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**IDENTIFICATION OF COUPLING PARAMETERS  
BETWEEN SHEAR STRENGTH BEHAVIOUR OF  
COMPACTED SOILS AND CHEMICAL'S EFFECTS  
WITH AN EVOLUTIONARY-BASED DATA MINING  
TECHNIQUE**

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32 **ABSTRACT**

33 When subjected to a very high-pH, most of the soil minerals undergo physico-chemical  
34 transformation. This could induce strong modifications of the shear strength behaviour of the  
35 soil. This issue is of high interest in the framework of the design of deep nuclear wastes  
36 repositories, since the degradation of the concrete lining of deep galleries after thousands of  
37 years will generate an alkaline solute ( $\text{pH} > 12$ ) that would circulate through the backfill, and  
38 alter its hydromechanical characteristics. A study was undertaken to assess the impact of  
39 high-pH fluid circulation on the shear strength behaviour of a backfill material. Because of  
40 the complexity of the existing constitutive theories, a new approach was used, based on  
41 evolutionary polynomial regression (EPR), for modelling of these processes. EPR is an  
42 evolutionary data mining technique that generates a transparent and structured representation  
43 of the behaviour of a system directly from data. An EPR model was developed and validated  
44 using results from a comprehensive set of triaxial tests. Through a sensitivity analysis, the  
45 EPR model permitted to identify the specific surface, and to a lesser extent the micropore void  
46 ratio, as coupling parameters between hydromechanical behaviour alteration during alkaline  
47 fluid circulation and a physical process.

48 **Keywords:** Nuclear waste repository; Chemo-mechanical couplings; Artificial Intelligence;  
49 Data Mining; soil modelling; Compacted soil.

## 50 1. INTRODUCTION

51 In the French concept of nuclear waste storage, the stability of the galleries will be  
52 ensured with a concrete lining and this repository will be backfilled after use. Among other  
53 functions, this backfill will limit the convergence of the galleries after the concrete lining  
54 breaks (i.e. after thousands of years); it should also constrain the bentonite seals intended to  
55 limit water circulation along the galleries during their hydration. One key point is the  
56 degradation of the concrete lining of the galleries that will generate alkali-rich and high-pH  
57 solutes (e.g. [1] ) that will then diffuse into the backfill. This will give rise to a phenomenon  
58 called the hyperalkaline plume. Under extremely alkaline conditions, i.e.  $\text{pH} > 12$ , most of the  
59 usual soil minerals undergo extensive physicochemical transformations (e.g. [2] [3] ). Very  
60 high pH water causes the dissolution of the soil primary minerals accompanied by the  
61 formation of secondary minerals like calcium silicate hydrates (CSH) and calcium aluminate  
62 hydrates (CAH) (pozzolanic reactions) (e.g. [4] [5] [6] [7] , [8] ). Many geochemical  
63 modelling studies have also been performed (e.g. [9] [10] ).

64 However, only very few studies ([11] [12] [13] ) have been carried out on these  
65 processes at the scale of compacted clay samples to characterise potential chemo-mechanical  
66 couplings between such high-pH water circulation and its impact on the geomechanical  
67 behaviour (shear strength, compressibility, permeability, etc.). In this context, Cuisinier et al.  
68 [15] [16] have carried out a study to depict the influence of the circulation of very high-pH  
69 water on the hydromechanical behaviour of compacted argillite, pure or mixed with an  
70 additive (sand, bentonite or quicklime), that are the candidate materials to be used for  
71 backfilling. The geomechanical behaviour and the microstructure of the considered materials  
72 were followed over a period of alkaline water circulation of 12 months. The impact of the  
73 alkaline fluid on the geomechanical properties of the materials appeared to be a direct  
74 function of the nature of the additive. The geomechanical behaviour of the sand-argillite

75 mixture remained almost stable over a period of 12 months of alkaline water circulation  
76 while, over the same period, dramatic modification of the lime-argillite mixture was observed.  
77 A subsequent step of this research would be to identify the key coupling parameter(s) between  
78 the modifications induced by the alkaline water circulation and the alteration of the  
79 hydromechanical behaviour of the tested mixtures. However, the large amount of tested  
80 configurations, the four different mixtures, and experimental conditions rendered difficult the  
81 determination of such coupling parameter(s).

82 In this context, a new approach is presented, based on evolutionary polynomial  
83 regression (EPR) to model the complex hydromechanical behaviour of the soil during alkaline  
84 fluid circulation. EPR is a data mining technique, based on evolutionary computing, aimed to  
85 search for polynomial structures representing a system. The key idea behind the EPR is to use  
86 evolutionary search for exponents of polynomial expressions by means of a genetic algorithm  
87 (GA) engine [17] . The main advantage of EPR over other data mining techniques such as  
88 neural networks (which is widely used in modelling of engineering systems) is that it  
89 provides a transparent and structured representation of the behaviour of the system in the form  
90 of a clear mathematical expression that is readily accessible to the user. EPR has shown its  
91 potential in application in modelling of complex behaviour of soils (e.g. [18] [19] ).

92 The main objective of the paper is to depict the different steps followed to achieve the  
93 identification of coupling parameters between modifications induced by the alkaline water  
94 circulation and the magnitude of the resultant alteration of the shear strength. First, the main  
95 trends of the impact on the shear strength of the different mixtures are presented. An emphasis  
96 is placed on the identification of candidate coupling parameters. In the second part of the  
97 paper, the steps followed to elaborate the EPR model are presented. An EPR model is  
98 developed and evaluated based on results from test data involving various additives  
99 circulation times (i.e. 0, 3, 6, and 12 month). Four cases of data, not employed for the training

100 phase, were chosen to be used in the testing stage to evaluate the generalisation capabilities of  
101 the developed model. In the last section, a parametric study is carried out where all  
102 parameters were set to their mean values except the one which was changed from its  
103 minimum to the maximum value in the training and testing data sets. The results of this  
104 analysis are discussed in the last section of the paper to identify the most adequate coupling  
105 parameter(s) between chemical effects and shear strength behaviour alteration.

106

## 107 **2. EXPERIMENTAL CHARACTERISATION OF THE IMPACT OF THE** 108 **CIRCULATION OF ALKALINE WATER**

109 In this section, details about the soil used and the experimental set up are first given.  
110 Then, an overview of the results, both from microscopic and geotechnical points of views are  
111 presented.

### 112 **2.1. Materials properties**

113 An outcrop of the Callovo-Oxfordian argillite provided the material used in this study.  
114 The Manois Argillite (MA) was carefully homogenised and crushed into a very fine grain  
115 powder. Chemical and XRD analyses indicated that the MA contains 26 to 32 % calcite, 22 to  
116 27 % quartz, and 41 to 49 % clays (fraction lower than 2  $\mu\text{m}$ ). The clays are mainly illite,  
117 kaolinite and an interstratified illite-smectite. The specific surface determined is  $40.4 \pm 1$   
118  $\text{m}^2 \cdot \text{g}^{-1}$ .

119 For the study of the backfilling of deep galleries, three different additives, intended to  
120 improve the properties of the argillite, were considered. The first mixture was made of a 50 %  
121 sand and 50 % MA, on a dry-weight basis. The addition of sand increases the dry density and  
122 the frictional characteristics of the compacted argillite (e.g. [20] [21] ). The second additive  
123 was MX-80 bentonite, which was selected to enhance the sealing properties of the backfill  
124 through improved swelling (e.g. [20] ). The mixture used was 20 % MX-80 and 80 % MA on

125 a dry-weight basis. The third additive used was quicklime, which improves both the cohesion  
126 and the friction angle of clayey materials (e.g. [22] [23] [24] [25] [26] ). A lime content of 4  
127 % with the remainder MA on a dry-weight basis, was selected. The characteristics of the  
128 materials are given in Table 1.

129

## 130 **2.2. Aging procedure and samples preparation**

131 Special cells were developed to impose a circulation of alkaline fluid through  
132 compacted samples of the different considered mixtures under accelerated conditions over a  
133 long period of time. Details about the development of these cells are available in [16] . The  
134 fluid was injected through the base of the cells and circulation was maintained up to 12  
135 months. A portlandite-saturated water with a pH of about 12.4 was used to simulate the  
136 cement-pore water. That composition was selected for ease of preparation and to insure  
137 chemical stability of the cement water. The experiments were conducted at an elevated  
138 temperature in order to speed up the kinetics of the chemical reactions. The dissolution  
139 kinetics of clay particles in high pH media and pozzolanic reactions increase sharply at high  
140 temperatures ([24] [2] ). The circulation of the selected cement water was performed under a  
141 high hydraulic gradient (50 m/m) and a high temperature (60°C), up to a circulation duration  
142 of 12 months. These conditions were much more severe than those expected in situ where a  
143 progressive saturation of the backfill by the alkaline water by diffusion is likely to occur.

144 The samples were prepared by static compaction in seven layers inside the circulation  
145 cells with a static compaction pressure was about 470 kPa. This pressure was used to prepare  
146 all tested samples. All mixtures in the study were prepared at their respective optimum water  
147 content determined from the standard Proctor test. The optimum water contents for each  
148 mixture statically compacted under a pressure of 470 kPa are given in Table 2 together with  
149 the initial dry density of each mixture when static compaction was used.

