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Farouk Menari,
Sabah Moussaoui,
Mourad Belgasmia,
Khelifa Abbeche

GAINING A DEEPER UNDERSTANDING OF THE BEHAVIOR OF SOIL MIXING UNDER THE AGING EFFECT BY COMPARING PREDICTIVE APPROACH AND PRACTICAL RESULTS

The object of this research is the behavior of soil mixing column.

The problem that this research aims to address is to better understand the behavior of soil mixtures under the effect of wetting-drying cycles (aging) and its impact on unconfined compressive strength.

The research consists of a parametric laboratory (experimental) research, with the preparation of different mixtures containing varying percentages of fine particles, cement, and water/cement (W/C) ratios. Eight different formulations were studied: a reference formulation, three formulations with 25% fine particles and different cement dosages, three formulations with 10% fine particles, and two with 5% fine particles. A reference sample was used to track the evolution of these results. This variation in mixture composition allows to observe the influence of particle size distribution, clay content, and cement content on the relative unconfined compressive strength of the prisms. The results show that the relative compressive strength of the prisms decreases by approximately 41% between 3 and 24 cycles, regardless of the cement content. It increases by 18 to 25% with increasing cement content for all formulations, but decreases by approximately 23% with increasing fine particle content. This research allowed to propose an equation to predict the evolution of relative compressive strength as a function of time, the number of wetting-drying cycles, cement content, and fine particle content. The various results obtained highlight the influence of fine particle and cement content on the performance and durability of soil mixing columns, and underscore the importance of conducting a thorough parametric research in the laboratory to facilitate the efficient and economical design of these columns.

Keywords: *fine particles, soil-mixing, durability, damage, aging cycle, compressive strength, cement dosage.*

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1. Introduction

Not all existing soils are good soils, hence the need to improve their characteristics, the importance this article topic lies in this objective.

To improve the mechanical properties of existing soils, a hydraulic binder is mechanically incorporated [1, 2]. Upon contact with the soil, it bonds with a stabilizing binder. This allows for the creation, without excavation, of stabilized soil columns, similar to rigid or semi-rigid columns. This technology offers considerable economic advantages due to reduced waste and rapid on-site implementation (using small drills), but predicting the material's strength is often difficult [3]. However, a high safety factor is used as a precaution, which increases the implementation cost [4]. Researches have shown [5] that the strength of the soil concrete is significantly influenced by the type of hydraulic binder used, the implementation during experimentation, the soil characteristics, and the curing conditions. Predictive models of the uniaxial compressive strength of jet grouting materials, based on data mining techniques, have been proposed [6]. In [7] demonstrated that the nature of the binder influences certain durability properties of soil concrete: carbonation (mass loss (ζ), carbonation depth (X_c), and water-accessible porosity (γ)) and the wetting/drying cycles (mass loss (ζ) and compressive strength (R_c)) of soil concrete.

Therefore, the relevance of this research is to improve the understanding of the behavior of soil-mixed materials. To this end, our approach consists of studying the influence of the aging phenomenon on a soil-mixed prism by varying the cement content, the concentration of fine particles, and the water/cement ratio, in order to observe their impact on the uniaxial compressive strength of these prisms. Previously, experimental researches on soil mixing were limited to artificial soils. The field of application of this material now extends to underground structures, even above-ground structures used as retaining walls, which require increased resistance.

Thus, *the object of this research* is the behavior of soil mixing column.

The aim of this research is to enhance the understanding of the behavior of soil mixing under the effect of aging.

To achieve this aim, the following tasks must be completed:

1) to determine the effect of the number of wetting-drying cycles on the relative compressive strength, and the development of a predictive model for the evolution of unconfined compressive strength as a function of different parameters;

2) to determine the effect of cement dosage on the relative compressive strength;

3) to determine the effect of fine particle dosage on the relative compressive strength.

2. Materials and Methods

2.1. Materials

2.1.1. Soil material (clay)

The soil sampling site is located in the commune of Amizour in Algeria. The subsoil layers are characterized by alternating layers of silty clay, marly clay, and gravelly clay. The physical and mechanical characteristics of the soil are summarized in Table 1 [8].

