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An experimental-based model for the assessment of the mechanical properties of road pavements using ground-penetrating radar

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1 **An experimental-based model for the assessment of the mechanical properties of road**  
2 **pavements using ground-penetrating radar**

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11

12 **ABSTRACT**

13 This work proposes an experimental-based model for the assessment of the stiffness of a road flexible  
14 pavement using ground-penetrating radar (GPR – 2 GHz horn antenna) and light falling weight  
15 deflectometer (LFWD) non-destructive testing (NDT) methods. It is known that the identification of  
16 early decay and loss of bearing capacity is a major challenge for effective roads maintenance and the  
17 implementation of pavement management systems (PMS). To this effect, a time-efficient  
18 methodology based on quantitative and qualitative modelling of road stiffness is developed. The  
19 viability of using a GPR system in combination with LFWD equipment is also proven.

20

21 **Keywords:** ground-penetrating radar (GPR); light falling weight deflectometer (LFWD); non-  
22 destructive testing (NDT); road flexible pavements; road stiffness; health monitoring and assessment;  
23 time-efficient methodology; quantitative and qualitative modelling; pavement management system  
24 (PMS).

25 **1. INTRODUCTION**

26 Reducing the number of accidents is a major priority and a challenging target to achieve for road  
27 administrators. Accidents are generally related to geometric issues [1] and unfavourable serviceability  
28 conditions [2]. Firstly, improper design of road geometric elements affects drivers' perception of the  
29 road trajectory. Secondly, low road serviceability levels lead, above all, to lack of friction between  
30 the vehicles and the road surface. With regard to the latter issue, the intercorrelation between  
31 pavement decay and frequency of accidents is well known [3]. To this effect, an extensive and time-  
32 efficient assessment of roads at the network level is crucial for road administrators and agencies to  
33 define priorities of intervention and decrease the likelihood of envisaged accidents.

34 Most of the damages in flexible pavements occur where the stiffness of the asphalt and load-bearing  
35 layers is low. Therefore, an effective assessment of the strength and deformation properties of these  
36 layers can lead to identifying causes and locating the depth of damages. In addition, a prompt  
37 detection of early decay and loss of bearing capacity represents the real challenge to tackle for road  
38 administrators.

39 It is known that the bearing capacity of subgrade soils can be evaluated by on-site [4, 5] and laboratory  
40 [6] tests. These mainly assess the deformation of the pavement when a constant stress is applied. Due  
41 to the high operational time and costs, these tests are usually carried out on a few road sections and  
42 provide only partial information on the stiffness of the layers. Furthermore, these methods are  
43 intrusive and require to close the highway entirely or partially, with implications for the driving safety  
44 of roads.

45 In view of the above limitations, non-destructive testing (NDT) methods have become popular for  
46 the assessment of the mechanical properties of pavements. Falling weight deflectometer (FWD) [7]  
47 and light falling weight deflectometer (LFWD) [8, 9] are widely used for the investigation of  
48 integrated flexible pavement structures and for construction quality control of unbound materials,  
49 respectively. Nevertheless, LFWD has found also effective application in the assessment of stiffness

50 of bound layers [10, 11]. The FWD method relies on the measurement of deflections produced by a  
51 known falling mass loading the pavement surface. The main limitation of this method is that data can  
52 be collected only at discrete points, thereby affecting time and cost of the operations. To fill this gap,  
53 fully equipped non-destructive testing lorries for estimation of pavement strength and deformation  
54 properties at traffic speed have been therefore developed. In this regard, the curviameter [12] uses  
55 geophones to measure the velocity of vertical displacements of the pavement under the passage of  
56 the rear axle of the truck. Collection velocity is 18 km/h. The deflection bowl is obtained by  
57 integration of the measurements from the geophones, which are placed in a chain system. The main  
58 limitation of this equipment relates with the integration process. In this regard, an accurate calibration  
59 of the geophones is required. Furthermore, the need to respect a constant speed and the impossibility  
60 to make measurements in curves with radius lower than 40m are worthy of mention. A traffic speed  
61 deflectometer (TSD) [13] is another moving deflectometer. It operates at speeds up to 90 km/h and it  
62 is equipped with a long and rigid beam placed inside a semi-truck. A dedicated dead weight of 100  
63 kN is located in the proximity of the rear axle. High-rate sensors, including Doppler sensors,  
64 accelerometers and laser distance sensors, ensure that vertical pavement deflection velocities are  
65 recorded. Deflection velocities divided by the instantaneous vehicle speed produce the deflection  
66 slopes at discrete points along the TSD route. Several internal and external factors may affect the  
67 accuracy and precision of TSD measurements. These include calibration and quality assurance  
68 procedures, wind and temperature during the measurement, pavement roughness and tire-pavement  
69 interaction [14]. Although all the aforementioned methods are reliable and time-efficient, estimation  
70 of the strength and deformation properties of pavement layers requires a multi-stage collection of  
71 complementary information from different equipment (e.g., ground-penetrating radar (GPR)). In  
72 addition, the integration of this information requires a repeat of the data collection stage for each  
73 equipment along the whole stretch of the investigated roadway.

74 GPR has been extensively used in highway engineering as a result of the high reliability in the  
75 assessment of the geometric properties and physical properties of the pavement layers. GPR systems  
76 equipped with air-coupled antennas and connected to vehicles are mostly used for data collection at  
77 traffic speed. The GPR working principles rely on the emission of electromagnetic (EM) waves  
78 towards the ground. The emitted waves are then reflected back from the targets (typically represented  
79 by the interfaces of the layers) and are received by a receiving antenna. The collected signal is  
80 therefore displayed and stored for data processing and interpretation purposes. To date, GPR is  
81 successfully utilised in several disciplines including civil engineering [11], demining [15],  
82 archaeology [16], geology [17], glaciology [18] and much more.

83 As a common practice in highway engineering, the GPR and FWD methods are used separately for  
84 the assessment of the geometric (i.e., evaluation of the layer thicknesses) and the strength and  
85 deformation properties (i.e., evaluation of the deflection bowl) of road flexible pavements,  
86 respectively. The integration of the above information allows to evaluate reliable values of stiffness  
87 modulus of the pavement layers.

88 In view of the aforementioned limitations and state-of-the-art practices in the assessment of the  
89 mechanical properties of flexible pavements, the development of a non-destructive testing  
90 methodology for real-time identification of early decay and loss of bearing capacity of roads at traffic  
91 speed would stand as a step forward compared with the traditional methods. Value added would be  
92 to provide an estimation of the pavement stiffness based on geometric, physical and mechanical  
93 attributes of the subsurface integrated into a unique model. This would emphasize strengths and  
94 narrow weaknesses of the above NDTs.

95 A first modelling approach was developed by Tosti et al. [19]. A ground-coupled GPR antenna system  
96 and LFWD equipment were used to collect a dense dataset on a flexible pavement structure. The  
97 model was based on the peak amplitudes of the GPR signals reflected at the interfaces of the road

98 layers and the stiffness moduli estimated using LFWD. The concept proposed by Tosti et al. [19] is  
99 here taken as a reference and it is further developed using an air-coupled GPR antenna system.  
100 It is important to emphasize the importance of the proposed methodology in assessing early decay  
101 and loss of bearing capacity of the load bearing layers more efficiently than the state-of-the-art NDT  
102 methods. This information would be crucial for road administrators in order to create comprehensive  
103 databases of the road pavement conditions at the network level for implementation in pavement  
104 management systems (PMSs). This would allow for prioritisation of road maintenance operations,  
105 reduction of costs and a decrease in the likelihood of envisaged accidents.

106 The paper is outlined as follows: in Section 2, the aim and objectives are presented. The theoretical  
107 framework is discussed in Section 3. Section 4 presents the methodology, whereas the experimental  
108 design (test site and equipment) is detailed in Section 5. The ground-truth information and the  
109 preliminary data analysis are discussed in Section 6. The modelling is presented in Section 7, whereas  
110 results and discussion are reported in Section 8. Finally, the conclusion and future prospects are  
111 discussed in Section 9.

