



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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► To cite this version:

Olivier Cuisinier, Akbar Javadi, Alireza Ahangar-Asr, Farimah Masrouri. Identification of coupling parameters between shear strength behaviour of compacted soils and chemical's effects with an evolutionary-based data mining technique. *Computers and Geotechnics*, 2013, 48 (6), pp.107 - 116. 10.1016/j.compgeo.2012.10.005 . hal-01718406

HAL Id: hal-01718406

<https://hal.science/hal-01718406>

Submitted on 5 Jul 2019

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

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

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

1. INTRODUCTION

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

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

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

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

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

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

2. EXPERIMENTAL CHARACTERISATION OF THE IMPACT OF THE CIRCULATION OF ALKALINE WATER

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

2.1. Materials properties

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

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

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

2.2. Aging procedure and samples preparation

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

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

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

2.3. Alteration of shear strength parameters by alkaline water circulation

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

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

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

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

2.4. Alteration of microstructural parameters by alkaline water circulation

In parallel to the determination of the shear strength behaviour, the microstructure of the samples was analysed before and after alkaline fluid circulation. Samples of cubic shapes and of volume comprised between 1 and 2 cm³ were taken in from the cells after the circulation period, then freeze-dried and kept inside desiccators. These were used to determine the microstructure of the different materials by using mercury intrusion porosimetry. The pore size distribution before and after 12 months of alkaline water circulation are compared in Figure 3. It can be seen that the impact of the alkaline water circulation is directly related to the nature of the additive employed to improve the behaviour of the argillite. When MX-80 is

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

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

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

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

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

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

3. MODELLING OF THE SOIL BEHAVIOUR USING EPR

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

3.1. Evolutionary polynomial regression

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

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

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

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

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

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

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

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 $d=m+1$ parameters a_j and a_0 (θ^T is the transposed vector); and $Z_{N \times d}$ is a matrix formed by I (unitary vector) for bias a_0 , and m vectors of variables Z_j . For a fixed j , the variables Z_j are a product of the independent predictor vectors of inputs, $X = \langle X_1 X_2 \dots X_k \rangle$.

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

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

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

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

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

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

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

3.2. Database used in developing the EPR model

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

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

$$\sigma'_1 - \sigma'_3 = \frac{-2.95 \times 10^5 \varepsilon_a^2}{\rho_d^3 \cdot SS^2} + \frac{4.68}{\rho_d^2 \cdot e_M^3} + \frac{0.01t}{e_M^3} + \frac{1.07 \times 10^5 \varepsilon_a + 5.97 \times 10^3 e_m^2 \cdot u}{e_M \cdot SS^2} - \frac{136.56}{e_m^3} - \frac{5.65 \times 10^3 \Delta u}{SS^3} + 2.99 \times 10^{-6} u \cdot \sigma_3'^2 - 3.23 \times 10^4 e_m^2$$

$$- \frac{10^{-5} e_m^3 \cdot t^3 \cdot \varepsilon_a \cdot \sigma_3'^3}{SS^3} - 1.22 \times 10^4 e_M + \frac{1.09 \times 10^5 e_M \cdot e_m^2 \cdot \varepsilon_a}{SS} - 2.18 \times 10^4 \rho_d + \frac{20.48 \rho_d \cdot e_M \cdot \varepsilon_a^3 \cdot \sigma_3'}{SS^2} - \frac{1.72 \times 10^{-3} \rho_d^2 \cdot \varepsilon_a}{e_M^3 \cdot e_m^3} + 45633.1$$

(6)

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

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

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

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

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

5. CONCLUSION

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

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

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

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

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Table 1. Properties of the tested materials.

	Liquid limit (%)	Plasticity index (%)	Solid density (Mg/m ³)	Cation exchange capacity (meq /100 g)
MHM argillite ¹	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 ²	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 ⁻³)	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 ⁻³)	Specific surface (m ² .g ⁻¹)	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