Table 1

Physical characteristics of clay

Characteristics		Value
Dry density, t/m^3		2.01
Water content, %		14.65
Degree of saturation, %		99
Wet density, t/m^3		2.27
Particle size	5 mm	85
	2 mm	75
	0.08 mm	68
Sedimentometry	20 µm	42
	2 µm	30
Atterberg limits	*Wl* (%)	36.81
	Ip	19.36

2.1.2. Cement

The research laboratory is located in the wilaya of Bejaia next to the wilaya of Setif, which highlights the use of cement from the factory: Groupe Industriel des Cimentsd' Algérie, Société des Ciments de Ain KEBIRA of type CEM II/A-L 42.5 N, Portland limestone cement (CPC), Table 2 [8].

Table 2

Characteristics of cement

Chemical analyses (%)	Value
Loss in the fire	6–8
Sulfate (SO_3) content	2.5–2.9
Magnesium Oxide (MgO) content	<3.5
Chloride (Cl^-) content	<0.08
Insoluble residue	NA
Potential clinker composition (%) (according to Bogue)	Value
C3S	60–65
C3A	6–10
Physical properties	Value
Normal consistency (%)	25.4–26
Hot expansion (mm)	<1 mm
Setting time (min)	Value
Start of capture	150 min
End of take	260 min
Compression resistance	Value
2 days (MPa)	23–26
28 days (MPa)	45–50

2.2. Methods (experimental procedures)

This work is largely based on experimentation. The scientific methods used in this research consist of subjecting soil mixing prisms to various accelerated aging tests (wetting-drying).

The objective of accelerated aging tests is to better understand the material's durability potential. In our research, wetting-drying tests were conducted. They were initiated after 180 days of endogenous curing, to compensate for the particularly slow hydration reactions of blast furnace slag and avoid their interaction with the influence of accelerated aging tests on material damage. The wetting-drying cycle is carried out according to the following protocol: 24 hours in an oven at 53°C (BINDERFED400) (LTPEstBejaia branch, Algeria) and 48 hours of immersion in water at 20°C. For the following cycles: 3, 6, 12 and 24 stated in [7].

Materials Procurement: initially, it was possible to procure samples to be able to make the various prisms. The Eastern Public Works Laboratory (LTPEst) in Bejaïa provided all the necessary resources for the smooth progress of our research, both in terms of equipment and personnel. To obtain the materials, they were processed as follows.

Soil clay material:

– *selection of the intervention site:* the site chosen for the collection of samples is located in the commune and district of Amizour, wilaya of Bejaïa, where the construction of 150 LPA is planned;
– *sampling:* samples were collected after excavation to a depth of more than 4.00 m (because the site in question was previously used for agriculture). The samples were preserved in polythene bags;
– *cleaning:* the cleanliness of the samples is of paramount importance; therefore a thorough cleaning of the samples was carried out;
– *oven-drying:* once the samples are brought to the laboratory, they will be placed in an oven BINDERFED400 (LTP Est Bejaia branch, Algeria) at a constant temperature of 150°C for 24 hours;
– *grinding:* after 24 hours in the oven, the samples will be ground to obtain the maximum number of fine particles;
– *sieving:* once the samples are ground, they are sieved; passing the material through sieves of different diameters and only the amount that passes through the 0.2 mm sieve is taken;
– *storage:* the quantity obtained by sieving will be stored in polythene bags in a place with constant temperature and humidity (Fig. 1).

a *b*

Fig. 1. Sample: *a* – before grinding; *b* – after grinding

Cement: cement from Ain Kbira was available at the building materials parks, so it was possible to purchase the necessary quantity.