150 After the compaction of the samples, the circulation cell was closed and transferred to  
151 the oven set to 60°C. The alkaline fluid circulation began immediately, with an injection  
152 pressure of 40 kPa. If the sample pore volume is used as the volume unit, about 18 pore  
153 volumes flowed through a sample of compacted MA each month, considering an initial  
154 permeability of the Manois argillite of about  $5.10^{-9}$  m.s<sup>-1</sup> for an initial porosity of 40 %.  
155 During the experiment, the fluid pH was periodically measured at the outlet of the cells. A  
156 few days after the fluid circulation began, it was observed that the pH stabilized at a value  
157 between 12 and 13. That pH value remained nearly constant throughout the experiment.

158

### 159 **2.3. Alteration of shear strength parameters by alkaline water circulation**

160 At the end of the circulation period, each cell was carefully dismantled. Triaxial core  
161 samples were then trimmed to the desired dimensions (diameter of 3.5 cm and height of 7 cm)  
162 and used to perform triaxial consolidated undrained tests with a measurement of the internal  
163 pore water pressure. All the mechanical tests were performed at room temperature (about  
164 20°C). The failure criterion was based on the maximum deviator stress for this study. The  
165 stress paths followed during the tests are given in Figure 1 and in Figure 2 where  $t$   
166 corresponds to the deviatoric stress  $(\sigma'_1 - \sigma'_3)/2$ , and  $s'$  to the mean stress  $(\sigma'_1 + \sigma'_3)/2$ . The  
167 shear strength envelope parameters determined during the tests are given in Table 3.

168 In the case of the pure MA argillite after its compaction, the initial effective cohesion  
169  $c'$  was 25.6 kPa and the effective friction angle  $\varphi'$  was 18.6°. It is representative of the  
170 behaviour of a compacted soil that is slightly overconsolidated. The alkaline fluid circulation  
171 for 12 months led to a slight modification of the shear strength behaviour. The effective  
172 friction angle increased to 22.2°, and this was accompanied by a reduction of the effective  
173 cohesion to 9.5 kPa (Table 3). For the Sand / MA argillite mixture, the effect of the alkaline  
174 fluid circulation was relatively limited. The alkaline fluid circulation over 12 months did not

175 significantly alter the mechanical behaviour of the sand / MA mixture. As it can be seen from  
176 Table 3, the circulation duration had no significant effect on the shear strength envelope  
177 parameters. Before any alkaline fluid circulation, it can be seen that the addition of 20 % of  
178 bentonite tends to lower the cohesion of the MA (Table 3). The effect of the MX-80 addition  
179 on the friction angle was not significant. After the alkaline fluid circulation period of 12  
180 months at 60°C, it can be seen in Table 3 that the effective friction angle decreased to 13.5°,  
181 while the effective cohesion increased to about 30 kPa.

182         The shear strength behaviour of the 4 % lime treated material was tested after 90 days  
183 of curing at constant water content at 20°C. If the maximum shear stress failure criterion is  
184 used, the effective cohesion is 50.3 kPa and the effective friction angle is 39.5°. The shear  
185 strength behaviour of the lime-treated material was determined after 3, 6 and 12 months of  
186 cement water circulation. Under these conditions, the effective cohesion is 282.5 kPa and the  
187 mean effective friction angle is 53.7°. The greatest change in the shear strength behaviour of  
188 the lime-treated MA occurred during the first three months of water circulation. Longer  
189 circulation periods slightly lowered the peak shear strength of the lime-treated MA.

190

#### 191 **2.4. Alteration of microstructural parameters by alkaline water circulation**

192 In parallel to the determination of the shear strength behaviour, the microstructure of the  
193 samples was analysed before and after alkaline fluid circulation. Samples of cubic shapes and  
194 of volume comprised between 1 and 2 cm<sup>3</sup> were taken in from the cells after the circulation  
195 period, then freeze-dried and kept inside desiccators. These were used to determine the  
196 microstructure of the different materials by using mercury intrusion porosimetry. The pore  
197 size distribution before and after 12 months of alkaline water circulation are compared in  
198 Figure 3. It can be seen that the impact of the alkaline water circulation is directly related to  
199 the nature of the additive employed to improve the behaviour of the argillite. When MX-80 is

200 present, an important increase in the amount of pores between 1 and 30  $\mu\text{m}$  can be evidenced  
201 after the fluid circulation. This has been attributed to the dissolution of the particles of MX-80  
202 bentonite under high pH environment [16] . Conversely, the stability of the microstructure of  
203 the mixture of argillite and sand is remarkable for the same period of circulation.

204 From Figure 3, it can be seen that the pore size distribution of each structure is made of two  
205 pore classes, a macropore class and a micropore class. In order to quantify the alteration of the  
206 microstructure, the evolution of the micropore and of the macropore volume over the  
207 circulation period can be monitored. These data are plotted in Figure 4, the volume being  
208 expressed as a micropore void ratio and a macropore void ratio. This Figure highlights the  
209 importance of the mixture composition in the reactivity of the material during the circulation  
210 of the alkaline fluid, and the trend of modification of microstructure. As an example, after 12  
211 months of alkaline water circulation, the macropore void ratio of the MX-80 - argillite  
212 increased from 0.44 to 0.69 while over the same circulation period, the macropore volume of  
213 the mixture of lime and argillite decreased from 0.25 down to 0.18.

214 The specific surface of the samples was also determined. It can be seen that the specific  
215 surface of the argillite is directly related to the nature of the additive (Table 3). The  
216 modification of the specific surface of the mixtures was also monitored. It can be seen that  
217 some additives induced dramatic modifications of the specific surface of the mixtures. Indeed,  
218 one effect of the alkaline fluid circulation was to induce the dissolution of clay particles (e.g.  
219 [2] ), that could result in a decrease in the specific surface of the soil. The modification of the  
220 specific surface as a function of the circulation time is directly related to the nature of the  
221 additive. While it remained stable in the case of the sand – argillite mixture after 12 months of  
222 circulation of alkaline water, it dropped from about 51,4  $\text{m}^2/\text{g}$  down to 12.2  $\text{m}^2/\text{g}$  after  
223 12 months of alkaline water circulations.

224

225 **2.5. Discussion of the experimental results – coupling parameter(s)**

226 These results showed that alkaline fluid circulation could induce important modification of  
227 the geomechanical characteristics of a compacted soil. The extent of the chemo-mechanical  
228 couplings was highly dependent on the nature of the additive mixed with the argillite. Indeed,  
229 while the geomechanical behaviour of the mixture of argillite and sand remained unchanged  
230 after the alkaline fluid circulation, intense modification of that of the lime-treated argillite was  
231 observed. Moreover, similar observations can be drawn from the results of the investigations  
232 made at the microscale. As an example, the MX-80 based mixture was highly reactive with a  
233 strong increase of the macropore void ratio while the lime-based mixture was only slightly  
234 modified at the microscopic level with a slight increase of the micropore void ratio.  
235 Moreover, while the specific surface of the MX-80 mixture decreased by almost 10% after 12  
236 months of water circulation, it decreased by 400 % in case of the lime-argillite mixture.  
237 Then, it is not straightforward to link the intensity of the modifications at the microscale, the  
238 nature of the additive, and the alteration of the geomechanical behaviour after the alkaline  
239 fluid circulation.

240 Therefore, if these results permit to assess how a given mixture is likely to behave when  
241 submitted to an alkaline fluid circulation, it is difficult to gather these observations together in  
242 a unique framework. Such a framework could be used to predict, at least qualitatively, how  
243 alkaline fluid circulation could alter the geomechanical properties as well as the  
244 microstructure of a mixture made of a different proportion of the constituents considered in  
245 this study. Despite the extensive experimental program already carried out, additional results  
246 obtained from other mixtures would be necessary to improve the representativeness of the  
247 results and predict the behaviour of a mixture not considered in the experimental program.  
248 The next section is devoted to the determination of such relationship.

249

### 250 3. MODELLING OF THE SOIL BEHAVIOUR USING EPR

251 This section presents an overview of the EPR technique and its application to  
252 modelling the shear strength behaviour of pure argillite and argillite containing three different  
253 additives under circulation of alkaline water.

254

#### 255 3.1. Evolutionary polynomial regression

256 EPR is a data-driven method based on evolutionary computing, aimed to search for  
257 polynomial structures representing a system. A physical system, having an output  $y$ ,  
258 dependent on a set of inputs  $X$  and parameters  $\theta$ , can be mathematically formulated as:

$$y = F(\mathbf{X}, \boldsymbol{\theta}) \quad (1)$$

259

260 where  $F$  is a function in an  $m$ -dimensional space and  $m$  is the number of inputs.