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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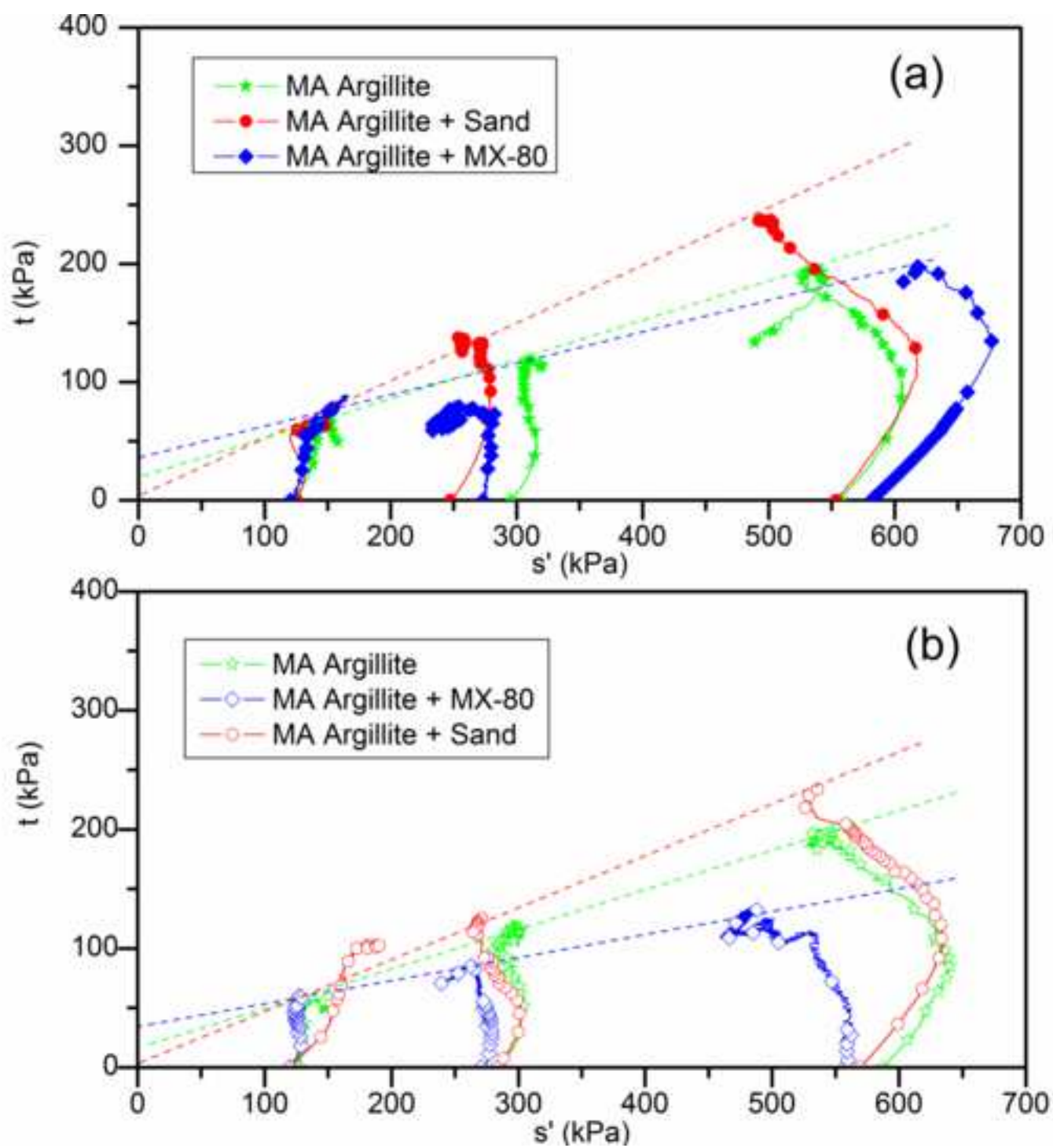