Preparation of the mixtures (test specimen): in this research, eight types of formulations were developed based on the percentage of soil and cement:

– formulation 1: 25% fine particles, 75% soil, and 200 kg/m^3 cement;
– formulation 2: 25% fine particles, 75% soil, and 250 kg/m^3 cement;
– formulation 3: 25% fine particles, 75% soil, and 300 kg/m^3 cement;
– formulation 4: 10% fine particles, 90% soil, and 200 kg/m^3 cement;
– formulation 5: 10% fine particles, 90% soil, and 250 kg/m^3 cement;
– formulation 6: 10% fine particles, 90% soil, and 300 kg/m^3 cement;
– formulation 7: 5% fine particles, 95% soil, and 200 kg/m^3 cement;
– formulation 8: 5% fine particles, 95% soil, and 300 kg/m^3 cement.

Since because of absence of sufficient quantity of fine particles, it is possible to use just two different dosages for formulations 7 and 8.

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Determination of clay, cement, and water quantity to be used for each formulation: the work consists of conducting several experiments with different water, cement, sand, and clay contents, in order to achieve a spread between 30 and 32 cm. The following dosage is found for each element is in Table 3:

– *mixing:* to be able to draw representative conclusions, the prisms must be homogeneous; to achieve this homogeneity, the clay and cement are mixed manually in a dry state (approximately 5 minutes), then mechanically mixed with water using a mixer for at least 10 minutes;

– *preparation of specimens:* in our case, 4 × 4 × 16 cm^3 prisms were used. The mold-filling procedure strongly influences the physical and mechanical properties of the soil mixtures. For all mixtures, filling is carried out no later than 45 minutes after the addition of cement. This limits the influence of the settling time before placement on the material characteristics. To optimize sample quality, mold filling must also take into account the workability of th e mixture. During this important step in specimen preparation, the objective is to extract as much air trapped as possible, regardless of the method used. The molds are filled in a single layer. The soil mixtures are compacted by percussion (15 blows) for formulations containing clay (Fig. 2);

– *conservation of specimens*: the conservation of specimens is in a climatic room at a temperature of 20°C, in a basin filled with water for 180 days (Fig. 3).

Table 3

Formulas for dry ground: constituents for 1 m^3 for mixture

Element	Cement, kg/m^3	Particle size <0.08 mm, kg/m^3	Particle >0.08 mm and <0.2 mm, kg/m^3	Water, kg/m^3
25% fine particles, 75% soil	200	242	742	556
	250	232	708	557
	300	221	673	556
10% fine particles, 90% soil	200	126	1145	453
	250	118	1094	456
	300	114	1058	454
5% fine particles, 95% soil	200	66	1293	415
	300	64	1212	416

Fig. 2. Making specimens

Fig. 3. Specimens preservation

Accelerated aging tests: the objective of accelerated aging tests is to better understand material's durability potential. Accelerated aging tests include humidification-drying cycles or chemical attacks. In our research, humidification-drying tests were performed. Accelerated aging tests are initiated after 180 days of endogenous curing to compensate for the particularly slow hydration reactions of blast furnace slag and avoid their interaction with the influence of accelerated aging tests on material damage.

Accelerated humidification-drying aging cycle: after 180 days of storage, the humidification-drying cycle was initiated according to the following protocol: 24 hours in an oven at 53°C (BINDERFED400) (LTP Est Bejaia branch, Algeria) and 48 hours of immersion in water at 20°C for the following cycles: 3, 6, 12, and 24 stated in [7, 9].

Specimen crushing tests: at the end of each cycle, the specimens were crushed using simple compression tests using a hydraulic press STRASSEN TEST, D20711, 810509 (LTP Est Bejaia branch, Algeria), Fig. 4 [8].

a *b*

Fig. 4. Specimens crushing tests:
a – crushing press; *b* – specimens after crushing

The simple compression crush test consists of applying an increasing axial load centered on a specimen (concrete, material) until it breaks, in order to measure its maximum resistance.

3. Results and Discussion

3.1. Wetting-drying cycles number effect on relative compressive strength

The evolution of relative compressive strength (f_c) as a function of fine particles percentage is shown in Fig. 5–7.

Fig. 8 illustrates the relationship between observed values and predicted values for formulation 3 based on an established model.

The red line represents the regression line; while the colored band indicated the model's confidence interval in Table 4 it is possible to see the coefficients error and tolerance estimation for formulation 3.