261 In EPR the evolutionary procedure is conducted in the way that it searches for the  
262 exponents of a polynomial function with a fixed maximum number of terms. During one  
263 execution it returns a number of expressions with increasing numbers of terms up to a limit  
264 set by the user, to allow the optimum number of terms to be selected. The general form of  
265 expression used in EPR can be presented as [17] :

$$y = \sum_{j=1}^m F(\mathbf{X}, f(\mathbf{X}), a_j) + a_0 \quad (2)$$

266

267 where  $y$  is the estimated vector of output of the process;  $a_j$  is a constant;  $F$  is a function  
268 constructed by the process;  $\mathbf{X}$  is the matrix of input variables;  $f$  is a function defined by the  
269 user; and  $m$  is the number of terms of the target expression. The first step in identification of  
270 the model structure is to transfer Eq. (2) into the following vector form:

$$Y_{N \times 1}(\theta, Z) = \begin{bmatrix} I_{N \times 1} & Z_{N \times m}^j \end{bmatrix} \times [a_0 \ a_1 \ \dots \ a_m]^T = Z_{N \times d} \times \theta_{d \times 1}^T \quad (3)$$

271

272 where  $Y_{N \times 1}(\theta, Z)$  is the least squares estimate vector of the  $N$  target values;  $\theta_{d \times 1}$  is the vector of  
 273  $d=m+1$  parameters  $a_j$  and  $a_0$  ( $\theta^T$  is the transposed vector); and  $Z_{N \times d}$  is a matrix formed by  $I$   
 274 (unitary vector) for bias  $a_0$ , and  $m$  vectors of variables  $Z_j$ . For a fixed  $j$ , the variables  $Z_j$  are a  
 275 product of the independent predictor vectors of inputs,  $X = \langle X_1 \ X_2 \ \dots \ X_k \rangle$ .

276 In general, EPR is a two-stage technique for constructing symbolic models. Initially,  
 277 using a standard genetic algorithm (GA), it searches for the best form of the function  
 278 structure, i.e. a combination of vectors of independent inputs,  $X_s, s=1:k$ , and secondly it  
 279 performs a least squares regression to find the adjustable parameters,  $\theta$ , for each combination  
 280 of inputs. In this way a global search algorithm is implemented for both the best set of input  
 281 combinations and related exponents simultaneously, according to the user-defined cost  
 282 function [17] . The adjustable parameters,  $a_j$ , are evaluated by means of the linear least  
 283 squares (LS) method based on minimization of the sum of squared errors (SSE) as the cost  
 284 function.

285 The global search for the best form of the EPR equation is performed by means of a standard  
 286 GA over the values in the user defined vector of exponents. The GA operates based on  
 287 Darwinian evolution which begins with random creation of an initial population of solutions.  
 288 Each parameter set in the population represents the individual's chromosomes. Each  
 289 individual is assigned a fitness based on how well it performs in its environment. Through  
 290 crossover and mutation operations, with the probabilities  $P_c$  and  $P_m$  respectively, the next  
 291 generation is created. Fit individuals are selected for mating, whereas weak individuals die  
 292 off. The mated parents create a child (offspring) with a chromosome set which is a mix of

293 parents' chromosomes. In EPR integer GA coding with single point crossover is used to  
294 determine the location of the candidate exponents.

295 The EPR process stops when the termination criterion, which can be either the  
296 maximum number of generations, the maximum number of terms in the target mathematical  
297 expression or a particular allowable error, is satisfied. A typical flow diagram for the EPR  
298 procedure is illustrated in Figure 5.

299 In the evolutionary process of building EPR models, a number of constraints can be  
300 implemented to control the output models in terms of the type of functions used, number of  
301 terms, range of exponents, number of generations etc. In this process there is a potential to  
302 achieve different models for a particular problem which enables the user to gain additional  
303 information for different scenarios [27] . Applying the EPR procedure, the evolutionary  
304 process starts from a constant mean of output values. By increasing the number of evolutions  
305 it gradually picks up different participating parameters in order to form equations describing  
306 the relationship between the parameters of the system. Each proposed model is trained using  
307 the training data and tested using the testing data provided. The level of accuracy at each  
308 stage is evaluated based on the coefficient of determination (COD) i.e., the fitness function as:  
309

$$\text{COD} = 1 - \frac{\sum_N (Y_a - Y_p)^2}{\sum_N \left( Y_a - \frac{1}{N} \sum_N Y_a \right)^2} \quad (4)$$

310  
311  
312 where  $Y_a$  is the actual value;  $Y_p$  is the EPR predicted value and  $N$  is the number of data on  
313 which COD is computed. If the model fitness is not acceptable or the other termination  
314 criteria (in terms of maximum number of generations and maximum number of terms) are not  
315 satisfied, the current model goes through another evolution in order to obtain a new model.

### 316 **3.2. Database used in developing the EPR model**

317 Results from 33 consolidated undrained triaxial tests conducted on samples of argillite  
318 (MA), lime-MA, sand-MA, bentonite-MA mixtures, subjected to different periods of  
319 exposure to alkaline water circulation, were used for development and validation of the EPR  
320 model. Of the total of 33 cases, 29 cases related to different circulation times (i.e. 0, 3, 6, 12  
321 months) were used for training of the EPR model. Of these 29 cases, 11 cases were related to  
322 no circulation (0 month of circulation), 5 cases to 3 months, 2 cases to 6 months and 11 cases  
323 to 12 months of circulation of the alkaline water through the samples. The remaining 4 cases  
324 (each relating to a different soil and circulation time) were kept unseen during the model  
325 development process and used to evaluate the developed model.

326 Eight parameters were used as input for the EPR model. These included the dry  
327 density ( $\rho_d$ ), alkaline water circulation time ( $t$ ), axial strain ( $\varepsilon_a$ ), pore pressure ( $u$ ) and the  
328 effective confining pressure ( $\sigma'_3$ ). It was also required to introduce parameters that could  
329 account for the physic-chemical processes induced by alkaline water circulation. It has been  
330 shown that a deep reorganisation of the structure occurred over the circulation period. This  
331 reorganisation can be accounted for by the balance between macro-pores ( $e_M$ ) and porosity of  
332 micro-pores ( $e_m$ ) that have been thus integrated in the analysis. Moreover, the alkaline water  
333 circulation can also alter the specific surface (SS) of the tested material to a different extent as  
334 a function of the nature of the additive. This parameter is related to dissolution of clay  
335 particles. The only output was considered to be the deviatoric stress ( $\sigma'_1 - \sigma'_3$ ). The following  
336 equation represents the EPR model developed through the above mentioned procedure:

337

$$\begin{aligned}
338 \quad \sigma'_1 - \sigma'_3 = & \frac{-2.95 \times 10^5 \varepsilon_a^2}{\rho_d^3 \cdot SS^2} + \frac{4.68}{\rho_d^2 \cdot e_M^3} + \frac{0.01t}{e_M^3} + \frac{1.07 \times 10^5 \varepsilon_a + 5.97 \times 10^3 e_m^2 \cdot u}{e_M \cdot SS^2} - \frac{136.56}{e_m^3} - \frac{5.65 \times 10^3 \Delta u}{SS^3} + 2.99 \times 10^{-6} u \cdot \sigma_3'^2 - 3.23 \times 10^4 e_m^2 \\
& - \frac{10^{-5} e_m^3 \cdot t^3 \cdot \varepsilon_a \cdot \sigma_3'^3}{SS^3} - 1.22 \times 10^4 e_M + \frac{1.09 \times 10^5 e_M \cdot e_m^2 \cdot \varepsilon_a}{SS} - 2.18 \times 10^4 \rho_d + \frac{20.48 \rho_d \cdot e_M \cdot \varepsilon_a^3 \cdot \sigma_3'}{SS^2} - \frac{1.72 \times 10^{-3} \rho_d^2 \cdot \varepsilon_a}{e_M^3 \cdot e_m^3} + 45633.1 \\
339 & \hspace{20em} (6) \\
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361 &
\end{aligned}$$

Figure 6 shows typical results of the training of the EPR model for sand-argillite, lime-argillite and MX-80-argillite mixtures at slightly different confining pressures after 12 months of circulation. The results are compared with actual measurements and it is shown that the EPR model has been able to capture satisfactorily the behaviour of the mixture, despite a slight tendency to overestimate the maximum shear strength. Figure 7 presents typical results of testing of the developed EPR model for pure argillite at confining pressure of 295kPa with no circulation, lime-argillite at confining pressure of 274kPa after 6 months of circulation and MX-80-argillite at confining pressure of 270kPa after 12 months circulation. It is shown that the developed model has also been able to generalise the training to conditions that were not introduced to the model during the training process. The values of coefficient of determination for training and testing are 93% and 94% respectively.

One of the major advantages of EPR is that it is capable of representing the relationship between the parameters in the form of a mathematical expression; therefore, parametric studies can be conducted to investigate the contribution of different parameters involved and to assess whether the developed model has been able to capture the physical relationships between various parameters of the system.

#### 4. SENSITIVITY ANALYSIS

A parametric study was carried out to evaluate the predictive capabilities of the proposed model and the effects of varying different input parameters on the output. This was done

362 through a basic approach to sensitivity analysis which is to fix all but one input variable to  
363 their mean values and vary the remaining one within the range of its maximum and minimum  
364 values. This procedure was repeated consecutively for input parameters and the results are  
365 shown in Figure 8. This sensitivity analysis aimed at determining a possible coupling  
366 parameter that could explain the changes in shear strength behaviour observed after the  
367 circulation of the alkaline fluid.