Figure 2
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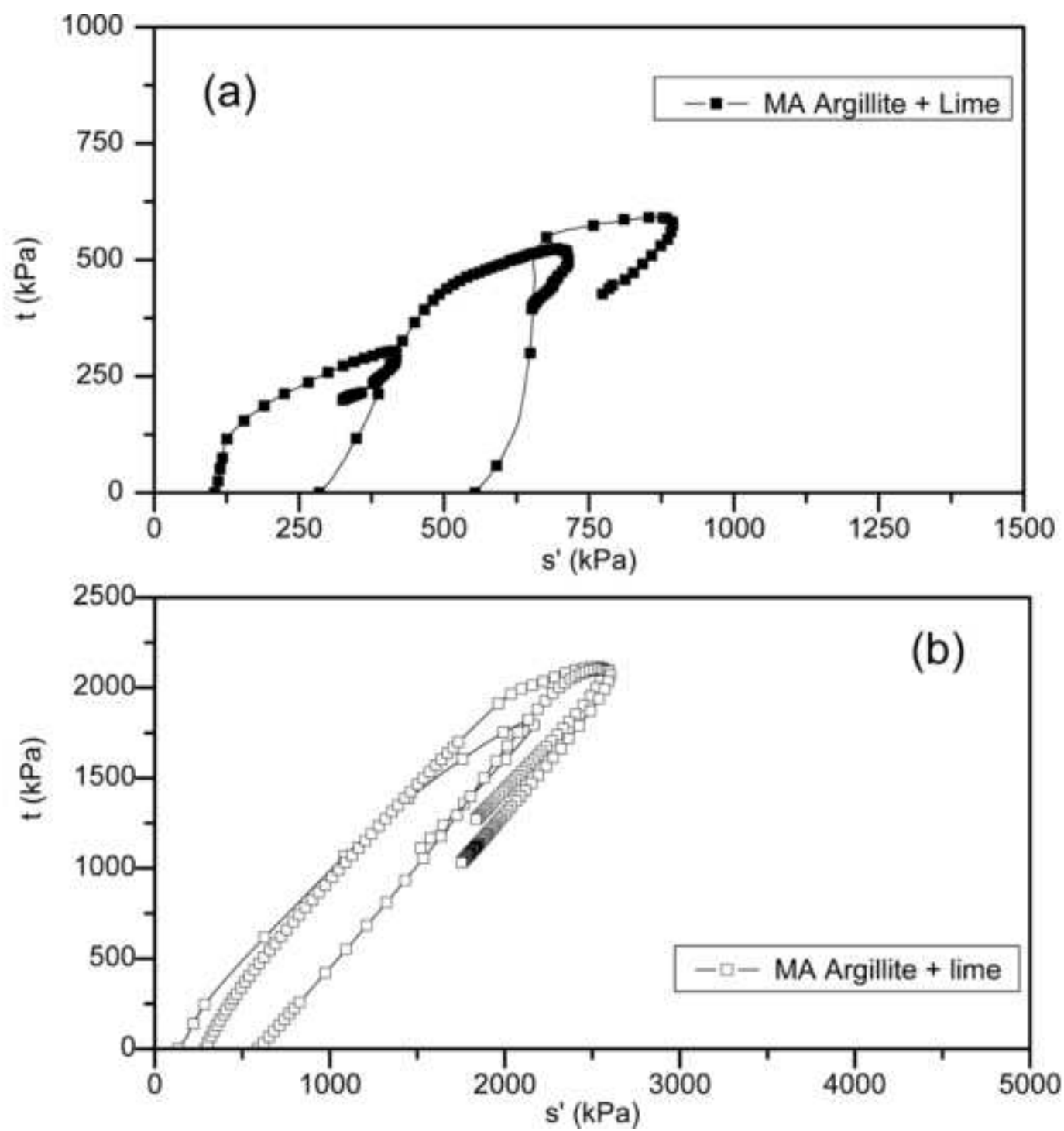