112

## 113 2. **AIM AND OBJECTIVES**

114 The primary aim of this project is to address a major challenge in the identification of early decay  
115 and loss of bearing capacity in road flexible pavements using GPR and LFWD. To achieve this aim,  
116 the following objectives are set:

- 117 • to develop a time-efficient methodology for estimating the stiffness of the pavement structure;
- 118 • to demonstrate the viability of using an air-coupled GPR antenna system in combination with  
119 LFWD equipment.

120

## 121 3. **THEORETICAL FRAMEWORK**

122 The GPR method is based on the theory of the EM fields. When an EM wave is emitted by a source,  
123 propagation is ruled by the dielectric properties of the medium that is passed through (case of non-

124 magnetic targets). In more detail, propagation speed and attenuation of the wave are related to the  
125 relative dielectric permittivity  $\epsilon_r$  [-] and the electrical conductivity  $\sigma$  [ $\text{Sm}^{-1}$ ], respectively. When a  
126 dielectric discontinuity is encountered, the radiated energy is partly reflected back to the receiving  
127 antenna and partly transmitted in depth. From the analysis of the collected signal, it is therefore  
128 possible to reconstruct the geometric features of the discontinuities.

129 Within this framework, the volumetric content of air and water that fills the inter-particle voids of  
130 pavement materials highly influences the dielectrics of the road pavement layers. However,  
131 compaction conditions of the pavement layers are also highly dependent on the content of inter-  
132 particle voids in construction materials. Hence, it is reasonable to assume that compaction of  
133 pavement materials may affect the EM behaviour of the layers [20]. With regards to the load-bearing  
134 layers and subgrade soils, it is also worth mentioning that soil particle compaction is highly dependent  
135 on their grain size distribution. This affects, in turn, the number of contacts between the grains and,  
136 hence, the shear strength of the material (along with the particle mineralogy and roughness) [21]. To  
137 this effect, compaction is performed on site after the laying out of loose soil granular materials. This  
138 allows to activate frictional resistance and interlocking of grains in order to reach a higher bearing  
139 capacity.

140 The strength of bearing soils in unsaturated conditions is also highly dependent on the physical state  
141 of water within the inter-particle voids. In this regard, it is known that free water can create differing  
142 physical-chemical bonds as a function of both size and type of soil particles. These bonds affect the  
143 cohesion between particles and, hence, the bearing capacity of subgrades. According to Mitchell [22],  
144 the dielectric properties of materials (e.g., dielectric loss and permittivity) are also dependent on the  
145 aforementioned inter-molecular bonds. Furthermore, Carpenter et al. [23] demonstrated how several  
146 pavement damages visible on the surface, such as transverse cracking, are caused by freeze-thaw  
147 cycling affecting the whole pavement structure. Indeed, this process induces a seasonal volumetric  
148 contraction and dilation of the unbound layers and, mostly, the base layer. More recently, Scullion

149 and Saarenketo [24] also proved the high correlation between the thermal susceptibility and the water  
150 suction in unbound bearing soils. Changes in the dielectric behaviour of soils were also found to be  
151 highly related to water suction effects.

152 In view of the aforementioned research, it is likely to expect a relationship between the dielectric and  
153 the strength and deformation properties of the unbound materials of road pavements [25, 26].

154 A road flexible pavement is generally described as a multi-layer structure composed of hot-mixed  
155 asphalt (HMA) bitumen-bound layers overlaying unbound granular courses. This structure is laid  
156 over a bearing subgrade [27]. It is known that the bond of the shallowest road layers is due to the high  
157 shear stresses transferred by the moving vehicles at the wheel-surface contact. Conversely, unbound  
158 granular materials are used for the construction of the foundation layers. These latter along with the  
159 subgrade soil receive stress generation from the above layers and bear the major structural  
160 contribution in terms of loads [28].

161 By considering a flexible pavement as a simplified homogenous half-space, the stress distribution  
162 with depth can be described using the theory of Boussinesq [e.g., 29] and its generalization to multi-  
163 layer configurations [30]. To this effect, the graphical solutions proposed by Forster and Ahlvin [31],  
164 clearly show that in the surroundings of a bearing area with a radius equal to 15 cm (e.g., case of a  
165 common lorry), most of the vertical stress concentrates beyond 7 cm of depth. This depth is typically  
166 out of the thickness of an HMA layer. This occurrence was also proved using numerical simulation  
167 [32]. Hence, it can be argued that loosely bound and unbound granular layers (especially the base  
168 layer) may heavily affect the mechanical behaviour of the whole road pavement structure. To this  
169 purpose, it is worth mentioning the research work of Scullion and Saarenkeeto [24]. The authors  
170 observed volumetric shrinkage caused by freezing in several base layers of different road flexible  
171 pavements. These contractions were one order of magnitude greater than shrinkage measured in the  
172 asphalt layers and were observed to cause cracking at the surface. Furthermore, structural rutting was

173 investigated by Oteng-Seifah and Manke [33] and Simpson et al. [34] and was related to deformations  
174 located in the base layer and the subgrade.

175 In view of the research studies above, it can be argued how thickness and development of the base  
176 layer may affect the bearing capacity of a whole pavement structure.

177 Further to the aforementioned geometric factors, it is known how the bearing capacity of flexible  
178 pavements may be highly affected by critical physical attributes [35], such as the content of clay. The  
179 upward passage of the smallest clay slurry particles from the subgrade by capillary actions lowers the  
180 strength and deformation properties of the pavement structure. To this effect, the correlation between  
181 clay content and plastic deformation of soils under load has been widely investigated in the literature  
182 [22]. From an EM standpoint, the viability of using GPR for detection of clay in dry and saturated  
183 soils has been demonstrated. As the applied EM field is affected by the presence of clay in a medium,  
184 relevant information can be estimated from the collected signal (in both the time and the frequency  
185 domain) [36, 37]. Attenuation of the EM waves is one of the most easily detectable effects related to  
186 the presence of clay in soils. In the case of dielectric materials, signal attenuation can be expressed  
187 by the propagation loss  $L = \exp\{-bz\}$  [38], with  $b$  being the attenuation coefficient and  $z$  being the  
188 investigation depth. The coefficient  $b$  is highly dependent on the electric conductivity of the medium  
189  $\sigma$  [ $\text{Sm}^{-1}$ ]. As clayey soils are typically characterised by high values of  $\sigma$  (mostly in wet conditions),  
190 then clay presence can be related to greater attenuations of the EM wave. In view of this, it can be  
191 argued that the amplitude of the received GPR signals is likely affected by the upward passage of  
192 clayey slurry particles towards the shallowest layers of a road flexible pavement.

193

#### 194 4. METHODOLOGY

195 The study focuses on the estimation of the stiffness of a road flexible pavement whereby a unique  
196 modulus for the overall pavement strength is considered. To this purpose, experimental tests are  
197 carried out using an air-coupled GPR antenna system and LFWD equipment.

198 Outliers are first filtered out from the LFWD dataset along with the relative GPR signals. A  
199 parametric model is therefore developed. In this regard, LFWD data are used as ground-truth  
200 measurements of pavement stiffness for modelling purposes. On the other hand, GPR data provide  
201 geometric and physical attributes about the pavement structure. The model parameters are first  
202 calibrated against the ~10% of data from the full dataset. A quantitative validation of the model  
203 viability is therefore carried out across the full road stretch length. Based on these outcomes, a  
204 qualitative approach for the estimation of the pavement stiffness is also developed.

205

## 206 5. EXPERIMENTAL DESIGN: TEST SITE AND EQUIPMENT

207 Experimental tests are carried out in the District of Rieti, Italy. To this purpose, 1500 m of a two-lane  
208 highway (one lane per direction) with a flexible pavement structure are investigated using GPR and  
209 LFWD equipment. From the available design drawings of the pavement structure, the superstructure  
210 is made of a 0.05-m-thick surface layer, a 0.10-m-thick bitumen-bond base layer and a 0.30-m-thick  
211 subbase layer (unbound granular material).