368 The sensitivity analysis was carried out considering four parameters (dry density, macropore  
369 void ratio, micropore void ratio and specific surface). It can be seen that the dry density did  
370 not permit to explain differences in maximum shear strength that have been observed in the  
371 experimental study. Even though there is a tendency for the maximum shear strength to  
372 increase with an increase in dry density, the calculated variation is much more limited (165-  
373 190kPa) compared to what has been observed experimentally for the tested mixtures (from  
374 hundred kPa up to several thousands of kPa). The same conclusion can be drawn from the  
375 sensitivity analysis for the macropore void ratio ( $e_M$ ). However, the results of the sensitivity  
376 analysis showed that the variation of the maximum deviatoric stress for all the tested samples  
377 can be explained mainly by the value of the specific surface of the samples, especially when  
378 its value is below  $100 \text{ m}^2.\text{g}^{-1}$  and to a lesser extent by the micropore void ratio. From a  
379 physical point of view, specific surface can be used as an indicator of the nature of the  
380 material as it reflects its clay content and therefore its mechanical behaviour before  
381 circulation. The addition of MX-80 bentonite to the Manois argillite results in a high value of  
382 the specific surface, which results in lowering of the mechanical characteristics compared to  
383 the initial material (Table 3). The addition of lime leads to the flocculation and aggregation of  
384 the clay particles that is responsible for a decrease in the specific surface of the Manois  
385 argillite, and an increase of the micropore void ratio. This was associated with a strong effect  
386 on the shear strength behaviour because addition of lime led to the formation of cementitious

387 compounds responsible for the increase in shear strength (Table 3) as evidenced by several  
388 authors (e.g. [24] ). The effect of the alkaline water circulation may also alter the specific  
389 surface of the tested material. Indeed, the main effect of the alkaline fluid circulation was to  
390 induce the dissolution of clay particles (e.g. [2] ), that could result in a decrease in the specific  
391 surface of the soil. The dissolved compounds may react with the calcium to form cementitious  
392 compounds responsible for the increase in shear strength. The formation of new cementitious  
393 compounds can lead to a closure of the smallest pores of the soil as evidenced by some  
394 researchers who studied lime-treated soils at microstructural level ([28] [29] ).

395         The combination of the two parameters permitted to explain the behaviour of the  
396 mixture of Manois argillite and of MX-80 bentonite. This sensitivity analysis shows that the  
397 model is also able to capture and represent the behaviour of the individual mixture. In fact, in  
398 the case of this mixture, the circulation led to a strong decrease of specific surface ( $-25 \text{ m}^2 \cdot \text{g}^{-1}$ )  
399 and an increase of the macropore void ratio without significant modification of the micropore  
400 void ratio.

401

## 402 **5. CONCLUSION**

403         A comprehensive study of the impact of alkaline fluid circulation on the mechanical  
404 behaviour of several mixtures made with Manois Argillite mixed with different additives has  
405 been carried out. Although this study permitted to assess the behaviour of the individual  
406 mixture, there was a need to develop a relationship able to describe the behaviour of the  
407 different mixtures in a single framework. The main objective of the paper was to present the  
408 development of this relationship, based on evolutionary polynomial regression (EPR), to  
409 model the complex hydromechanical behaviour of the soil during alkaline fluid circulation.

410 Overall, the results show that the EPR model, trained from pure experimental data, was able  
411 to capture the main trends of the behaviour of the different mixtures after the fluid circulation  
412 with a reasonable accuracy for both training and testing sets of data.

413 This model was then used to perform a sensitivity analysis in order to identify the best  
414 possible coupling parameters between chemical's effect and the shear strength behaviour. It  
415 appeared that the most appropriate parameter is the specific surface of the mixture. The  
416 specific surface is able to describe the differences at the initial state (before circulation),  
417 reflecting the composition of the mixture, i.e. the nature of the additive, and the differences in  
418 their shear strength behaviour. Moreover, specific surface is sensitive to the alkaline fluid  
419 circulation duration, and its impact on the shear strength behaviour of each individual  
420 mixture. To a lesser extent, the micropore void ratio appeared to be a coupling parameter,  
421 even though the shear strength behaviour of the different mixtures is less sensitive to it.

422 This study showed that the mechanical alteration of the backfill can be assessed from  
423 monitoring of the specific surface modification of the material that is to be used. Additional  
424 research is however required to better characterise the physico-chemical processes responsible  
425 for the modification of the specific surface and the micropore void ratio, and the  
426 corresponding increase in shear strength.

427

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**Table 1. Properties of the tested materials.**

	Liquid limit (%)	Plasticity index (%)	Solid density (Mg/m <sup>3</sup> )	Cation exchange capacity (meq /100 g)
MHM argillite <sup>1</sup>	31.0	17.9	2.70	6.0 to 14
MA	51.0	11.2	2.68	23
Calcareous sand	non plastic	non plastic	2.71	-
MX-80 <sup>2</sup>	520	458	2.65	97

1: data of MHM argillite from [Deroo \(2002\)](#)

2: data from [Marcial et al. \(2002\)](#) and [Neaman et al. \(2003\)](#)

**Table 2. Characteristics of the different mixtures after compaction (MA : Manois Argillite).**

Mixture	MA	MA + 50 % Sand	MA + 20 % MX-80	MA + 4 % lime
Optimum water content (%)	23.0	15.5	25.5	25.5
Dry density (Mg.m <sup>-3</sup> )	1.61	1.83	1.54	1.50

**Table 3. Characteristics of the samples as a function of the circulation duration.**

Mixture	Circulation duration (months)	Water content (%)	Dry weight (Mg.m <sup>-3</sup> )	Specific surface (m <sup>2</sup> .g <sup>-1</sup> )	Effective friction angle (°)	Effective cohesion (kPa)
Pure argillite	0	23.0	1.61	156.6	18.6	25.6
	12	27.5	1.54	142.0	22.2	9.5
50 % Argillite + 50 % sand	0	15.5	1.83	67.5	28.9	0
	3	17.1	1.86	71.7		
	6	14.9	1.85	67.5	26.8*	0*
	12	16.2	1.88	74.6		
80 % Argillite + 20 % MX-80	0	25.5	1.54	205.6	18.1	0
	12	34.5	1.34	182.6	13.5	30.0
96 % Argillite + 4 % lime	0	25.5	1.55	51.4	39.5	50.3
	3	29.0	1.49	24.5		
	6	29.9	1.47	19.6	53.7*	282.5*
	12	29.7	1.48	12.2		

\* : no significant influence of circulation duration on shear strength parameter.

## FIGURES CAPTIONS

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**Figure 1.** Mechanical behaviour of the mixtures before (a) and after (b) 12 months of alkaline water circulation at 60°C.

**Figure 2.** Mechanical behaviour of the mixture of lime and MA argillite before (a) and after (b) 12 month of alkaline water circulation at 60°C.

**Figure 3.** Influence of 12 months of alkaline water circulation on the pore size distribution of the tested materials.

**Figure 4.** Evolution of the porosity due to the circulation of the alkaline water.

**Figure 5.** Typical flow diagram for EPR procedure.

**Figure 6.** Typical training results of the EPR model: (a) Sand-argillite,  $\sigma'_3=569\text{kPa}$ , (b) Lime-argillite  $\sigma'_3=587$ , (c) MX-80-argillite,  $\sigma'_3=557\text{kPa}$ , after 12 months circulation.

**Figure 7.** Typical testing results of the EPR model: (a) Pure argillite,  $\sigma'_3=295\text{kPa}$ , No circulation; (b) Lime-argillite  $\sigma'_3=274$ , 6 month circulation; (c) MX-80-argillite,  $\sigma'_3=270\text{kPa}$ , 12 months circulation.