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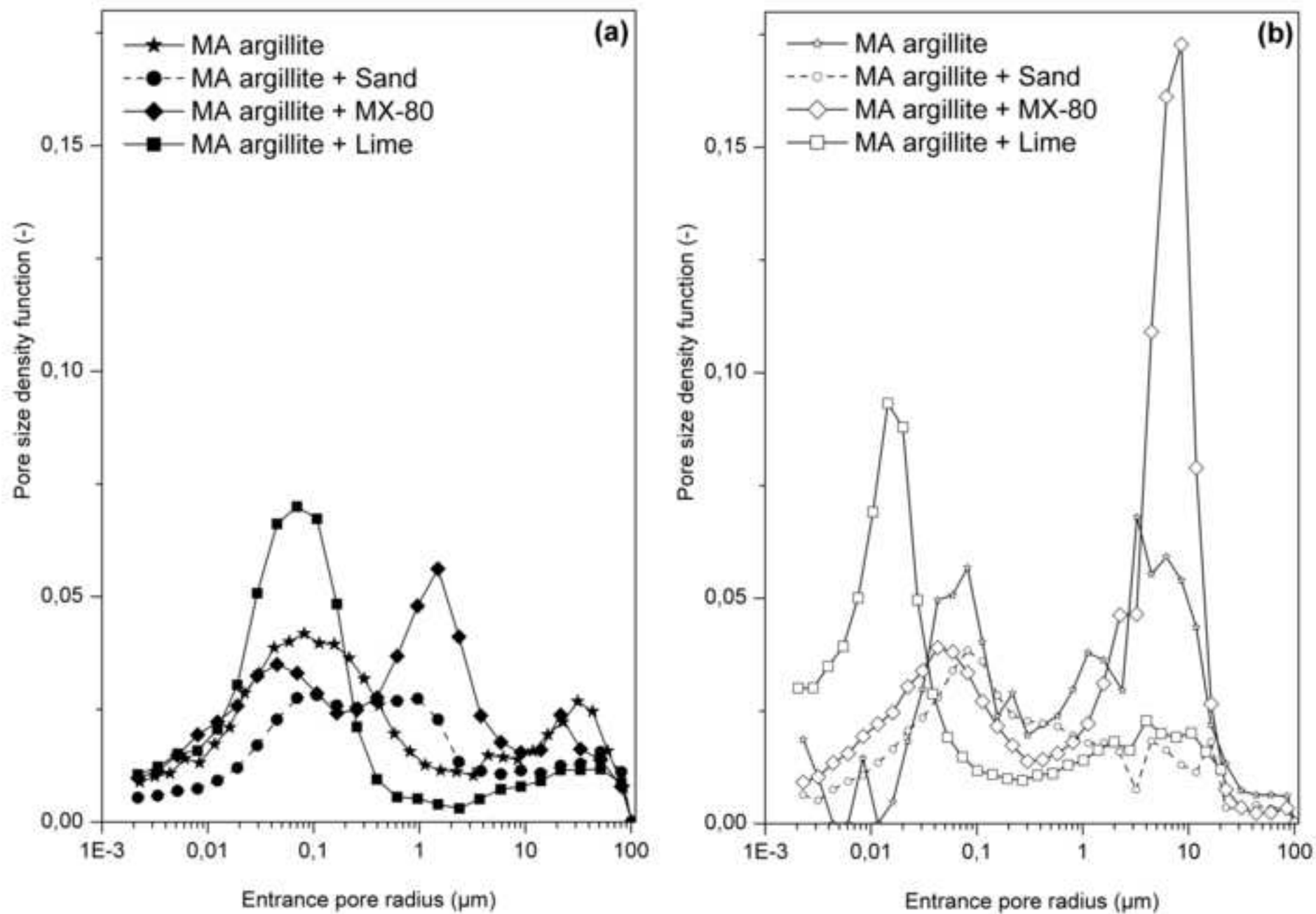


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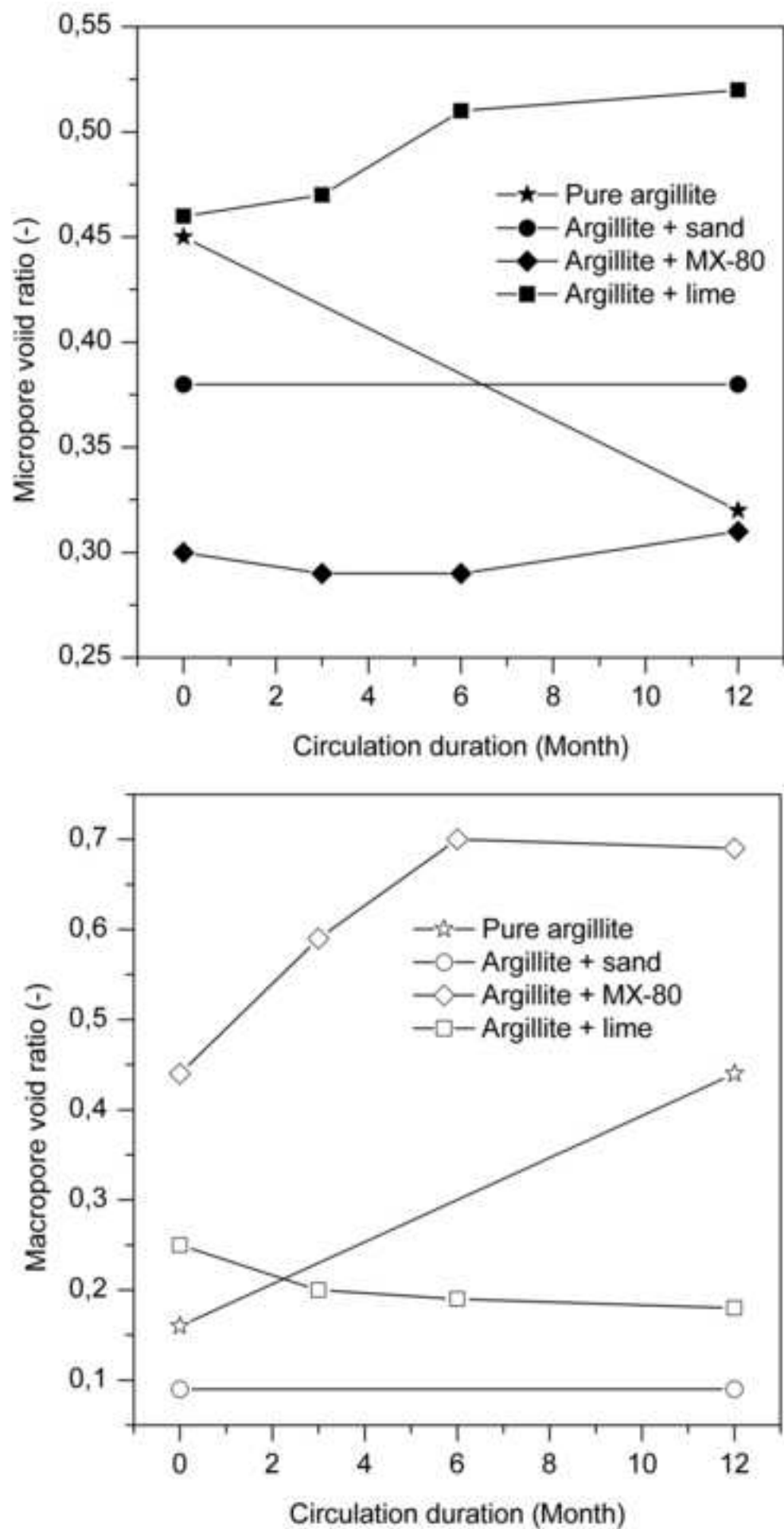