212 With regard to the GPR equipment, the RIS Hi-Pave HR1 2000 air-coupled antenna system,  
213 manufactured by IDS Georadar, is used. The system is equipped with a mono-static antenna of 2 GHz  
214 central frequency, mounted behind an instrumented van. The high frequency of investigation and type  
215 of antenna system allow to collect reflections of the GPR signal from the interfaces between the  
216 thinner surface layers as well as to perform the investigation at traffic speed. Traces are collected  
217 every 0.027 m to allow further statistical analyses about the optimal horizontal sampling resolution.

218 Tests for the collection of ground-truth data of pavement stiffness are carried out using the LFWD  
219 Prima 100 manufactured by Carl Bro Pavement Consultants Kolding. The equipment is composed of  
220 a circular metal plate (diameter 100 mm) loaded by a 10 kg hammer and a set of geophones that allow  
221 to record the pavement deflections  $\delta_c$  [ $\mu\text{m}$ ]. The LFWD investigation points are spaced 10 m from  
222 one another so that 151 points are collected along the investigated road stretch. It is worth noting that

223 LFWD is a less acknowledged piece of testing equipment than the FWD for the investigation of the  
224 stiffness of bound layers. Nevertheless, LFWD is used in this study for calibration and validation  
225 purposes for consistency with past research on GPR [19] and LFWD [9, 10] as well as to foster the  
226 time-efficiency of the proposed methodology.

227

## 228 6. GROUND-TRUTH INFORMATION AND PRELIMINARY DATA ANALYSIS

229 An “equipollent” modulus of stiffness  $E_{MEA,x}$  at a generic position  $x$  (corresponding to a generic load  
230 point) is calculated implementing the deflections from LFWD in the Boussinesq solution [e.g., 29]  
231 as follows [39]:

$$232 \quad E_{MEA,x} = \frac{k(1-\nu^2)\sigma_x R}{\delta_{c,x}} \quad (1)$$

233 where  $k$  is a constant equal to 2 (case of flexible pavements),  $\nu$  [-] is the Poisson ratio,  $\sigma_x$  [MPa] is the  
234 load stress,  $R$  [mm] is the plate radius and  $\delta_{c,x}$  [ $\mu\text{m}$ ] is the deflection measured at the center of the  
235 LFWD plate. A number of 6 loading tests were performed at each survey point to ensure statistically  
236 significant data outputs [8]. Correction of the estimated stiffness due to temperature effects is not  
237 applied to the LFWD data, as the test conditions are close to the benchmark temperature suggested  
238 in the literature [40].

239 The use of LFWD deals satisfactorily with the model outline discussed above, as the expected  
240 maximum depth of the bottom of the base layer is, by design drawings, around 15 cm. This depth  
241 matches well the maximum depth of the deflection basin expected for this equipment in road  
242 pavement investigations [9]. From now on, values of  $E_{MEA,x}$  estimated by Eq. (1) will be used as  
243 ground-truth data for modelling purposes. This parameter will be referred to as “measured stiffness  
244 modulus”  $E_{MEA,x}$  at a generic position  $x$ .

245 Each dataset of 6 LFWD measurements collected at the 151 investigation points along the “full” road  
246 stretch length  $l_{tot}$  is processed in terms of force applied, vertical stress and deflections. Datasets with  
247 low statistical significance [9] are discarded in full and the relative investigation points are removed

248 from the statistical population. In view of this, the relevant LFWD investigation points are reduced  
249 from 151 to 120 so that a 1200m-long road stretch (from now on referred to as “processed road  
250 stretch”  $l_{proc}$ ) is considered for modelling purposes. The related GPR traces are also consistently  
251 filtered out from the GPR dataset. A standard processing scheme for road inspections is applied to  
252 the GPR data [41]. In this regard, the zero-offset removal, the bandpass filtering and the cut-off of  
253 the air layer are applied.

## 254 7. MODELLING 255

### 256 7.1 Model outline

257 An experimental-based parametric model for the estimation of the stiffness of road flexible  
258 pavements is developed. Strength and deformation properties of a road flexible pavement at a generic  
259 position  $x$  are expressed, in terms of stiffness modulus  $E'_{MOD,x}$  [MPa], as follows:

$$260 \quad E'_{MOD,x} = \alpha(E_{MOD,x}) E_{MOD,x} \quad (2)$$

261 with  $\alpha(E_{MOD,x})$  being a fitting function and  $E_{MOD,x}$  [MPa] being a first approximation stiffness  
262 modulus. This latter parameter is defined as follows:

$$263 \quad E_{MOD,x} = \tau_{b,x} \beta_x \gamma_x \quad (3)$$

264 where  $\tau_{b,x}$  [m] accounts for the thickness of the base layer,  $\beta_x$  [MPa m<sup>-1</sup>] is a scale factor and  $\gamma_x$  [-]  
265 takes into account the contribution of clay to the stiffness modulus.

266 The modelled stiffness modulus  $E'_{MOD,x}$  in Eq. (2) is estimated through calibration of the  $\alpha(E_{MOD,x})$   
267 fitting function and the relative first approximation stiffness modulus  $E_{MOD,x}$  (Eq. (3)). This latter  
268 requires in turn calibration of the  $\beta_x$  and  $\gamma_x$  parameters, whereas  $\tau_{b,x}$  is a constant value taken from the  
269 trend of the base layer thickness. Calibration of the above parameters is carried out over a 100m-long  
270 distance within the 1200m-long processed road stretch  $l_{proc}$ .

271

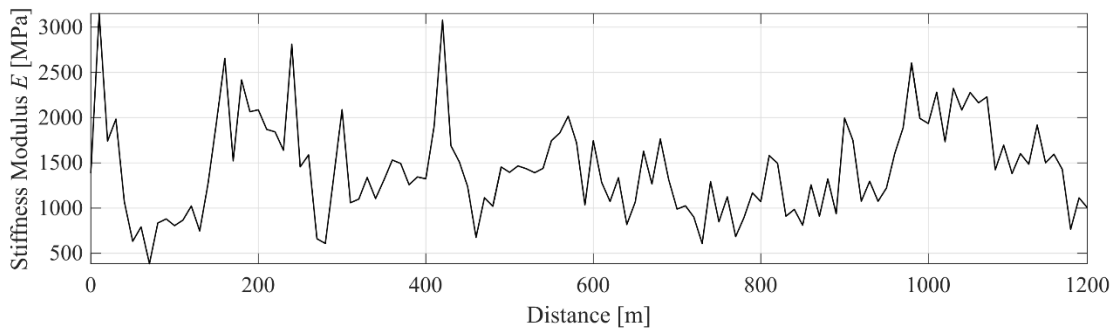
272 **7.2 Evaluation of the base layer thickness**

273 The thickness of the base layer  $\tau_{b,x}$  is assessed with reference to the two-way travel time (TWTT)  
274 distance covered by the GPR signal to pass through the concerning layer [42]. The value of this  
275 parameter at a generic position  $x$  is calculated as follows:

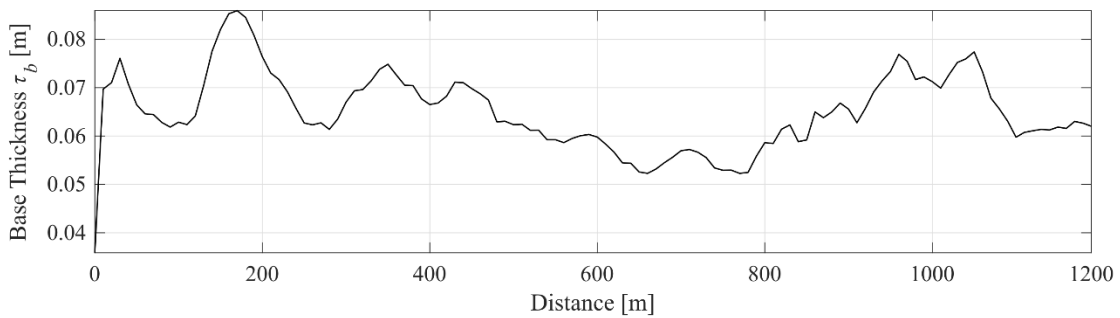
276 
$$\tau_{b,x} = \frac{c \Delta t_x}{2\sqrt{\varepsilon_{r,b,x}}} \quad (4)$$

277 where  $c$  [ $\text{ms}^{-1}$ ] is the wave velocity of propagation in the free space,  $\Delta t_x$  [s] is the temporal distance  
278 between the reflection amplitude peaks of the top and the bottom of the base layer (i.e., the peak-to-  
279 peak time distance), and  $\varepsilon_{r,b,x}$  [-] is the relative dielectric permittivity of the material passed through  
280 within the base layer.