**Figure 8.** Sensitivity analysis considering effect of (a) dry density, (b) specific surface, (c) macroporosity and (d) microporosity

Figure 1

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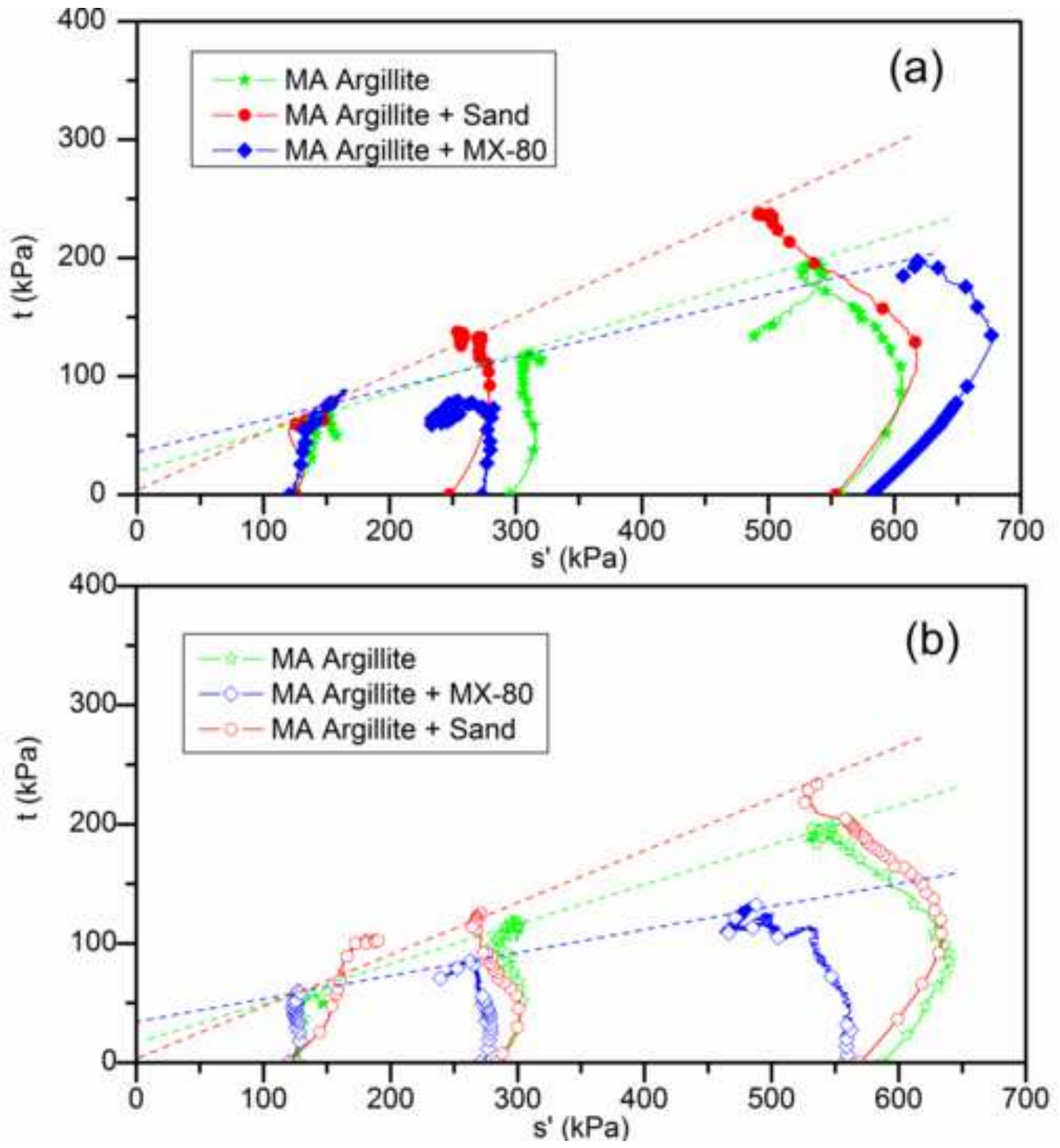


Figure 2

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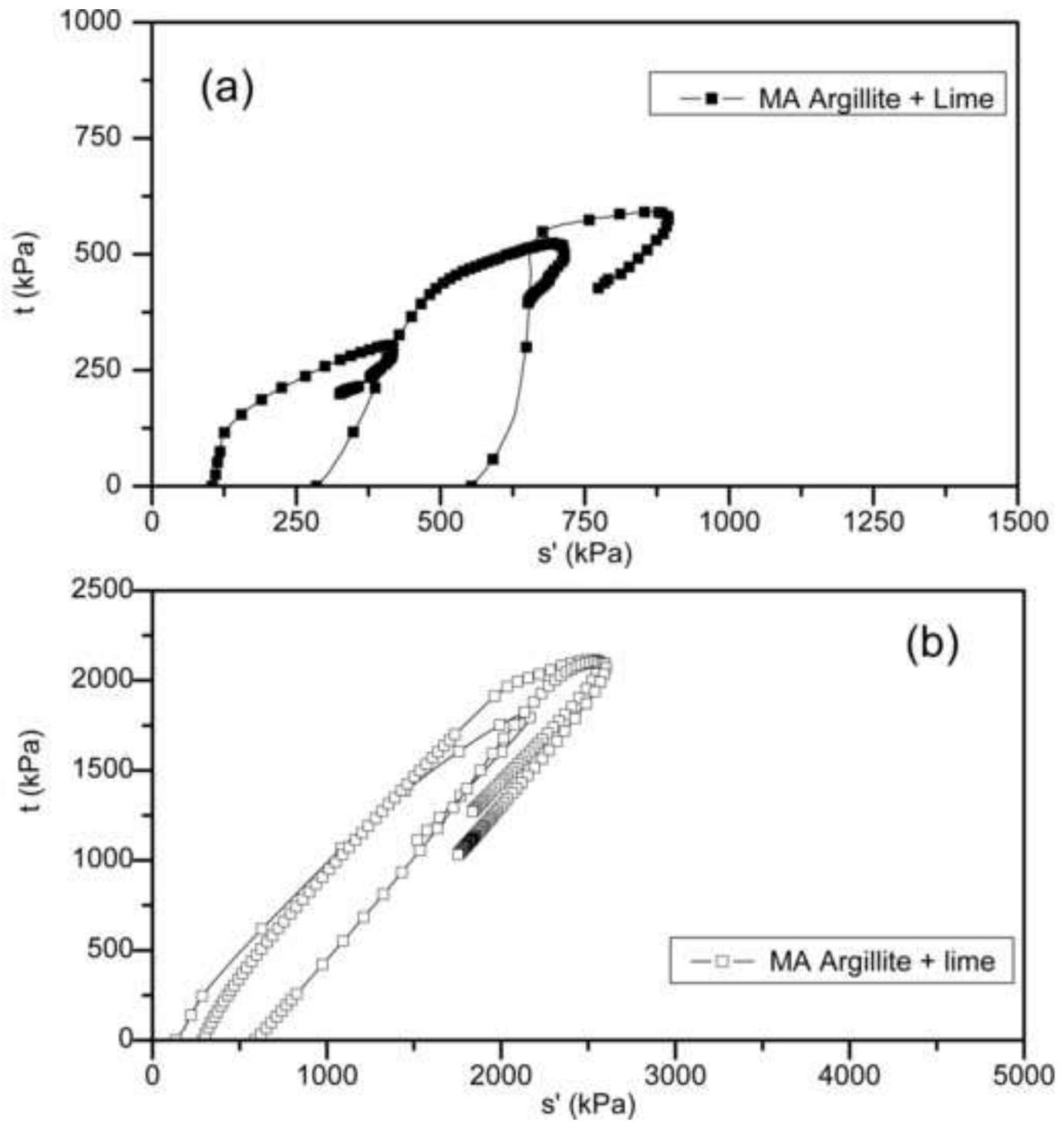