Figure 5

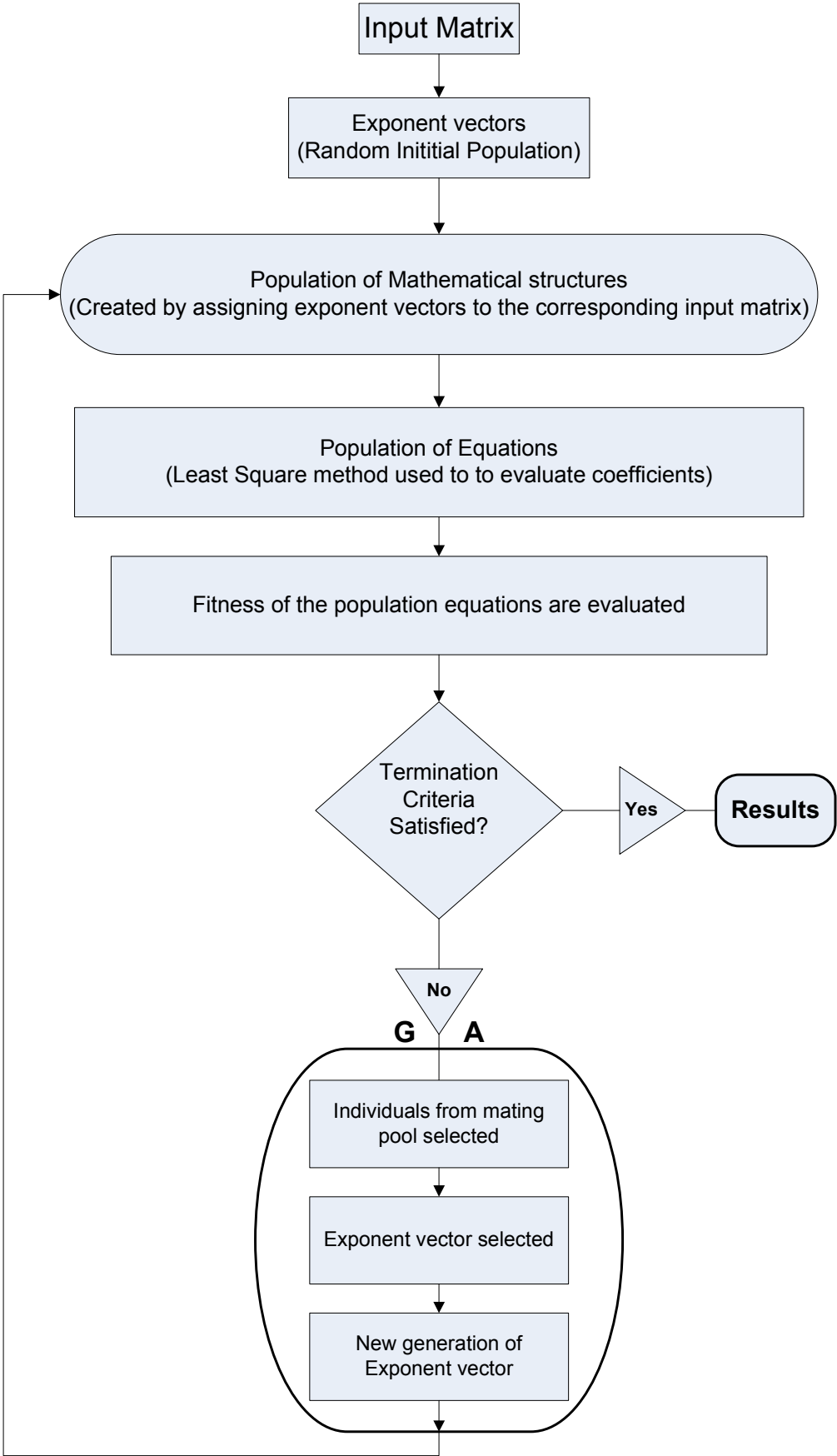