281 Fig. 1 depicts a comparison between trends of measured stiffness modulus  $E_{MEA,x}$  (Fig. 1(a)) and base  
282 layer thickness  $\tau_{b,x}$  (Fig. 1(b)). The similarity between the two trends is shown; hence, a correlation  
283 between these two parameters could be likely deemed.



(a)



(b)

284  
285 **Fig. 1.** Comparison between trends of (a) measured stiffness modulus (LFWD – Eq. (1)) and (b) base

286 layer thickness (GPR – Eq. (4)).

287

### 288 **7.3 Model calibration**

289 A 100 m-long section ( $l_{cal}$ ), located between markers 170 m and 270 m of the processed road stretch  
290  $l_{proc}$ , is randomly selected for calibration purposes. This distance represents the 6.7% and the 8.3% of  
291 the "full" ( $l_{tot} = 1500$  m) and the "processed" ( $l_{proc} = 1200$  m) road stretch lengths, respectively.

292 It is worth noting that the outcomes of the calibration process discussed hereafter are representative  
293 of the specific testing conditions of this study. These include the flexible pavement structure  
294 described in Section 5 and the percentage of ground-truth data of pavement stiffness taken for  
295 calibration purposes. Hence, other values of the calibration parameters apply in the case of different  
296 boundary conditions.

297

#### 298 **7.3.1 Dimensional scaling**

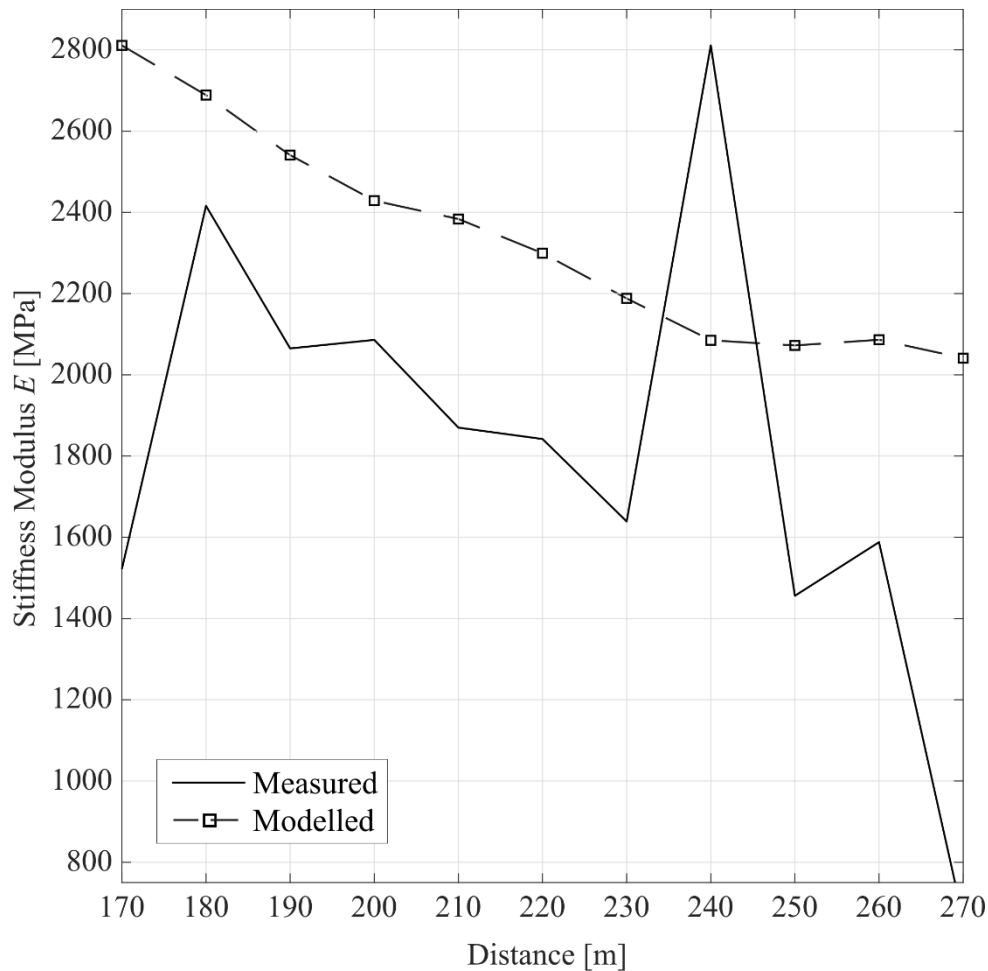
299 The scale factor  $\beta_x$  is set as:

$$300 \quad \beta_x = \frac{E_{MEA,x,MAX[l_{proc}]}}{\tau_{b,x,MAX[l_{cal}]}} \quad (5)$$

301 where  $E_{MEA,x,MAX[l_{proc}]}$  is the maximum value of stiffness modulus estimated throughout the 120  
302 investigation points within the processed distance  $l_{proc} = 1200$  m using Eq. (1), and  $\tau_{b,x,MAX}$  is the  
303 maximum thickness of the base layer calculated using Eq. (4) within the randomly selected calibration  
304 road stretch  $l_{cal}$ .

305 Fig. 2 shows the trend of preliminarily modelled stiffness modulus  $E_{MOD,x}^* = \beta_x \tau_{b,x}$  along the  
306 calibration road stretch. It can be seen how the preliminary application of the model generally tends  
307 to overestimate the measured ground-truth data. This mismatch is further addressed in Section 7.3.3  
308 using a dedicated fitting function.

309



310  
 311 **Fig. 2.** Comparison between trends of measured (solid line) and preliminarily modelled (dashed line  
 312 with square markers) stiffness modulus along the 100m-long calibration road stretch.

313

### 314 7.3.2 Clay contribution

315 The amplitude of the central peak of the frequency spectrum  $A_p$  is considered as the benchmark  
 316 parameter to account for the presence of clay rising from the foundation level [27, 28]. To this  
 317 purpose, geological maps of the site [43] are analysed and the investigated stretch of road is classified  
 318 as belonging to a poorly-clayey geological area. Hence, highly attenuated frequency spectra are  
 319 interpreted as indicators of likely presence of clay and are related to areas of early decay and loss of  
 320 road bearing capacity. On the contrary, standard frequency spectra are interpreted as indicators of  
 321 stability in terms of strength and deformation properties of the pavement.