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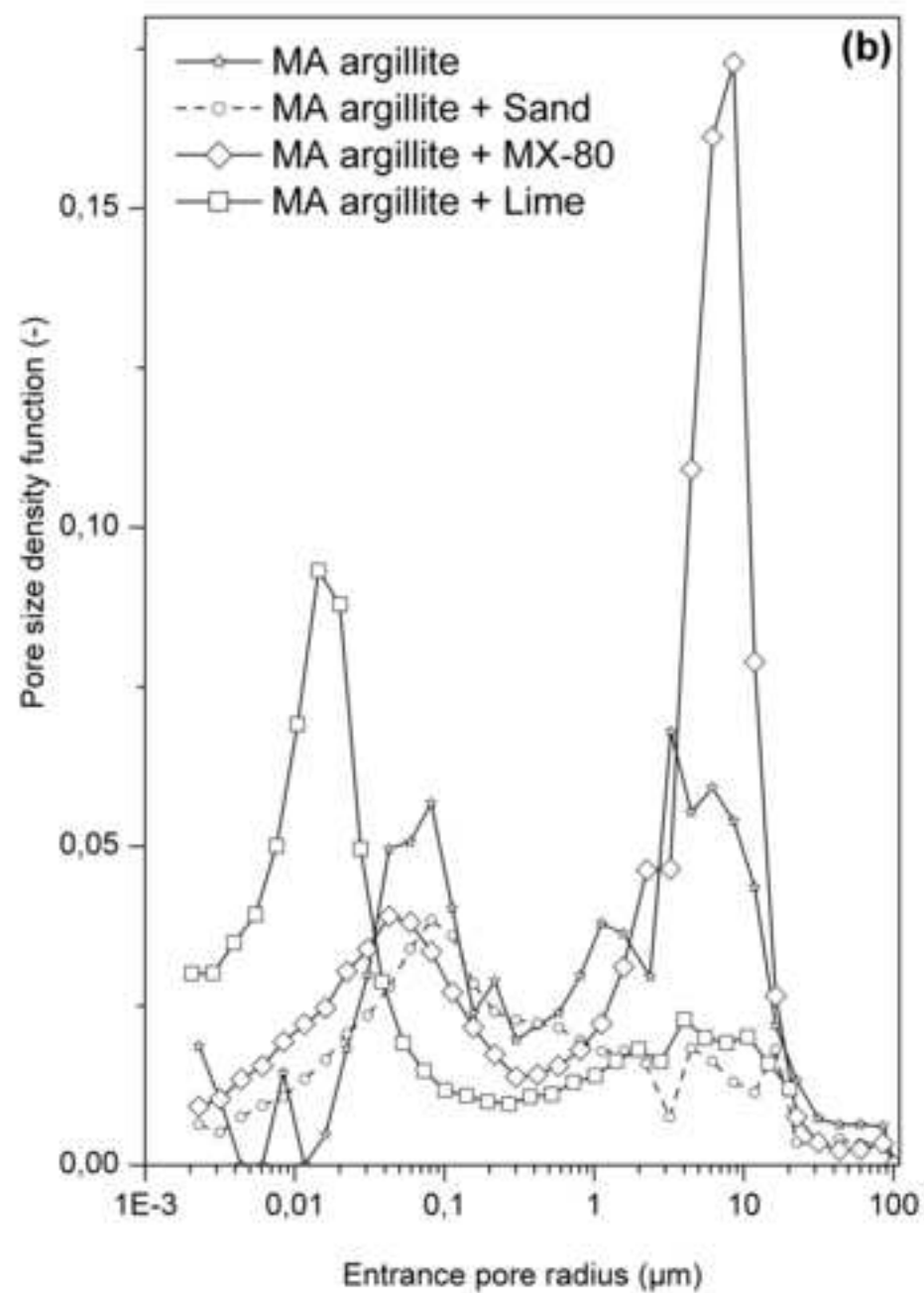
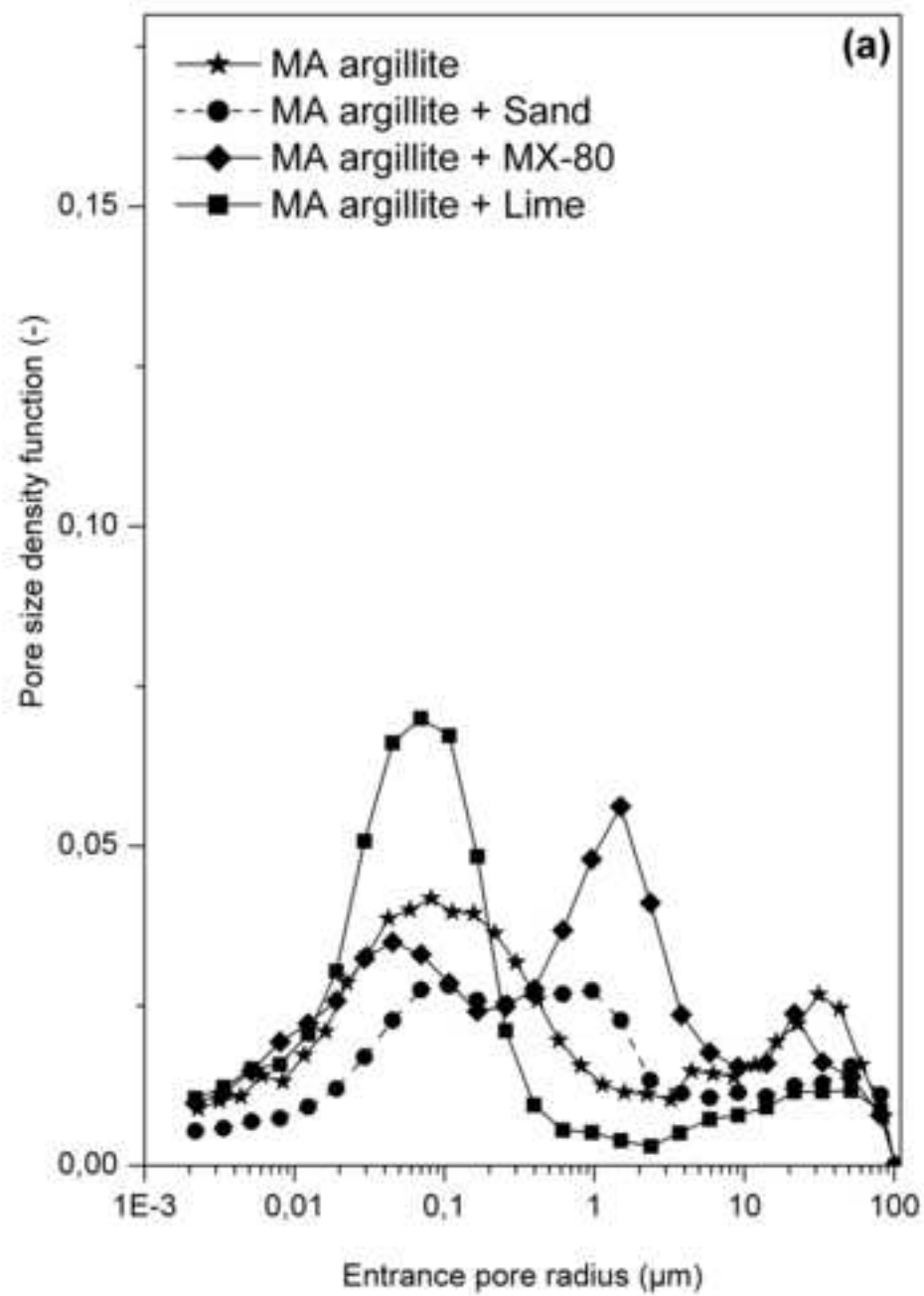


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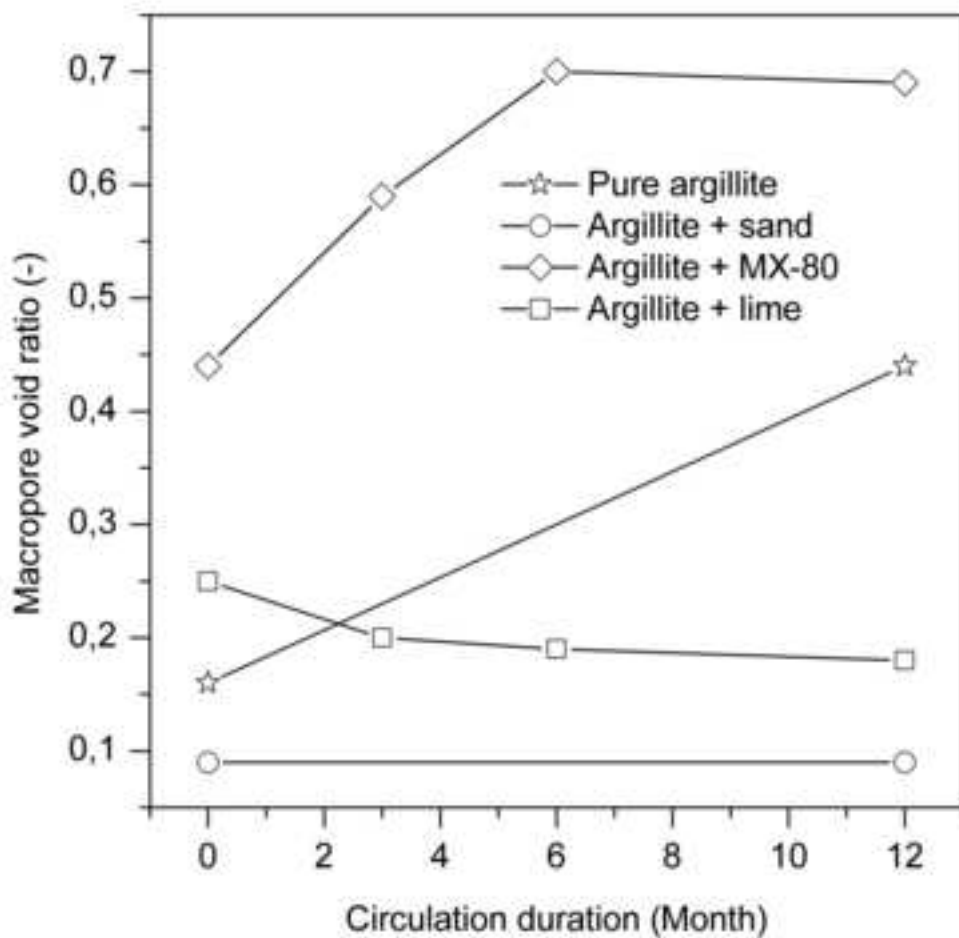
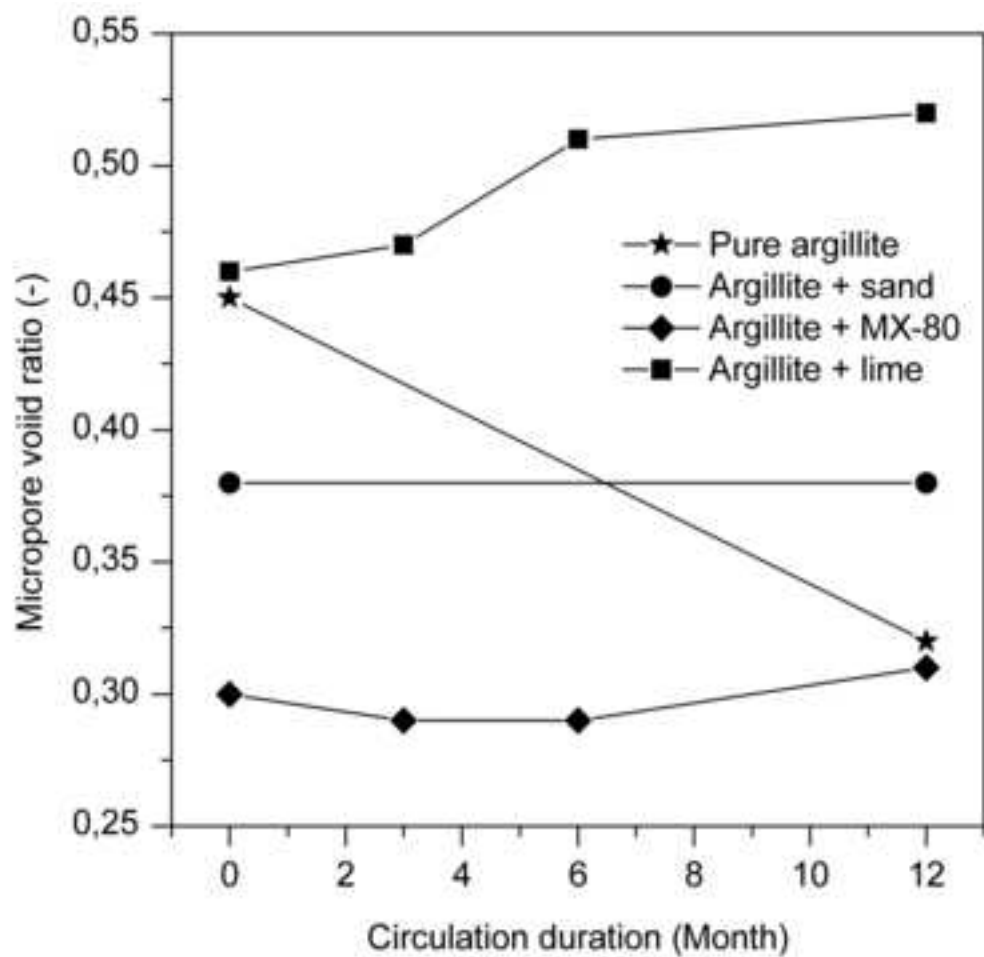


