laboratoire,” *Bull. Lab. Ponts Chaussées*, no. 279,
543 p. pp–47, 2013.
- 544 [3] C. Mauduit, F. Hammoum, J.-M. Piau, V. Mauduit, S. Ludwig, and D. Hamon, “Quantifying
545 expansion effects induced by Freeze-Thaw cycles in partially water saturated bituminous mix:
546 Laboratory Experiments,” *Road Mater. Pavement Des.*, vol. 11, no. sup1, pp. 443–457, 2010.
- 547 [4] S. Lamothe, D. Perraton, and H. Di Benedetto, “Contraction and expansion of partially saturated
548 hot mix asphalt samples exposed to freeze–thaw cycles,” *Road Mater. Pavement Des.*, vol. 16,
549 no. 2, pp. 277–299, 2015.
- 550 [5] S.Caro, E.Masad, A.Bhasin, and D.N.Little, “Moisture susceptibility of asphalt mixtures part 1:
551 Mechanisms,” *Int. J. Pavement Eng.*, vol. 9, no. 2, pp. 81–98, Apr. 2008.
- 552 [6] S.Caro, E.Masad, A.Bhasin, and D.N.Little, “Moisture susceptibility of asphalt mixtures part 2:
553 Characterisation and modeling,” *Int. J. Pavement Eng.*, vol. 9, no. 2, pp. 99–114, 2008.
- 554 [7] R. Roberson and J. Siekmeier, “Determining material moisture characteristics for pavement
555 drainage and mechanistic empirical design,” *Res. Bull. Minn. Dep. Transp. Off. Mater. Road
556 Res.*, 2002.
- 557 [8] X. Chen and B. Huang, “Evaluation of moisture damage in hot mix asphalt using simple
558 performance and superpave indirect tensile tests,” *Constr. Build. Mater.*, vol. 22, no. 9, pp.
559 1950–1962, 2008.
- 560 [9] E. Özgan and S. Serin, “Investigation of certain engineering characteristics of asphalt concrete
561 exposed to freeze–thaw cycles,” *Cold Reg. Sci. Technol.*, vol. 85, pp. 131–136, 2013.

- 562 [10] W. Si, B. Ma, N. Li, J. Ren, and H. Wang, "Reliability-based assessment of deteriorating
563 performance to asphalt pavement under freeze–thaw cycles in cold regions," *Constr. Build.*
564 *Mater.*, vol. 68, pp. 572–579, 2014.
- 565 [11] H. Xu, W. Guo, and Y. Tan, "Permeability of asphalt mixtures exposed to freeze–thaw cycles,"
566 *Cold Reg. Sci. Technol.*, vol. 123, pp. 99–106, Mar. 2016.
- 567 [12] H. Xu, W. Guo, and Y. Tan, "Internal structure evolution of asphalt mixtures during freeze–thaw
568 cycles," *Mater. Des.*, vol. 86, pp. 436–446, 2015.
- 569 [13] S. Lamothe, D. Perraton, and H. D. Benedetto, "Degradation of hot mix asphalt samples
570 subjected to freeze-thaw cycles and partially saturated with water or brine," *Road Mater.*
571 *Pavement Des.*, vol. 18, no. 4, pp. 849–864, Jul. 2017.
- 572 [14] "NF EN 13108-1 - Mélanges bitumineux - Spécifications des matériaux - Partie 1 : enrobés
573 bitumineux." AFNOR, 2008.
- 574 [15] "NF P98-250-5, Essais relatifs aux chaussées - Préparation des mélanges hydrocarbonés - Partie
575 5 : mesure en laboratoire de la masse volumique apparente d'un corps d'épreuve au banc
576 gammadensimétrique." AFNOR, March-1993.
- 577 [16] C. Mauduit *et al.*, "Experimental investigation of frost/thaw effects on bituminous mixes under
578 wet conditions," in *Asphalt Pavements*, CRC Press, 2014, pp. 139–146.
- 579 [17] C.Huet, "Etude par méthode d'impédance du comportement viscoélastique des matériaux
580 hydrocarbonés," Université de Paris, 1963.
- 581 [18] Heck JV, "Modélisation des déformations réversibles et permanentes des enrobés bitumineux -
582 Application à l'ornièrage des chaussées," Thèse, Université de Nantes, 2001.
- 583 [19] "NF EN 12697-26 - Mélanges bitumineux - Méthodes d'essai pour mélange hydrocarboné à
584 chaud - Partie 26 : module de rigidité." AFNOR, Jun-2012.