322 The stair function  $\gamma(A_{p,x})$  is defined from the analysis of the central peak amplitude  $A_{p,x}$  of the

323 frequency spectrum of the GPR signal collected at a generic position  $x$  within the calibration road  
 324 stretch  $l_{cal}$ . This function is developed to lower the modelled stiffness modulus when the value of  $A_{p,x}$   
 325 is lower than a reference optimal threshold value (i.e., when the spectrum is attenuated). It is  
 326 expressed as follows:

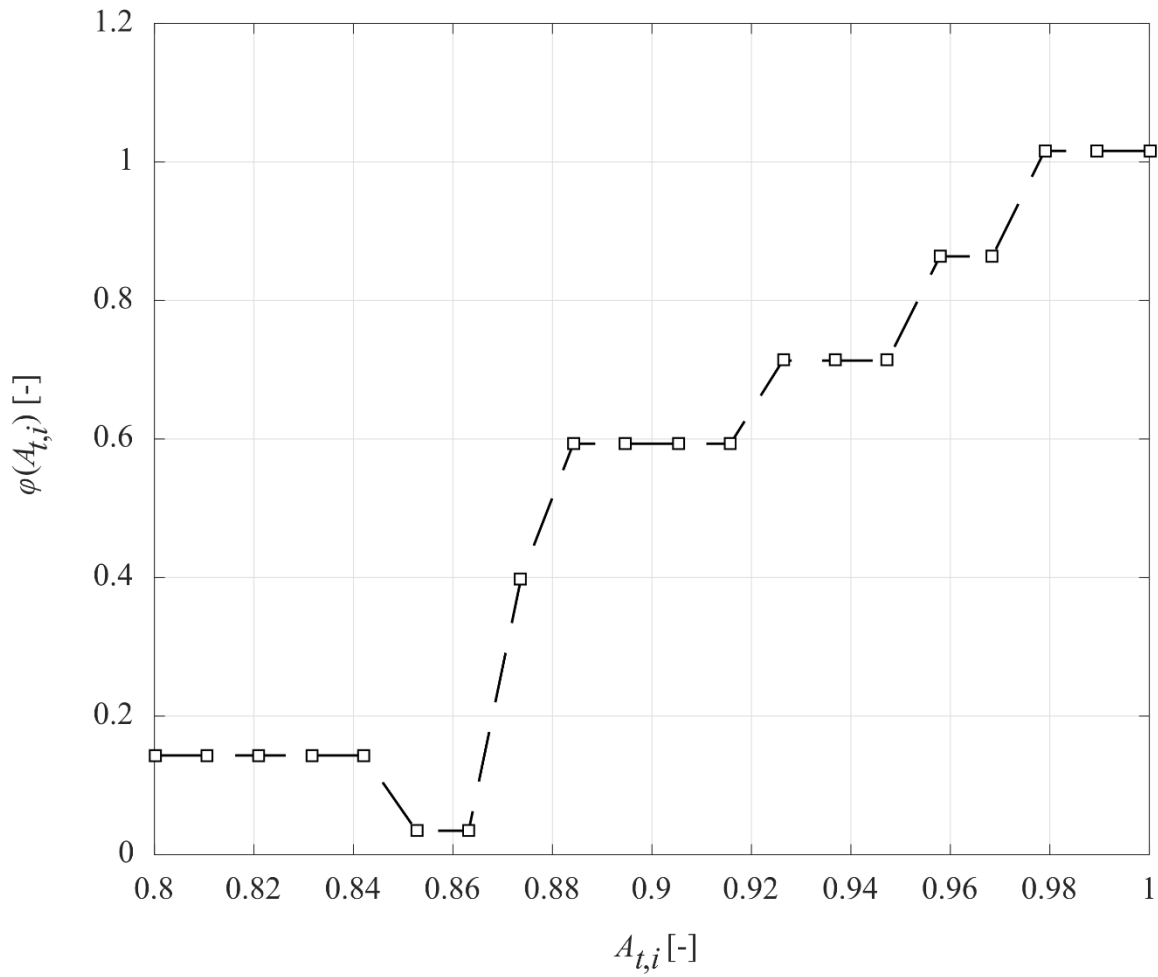
$$327 \quad \gamma(A_{p,x}) = \begin{cases} 0.80 & \text{if } A_{p,x}^{[0,1]} < A_t \\ 1 & \text{otherwise} \end{cases} \quad (6)$$

328 where  $A_{p,x}^{[0,1]}$  is the central peak amplitude of the frequency spectrum, normalised in the calibration  
 329 range  $l_{cal}$  and  $A_t$  is the set threshold. The threshold  $A_t$  is defined after running the model for each  $i^{th}$   
 330 value  $A_{t,i}$ , with  $i$  ranging between 0.80 and 1 at steps of 0.01. The trend of the  $i^{th}$  values of  $A_{t,i}$  in the  
 331 defined range is described by the following objective function  $\varphi(A_{t,i})$ :

$$332 \quad \varphi(A_{t,i}) = \sqrt{\frac{\sum_{x=0}^{l_{cal}} |E_{MOD,x,A_{t,i}} - E_{MEA,x}|^2}{\sum_{x=0}^{l_{cal}} E_{MOD,x,A_{t,i}}^2}} \quad (7)$$

333 expressing the mismatch between the modelled ( $E_{MOD,x,A_{t,i}}$ ) and the measured ( $E_{MEA,x}$ ) stiffness  
 334 modulus. Fig. 3 shows the performance of the model with varying values of  $A_{t,i}$ . A minimum value  
 335 of 0.034 for  $\varphi(A_{t,i})$  is reached when  $A_{t,i}$  is equal to 0.857; hence, this value is taken as the optimal  
 336 threshold expressing  $A_t$ .

337



338

339

**Fig. 3.** The trend of the objective function  $\varphi(A_{t,i})$  with varying values of  $A_{t,i}$ .

340

341

It is worth specifying that the  $\chi(A_{p,x})$  parameter improves the model matching at the local maximum and minimum points of the measured trend of stiffness, whereas the overall model overestimation is addressed using a dedicated fitting function, as detailed further in Section 7.3.3.

344

345

### 7.3.3 The fitting function

346

A percentile analysis of measured and modelled stiffness moduli (Fig. 4(a)) is performed to ensure accurate evaluation of the model overestimation. The ratio of the modelled to the measured percentiles (Fig. 4(b)) is therefore calculated as a reductive factor for compensation purposes. Hence, the continuous function  $\alpha(E_{MOD,x})$  is derived using the following third-degree polynomial fitting

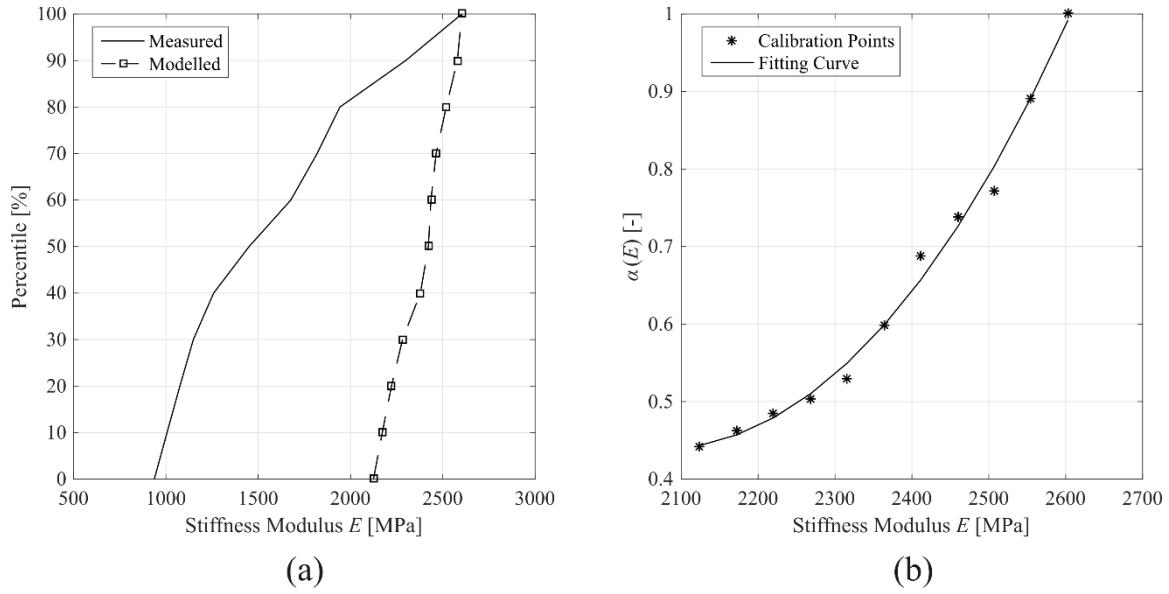
349

350 relationship:

351 
$$\alpha(E_{MOD,x}) = \sum_{i=0}^3 a_i E_{MOD,x}^i \quad (8)$$

352 The values of the fitting parameters  $a_i$  are reported in Table 1.

353



354

355 **Fig. 4.** (a) Percentile analysis of measured (solid line) and modelled (dashed line with square markers)

356 stiffness moduli; (b) fitting function  $\alpha(E_{MOD,x})$  expressed by Eq. (8).