Figure 5

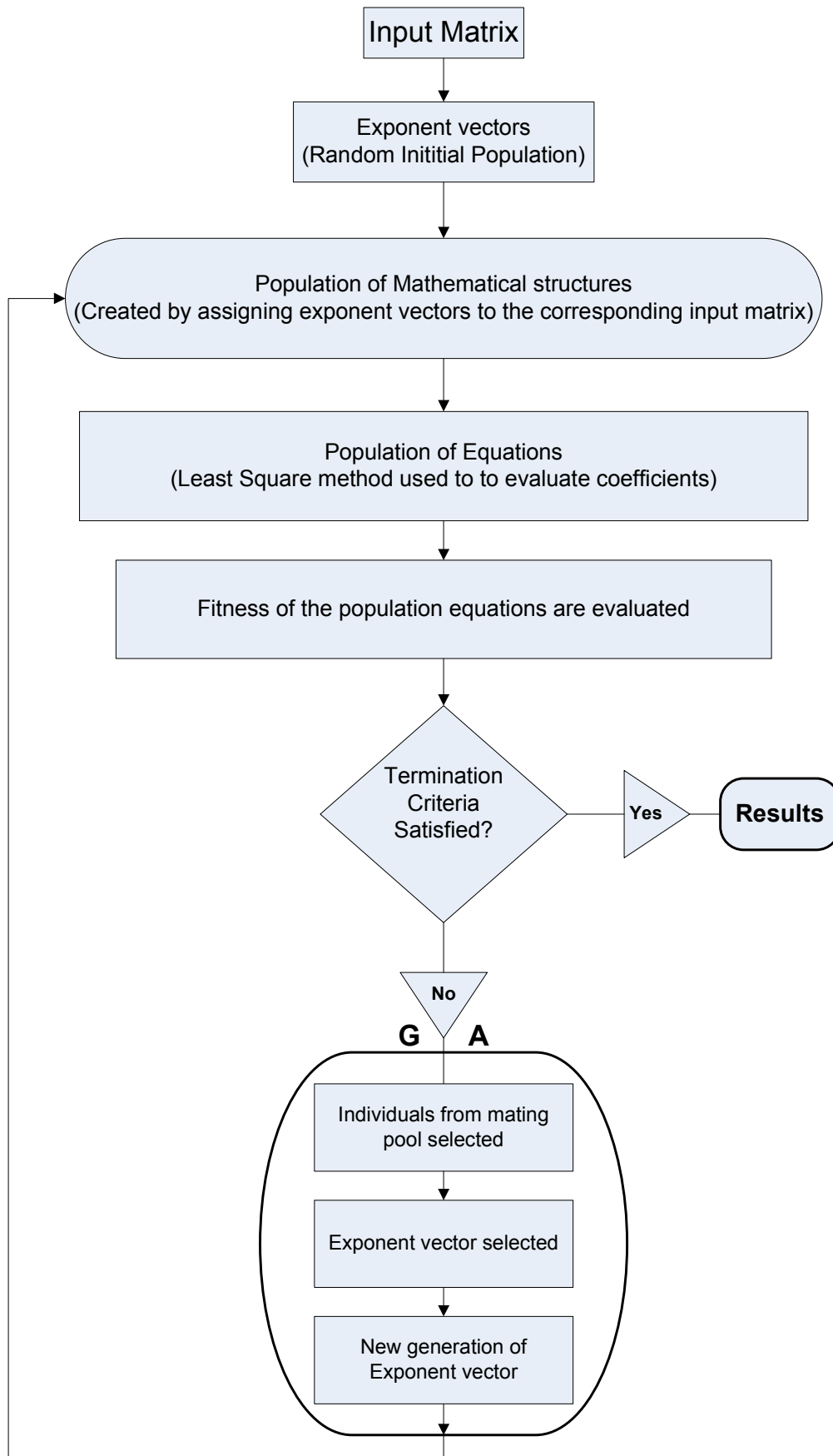


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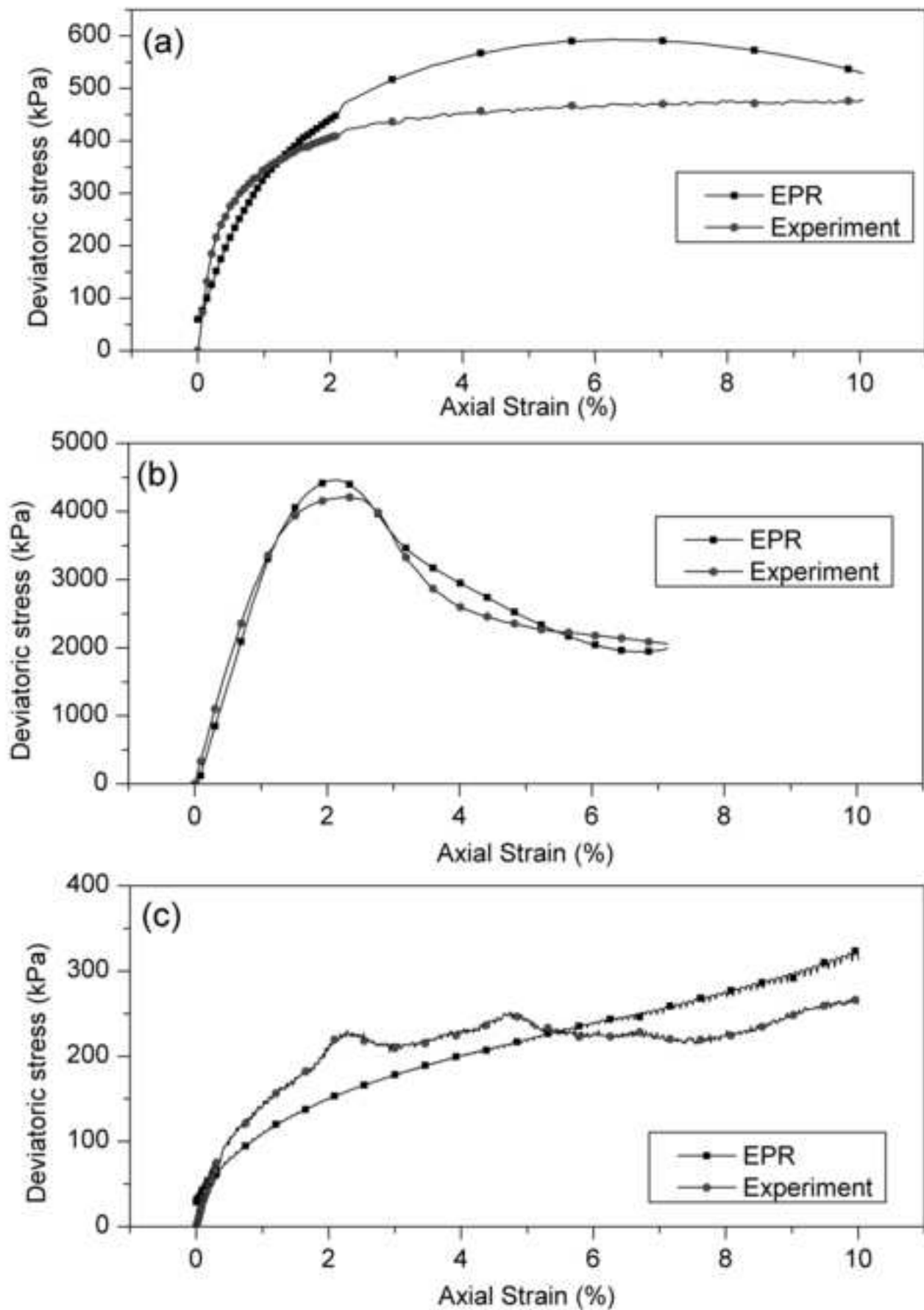