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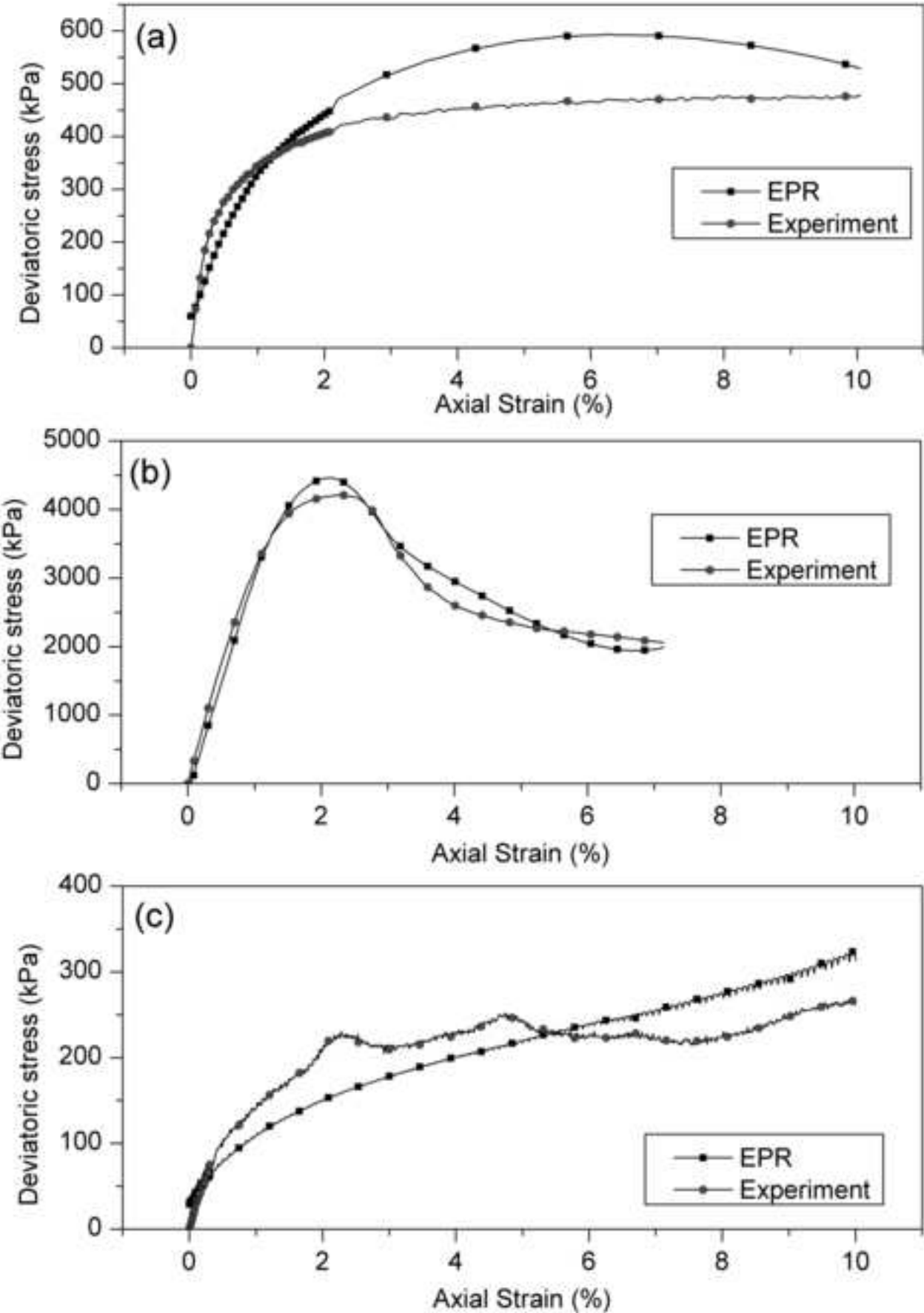