357

358 Table 1 – Fitting parameters  $a_i$  in Eq. (8).

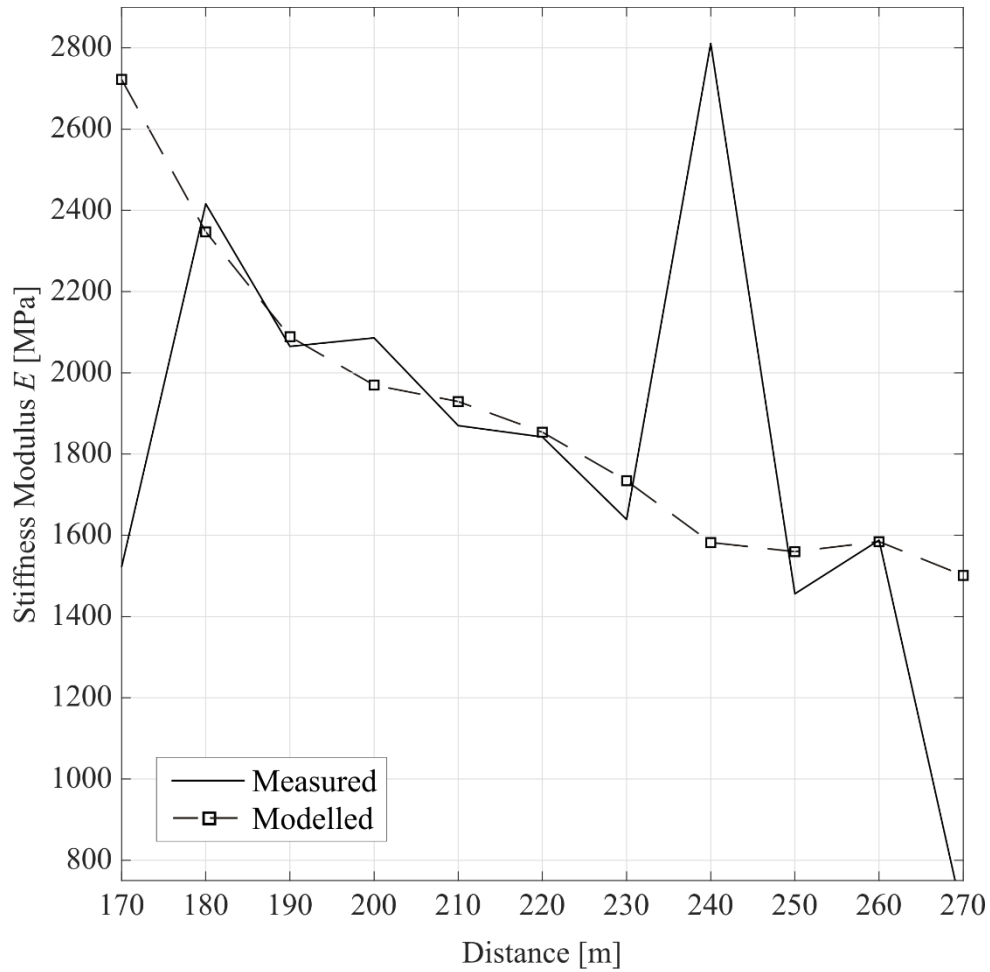
$a_0$	$a_1$	$a_2$	$a_3$
-22.618	0.027	$-1.24 \times 10^{-6}$	$1.74 \times 10^{-9}$

359

360 The adjusted modelled trend of stiffness modulus is therefore derived working out the value of the

361 fitting function  $\alpha(E_{MOD,x})$  from Eq. (8) into Eq. (2). Figure 5 shows the comparison between trends

362 of measured and (adjusted) modelled stiffness modulus along the calibration road stretch.



363

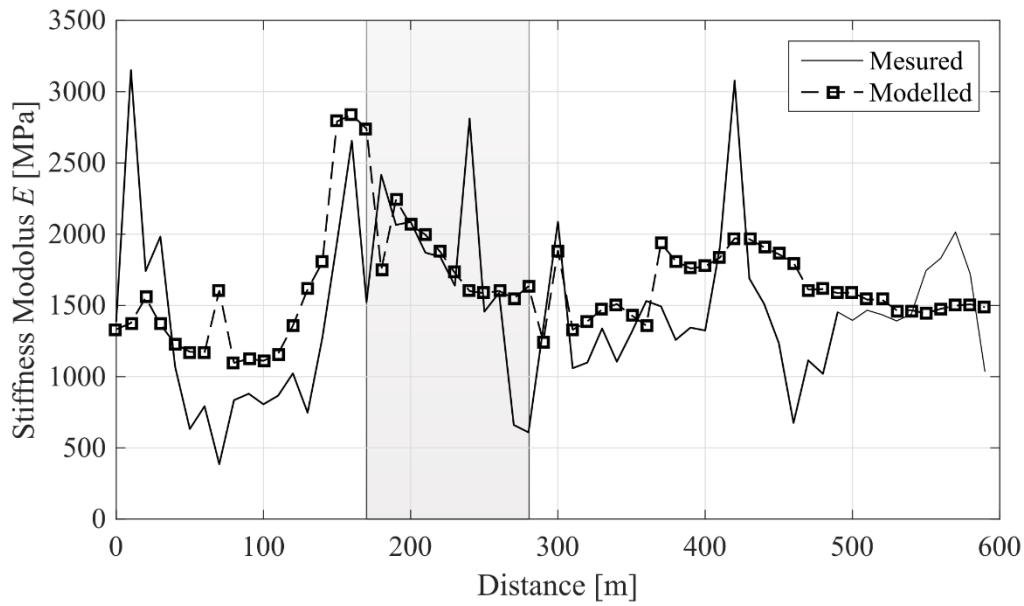
364 **Fig. 5.** Comparison between trends of measured (solid line) and modelled (dashed line with square  
 365 markers) stiffness modulus after the application of the fitting function  $\alpha(E_{MOD,x})$  (Eq. (8)).

366

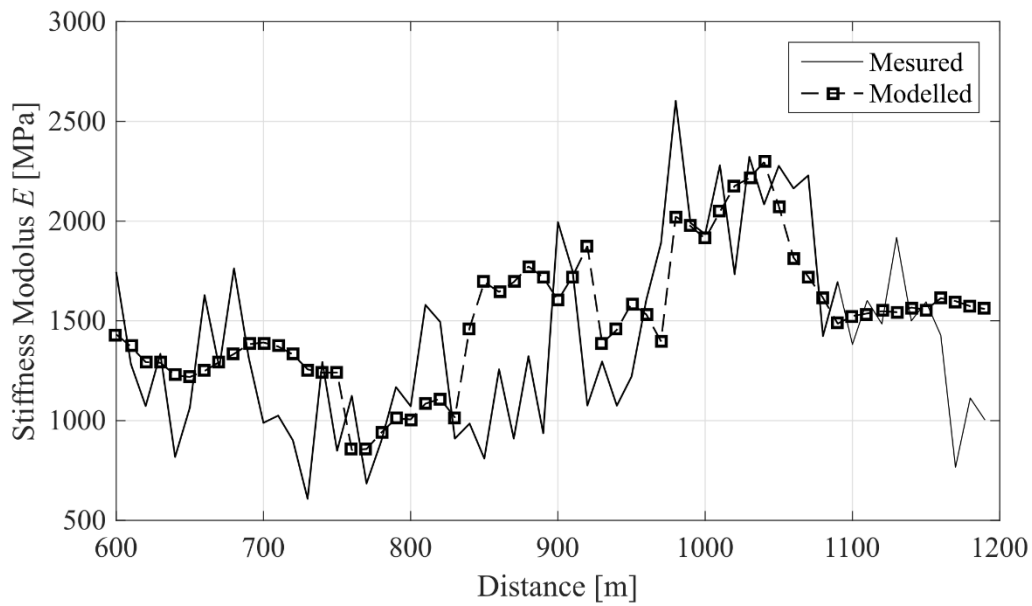
367 **8. RESULTS AND DISCUSSION**

368 **8.1. Validation of the quantitative model**

369 The trend of modelled values of fully-calibrated stiffness modulus  $E'_{MOD,x}$  is estimated along the  
 370 processed road stretch length  $l_{tot}$ . An overall comparison between trends of measured and modelled  
 371 stiffness modulus is shown in Fig. 6. For the sake of clarity with the data interpretation, the 1200 m  
 372 road stretch length is divided into two sub-areas, i.e., from markers “0 m to 600 m” and “600 m to  
 373 1200 m”. The area related to the calibration road stretch is marked in grey.