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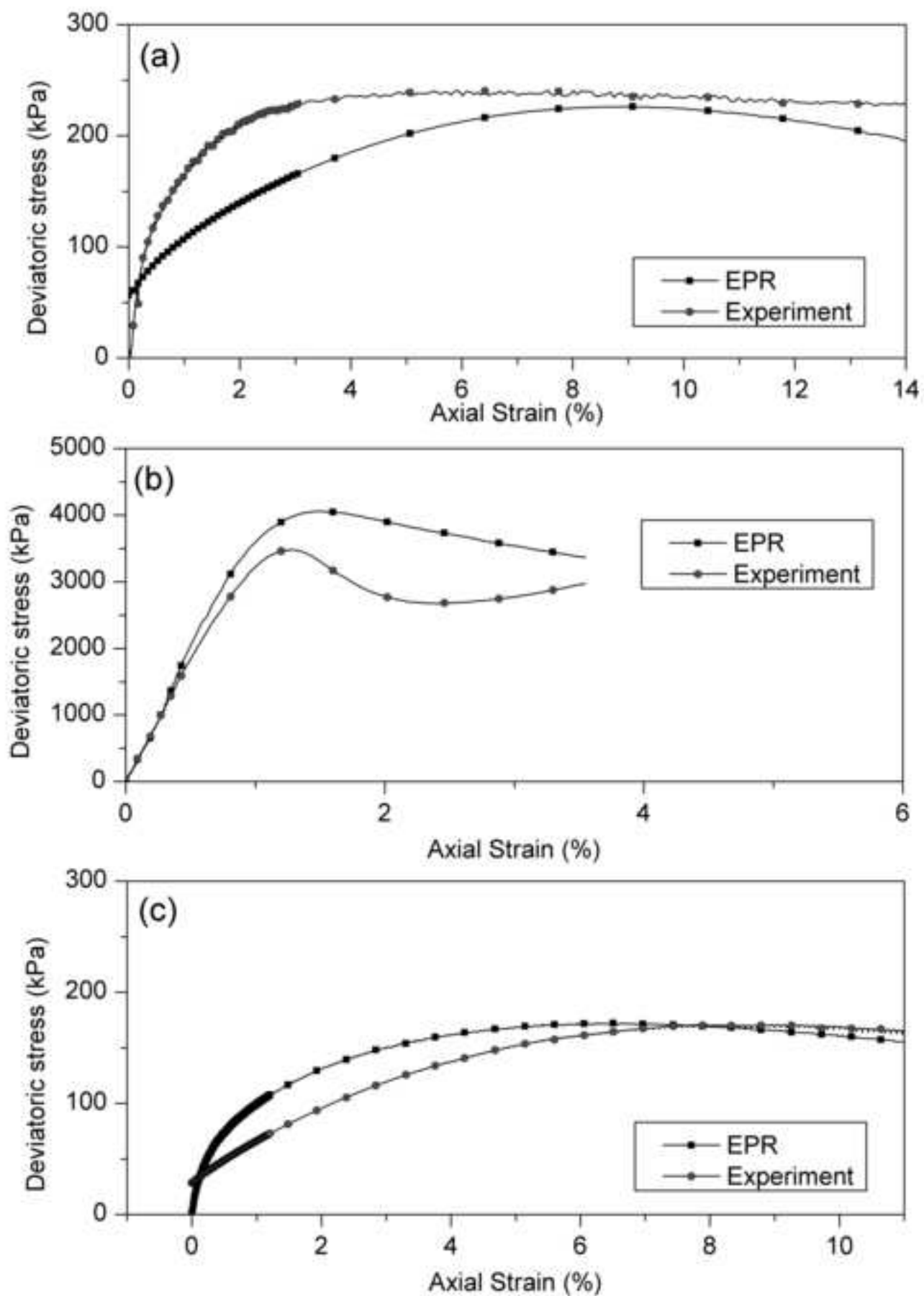
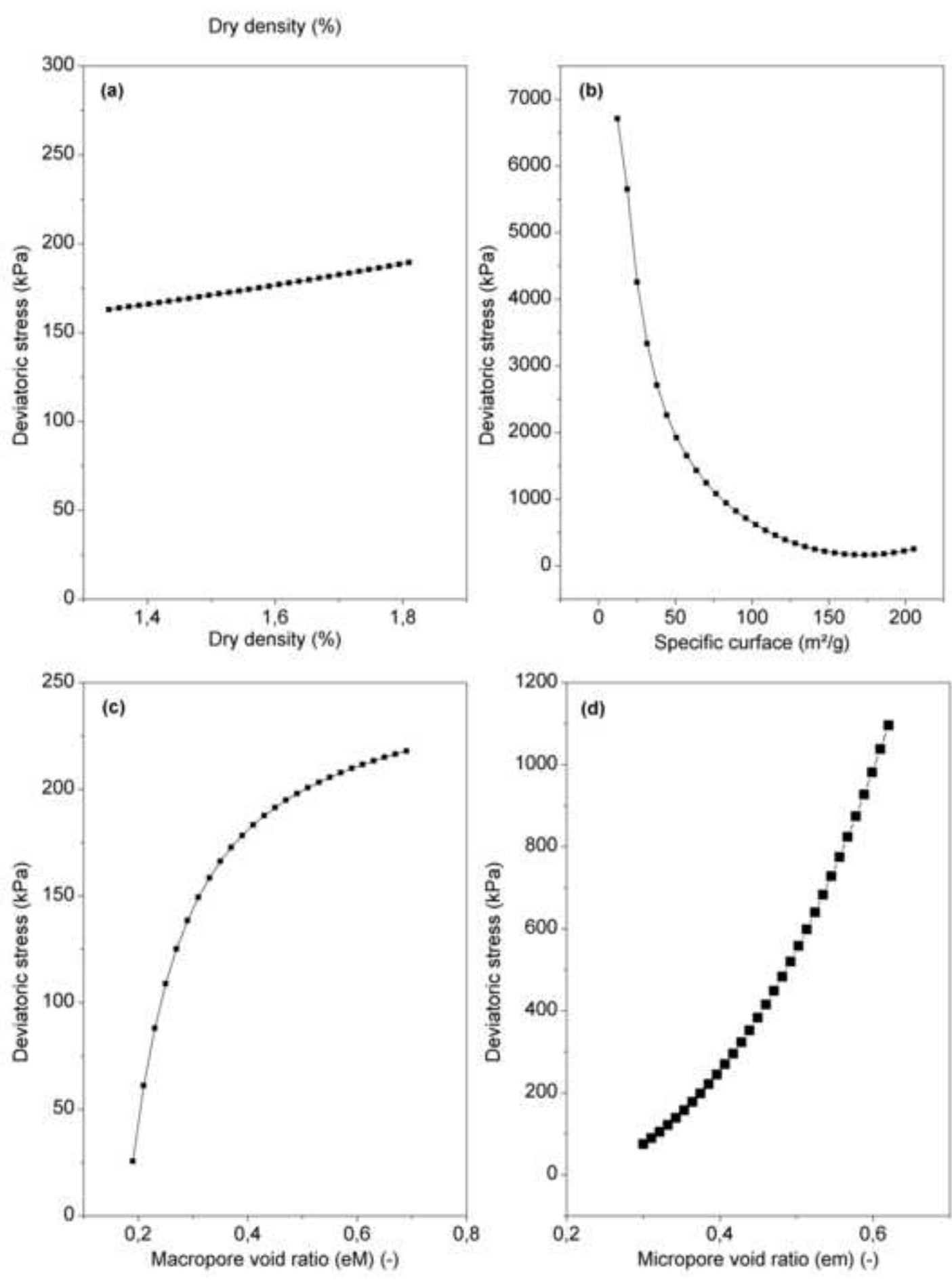


Figure 8

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## Research Highlights

### **Identification of coupling parameters between shear strength behavior and chemical's effects with an evolutionary-based data mining technique**

Cuisinier, O., Javadi, A.A., Ahangar, A. & Masroufi, F.

- Development a constitutive law to model behaviour of soil during alkaline fluid circulation.
- EPR model captured many trends of the behaviour of the different mixtures considered
- The most appropriate coupling parameter is the specific surface of the mixture.