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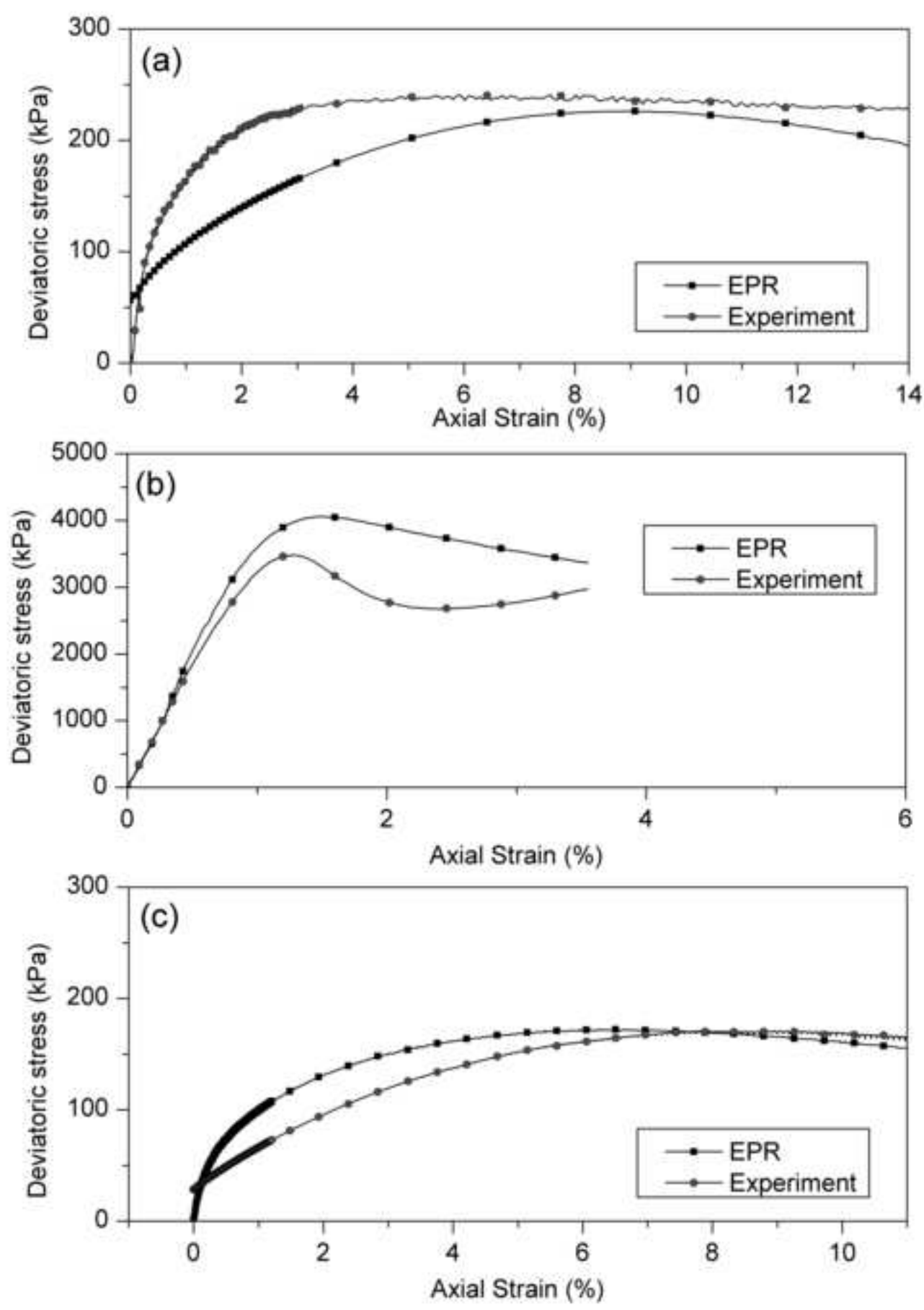
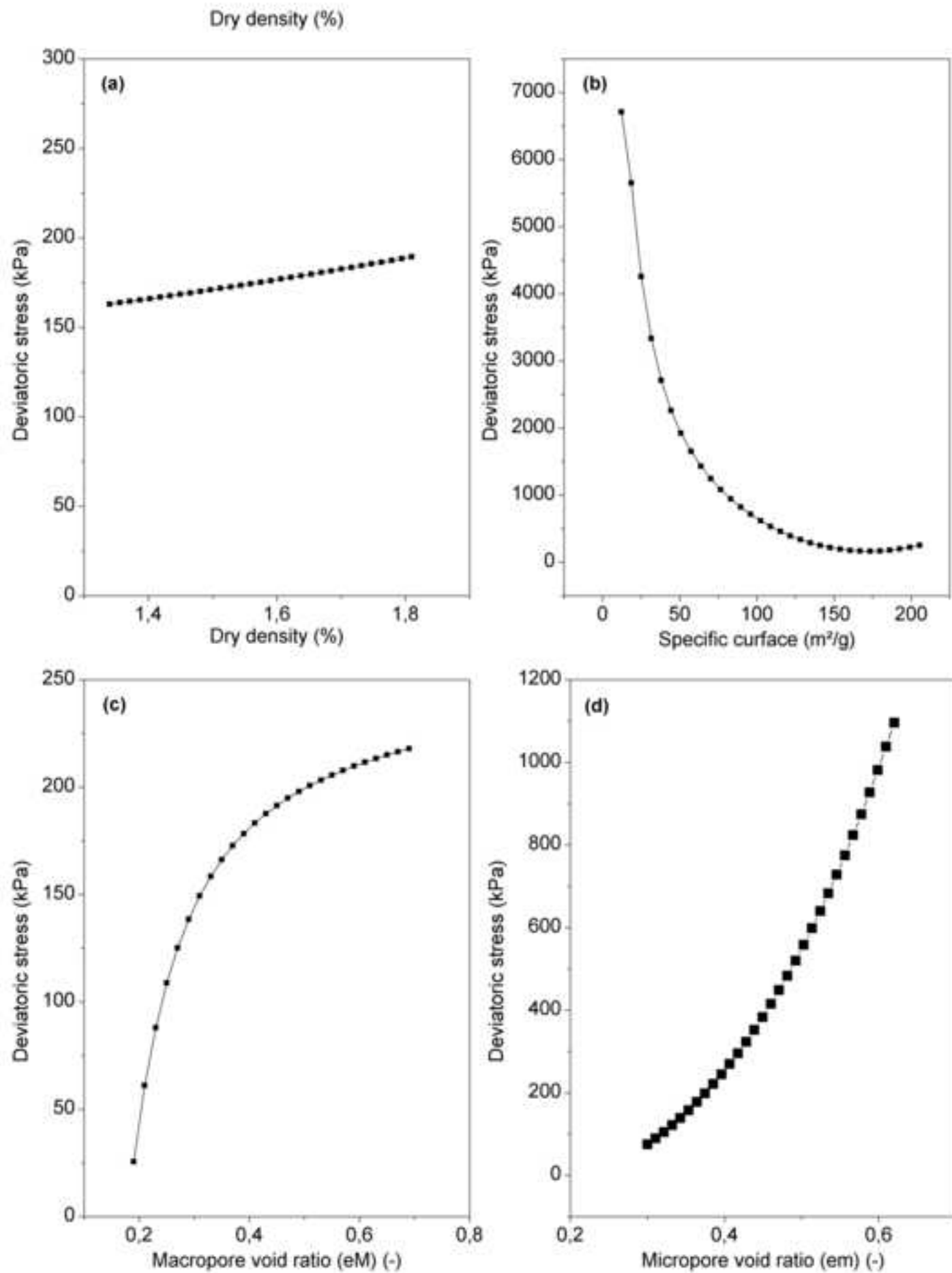


Figure 8
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Research Highlights

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. & Masroui, 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.