(a)



(b)

374

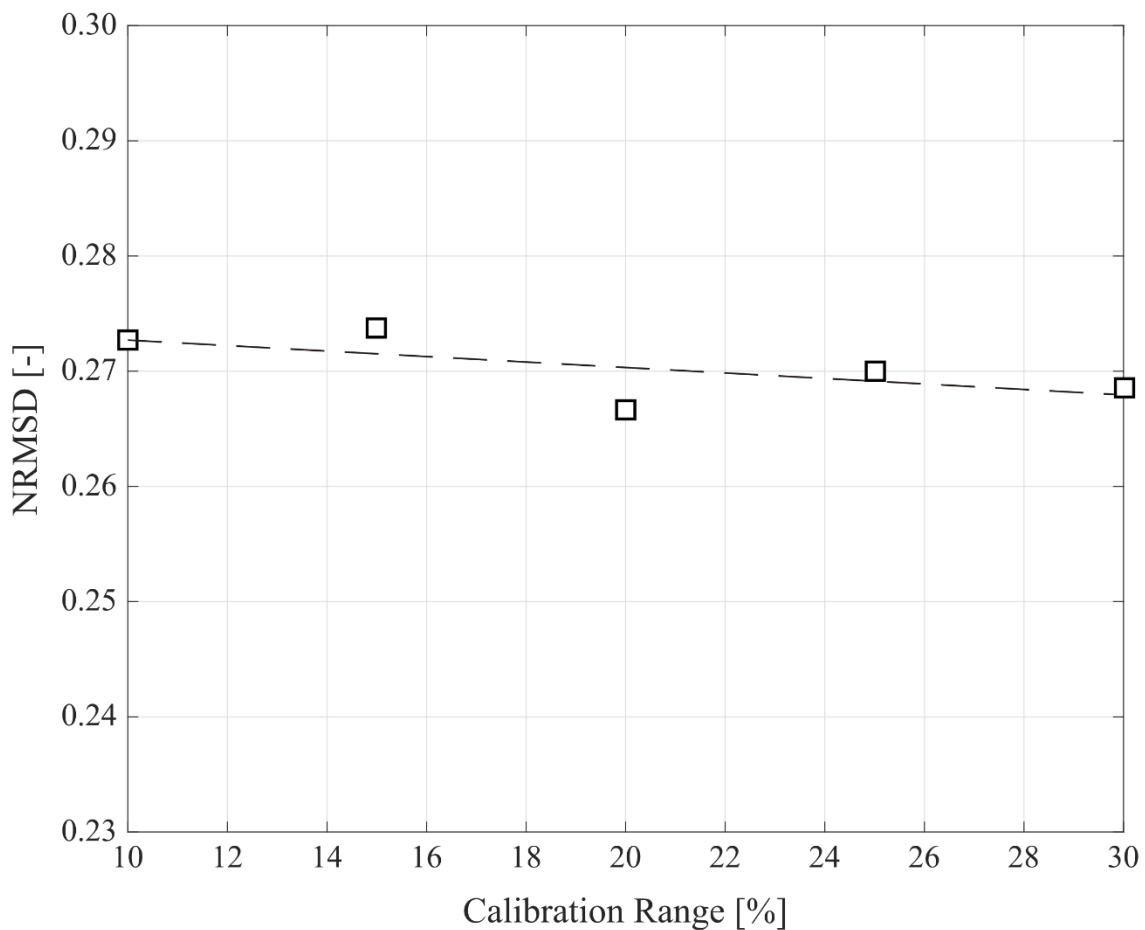
375

376 **Fig. 6.** Comparison between trends of measured  $E_{MEA,x}$  (solid line) and modelled  $E'_{MOD,x}$  (dashed line  
 377 with square markers) stiffness modulus after the application of the fully-calibrated model. The area  
 378 related to the calibration road stretch is marked in grey. (a) Markers “0 m – 600 m”; (b) markers “600  
 379 m – 1200 m”.

380

381 A relatively good reliability of the model for the interpretation of the actual road pavement stiffness  
382 is proven. A few areas of ground-truth data misinterpretation from the model are still recognizable in  
383 the neighbourhood of markers “100 m”, “400 m”, “550 m” (Fig. 6(a)) and “900 m” (Fig. 6(b)). The  
384 normalised root-mean-square deviation (NRMSD) is equal to 0.273. This provides a quantitative  
385 measurement of disagreement between measured and modelled datasets of stiffness modulus.

386 The assumption made on the percentage size of the LFW D calibration points (i.e., ~10% of the data  
387 from the full dataset) is further investigated to verify the robustness of the model. To this purpose,  
388 the fully-calibrated model is applied with calibration data ranges comprised between 10% and 30%  
389 in steps of 5%; hence the relative values of NRMSD are found and plotted (Fig. (7)).



390  
391 **Fig. 7.** The trend of NRMSD values of the model against the percentage range “10% - 30%” of LFW D  
392 calibration points.

393 It is worth noting how the robustness of the model has a weak dependence on the percentage range  
394 of calibration points. This is proved by the slight variability of the NRMSD values and the fair  
395 horizontality of the least square fitting trend line. Thereby, it is possible to argue that a robust  
396 calibration can be performed using ~10% of ground-truth calibration points, whereas the length of  
397 the relative full dataset is at least the same as the length of the road stretch investigated in this study.  
398 This may represent an invaluable outcome for the development of a more time-efficient methodology  
399 for the estimation of the stiffness of road flexible pavements. In fact, the use of FWD could be  
400 potentially limited to the ~10% only of the full length of the roadway whereas the rest of the survey  
401 could be carried out using an air-coupled GPR system for a more time-efficient data collection.

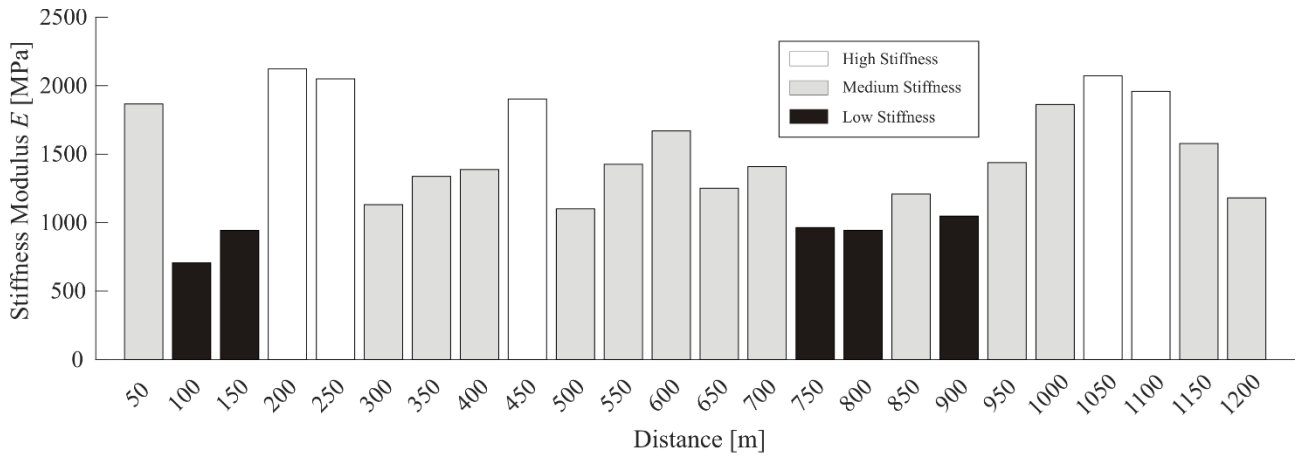
402

## 403 **8.2 Qualitative modelling of road pavement stiffness**

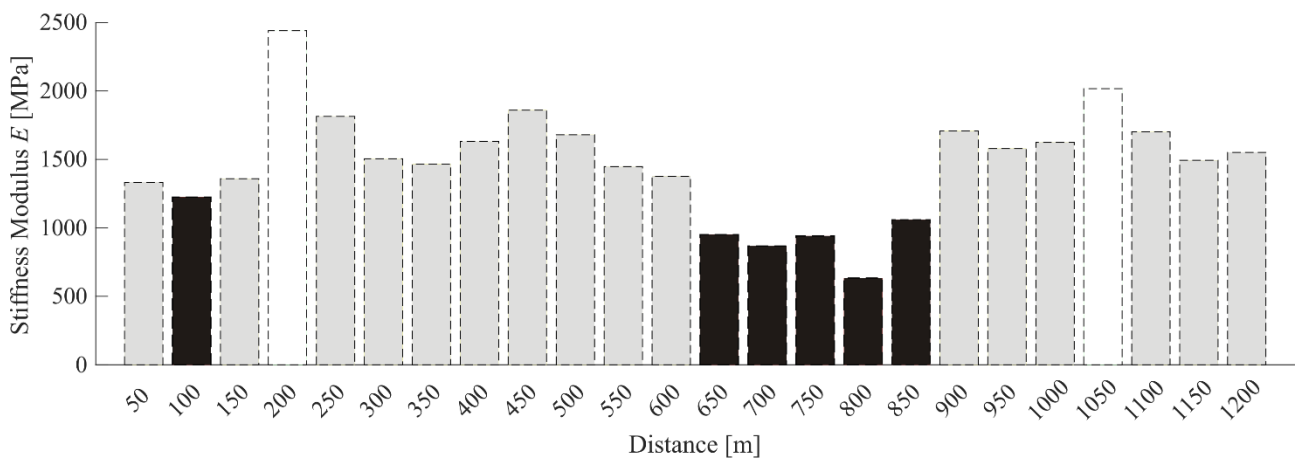
404 To foster the viability of using air-coupled GPR antenna systems in combination with FWD systems  
405 in PMSs, a qualitative and streamlined approach to estimate stiffness of road flexible pavements is  
406 further proposed. The rationale behind this process is to provide rapid identification of early decay  
407 and loss of bearing capacity areas at the network level. Hence, time and cost of further and more  
408 detailed investigations can be planned and allocated more effectively.

409 Stiffness moduli estimated from Eq. (1) and Eq. (2) are here considered as ground-truth and modelled  
410 values, respectively. The investigated road stretch is divided into 50m-long value ranges of stiffness  
411 modulus wherein the average value is taken as a benchmark. Three classes of stiffness are therefore  
412 identified, i.e., “high stiffness”, “medium stiffness” and “low stiffness” classes. These are set as a  
413 function of two thresholds, arbitrarily fixed at 1900 MPa and 1100 MPa, according to the overall  
414 trend of modelled stiffness moduli. This step allows for customisation of the methodology as per the  
415 specific requirements of the survey. Fig. (8) shows the outcomes of the qualitative modelling.

416



(a)



(b)

417

418  
 419 **Fig. 8.** Comparison between the three qualitative classes of stiffness modulus: (a) measured stiffness  
 420 modulus (bar charts with solid contour lines); (b) modelled stiffness modulus (bar charts with dashed  
 421 contour lines).

422

423 From the comparison between measured and modelled stiffness by the qualitative approach, matches  
 424 of two main areas of lowest stiffness are observed in the value ranges “100 m – 150 m” and 700 m –  
 425 900 m”. In addition, a good match between highest stiffness moduli is noticed in the value ranges  
 426 “200 m – 250 m” and “1050 m – 1100 m”. The remaining intervals match well with intermediate  
 427 stiffness conditions of the road pavement.

428 It is worth noting the relative range of applicability of the proposed approach. The set values of the  
 429 threshold are specific to the dataset collected in this investigation. Hence, they may change for a

430 different dataset (e.g., the same pavement structure at a different life cycle stage or another road  
431 pavement with a different cross section and/or construction materials). To this effect, the proposed  
432 methodology is reliable and can be used to investigate other road flexible pavements only if suitable  
433 threshold values are set after a preliminary data analysis at the network level.

434

## 435 9. CONCLUSION AND FUTURE PROSPECTS

436 This work proposes an experimental-based model for the assessment of stiffness in a road flexible  
437 pavement using ground-penetrating radar (GPR) and light falling weight deflectometer (LFWD). The  
438 model uses ground-truth data of road stiffness inferred from LFWD as well as geometric and physical  
439 information of the pavement structure derived from a GPR system equipped with a 2 GHz horn  
440 antenna.

441 To this purpose, 1500 m of a two-lane highway (one lane per direction) with a flexible pavement  
442 structure are investigated. After filtering out the outliers from the collected LFWD data (and the  
443 relative GPR traces), the model is calibrated via an optimisation process using the ground-truth  
444 stiffness moduli at the investigation points of a randomly-selected 100m-long road stretch (i.e., ~10%  
445 of the processed dataset), the thickness of the base layer and the central-peak amplitudes of the  
446 frequency spectrum. These latter parameters are both estimated using GPR and account for the  
447 structural quality of the pavement and the clay content in the load-bearing layers, respectively.

448 In addition to the quantitative approach for the estimation of the pavement stiffness modulus, a  
449 qualitative procedure is further developed. The investigated road stretch is divided into 50m-long  
450 value ranges of stiffness modulus, wherein the average value is taken as a benchmark. Three classes  
451 of pavement stiffness (i.e., “high stiffness”, “medium stiffness” and “low stiffness”) are therefore set  
452 based on two arbitrarily-fixed threshold values. These are selected according to the overall trend of  
453 modelled stiffness moduli and allow for customisation of the methodology as per the specific  
454 requirements of the survey.

455 The model viability is finally evaluated by quantitative and qualitative comparison of measured and  
456 modelled stiffness moduli. The quantitative analysis of the outputs shows a value of the normalised  
457 root-mean-square deviation (NRMSD) equal to 0.273. Hence, a relatively good agreement between  
458 measured and modelled data is proven. This outcome is also confirmed by the quantitative analysis,  
459 whereby good matches of the defined stiffness classes are found across the whole investigated road  
460 stretch.

461 It is important to emphasize the importance of the proposed methodology for extensive and time-  
462 efficient assessment of roads at the network level and potential implementation in pavement  
463 management systems (PMS). This could be crucial for road administrators and agencies in order to  
464 define priorities of intervention, allocate costs effectively and decrease the likelihood of envisaged  
465 accidents.

466 Future research could task itself with enriching the database for the development of the proposed  
467 methodology with a larger data sample from different road sections. In addition, different sources of  
468 ground-truth data for collection of stiffness moduli (e.g. falling weight deflectometer, curviameter,  
469 traffic speed deflectometer) could be used for the investigation of deeper domains and/or the  
470 gathering of more dense data. Comparison of model outputs against the actual strength and  
471 deformation data would allow for the understanding of the viability of different ground-truth  
472 equipment for modelling purposes.

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