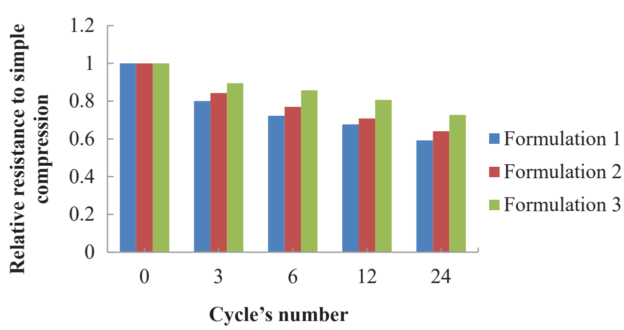

Fig. 5. Evolution of the relative resistance to simple compression as a function of cycle's number for formulation 1, 2 and 3

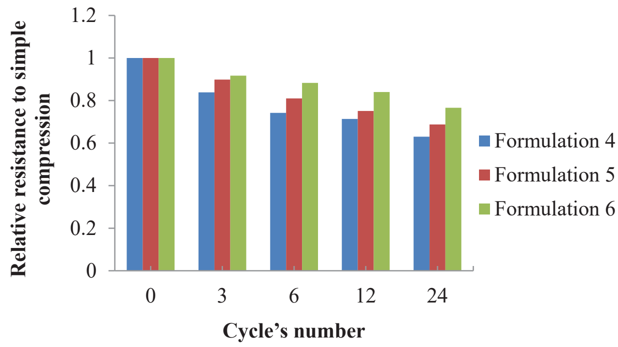

Fig. 6. Evolution of relative resistance to simple compression as a function of cycle's number for formulation 4, 5 and 6

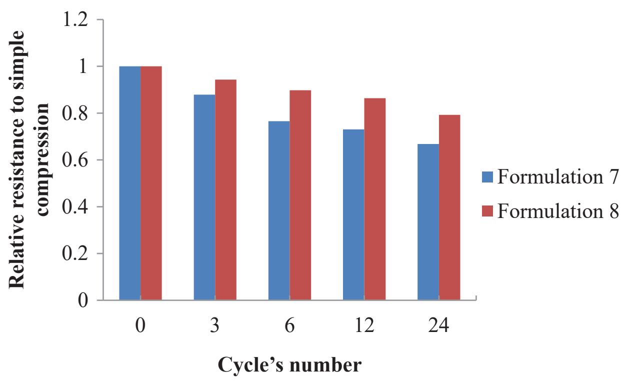

Fig. 7. Evolution of relative resistance to simple compression as a function of cycle's number for formulation 7 and 8

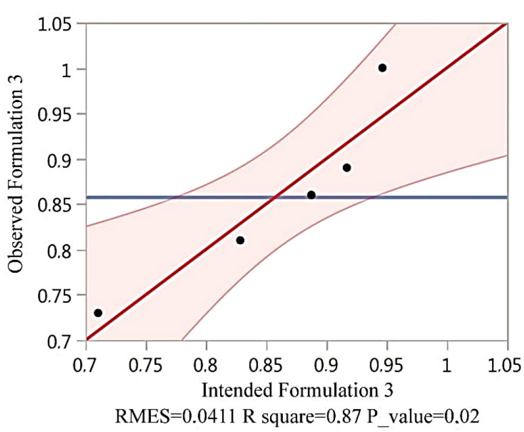

Fig. 8. Correlation between the observed and predicted values for formulation 3

Table 4

Coefficients error and tolerance estimation for formulation 3

Estimation of coefficients				
Term	Estimation	Error standard	*t* ration	Probability > [*t*]
Constant	0.9465	0.0268	35.32	<0.0001
Cycle number	–0.009833	0.002167	–4.54	0.0200

The forecasting formula of formulation 3 is as follows

$$y = 0.9465 - 0.00983333 \cdot CN, \quad (1)$$

where CN – cycle number.

Fig. 8, 9 illustrates the relationship between observed values and predicted values for formulation 3 and 6, based on an established model. The red line represents the regression line, while the colored band indicated the model's confidence interval [10].

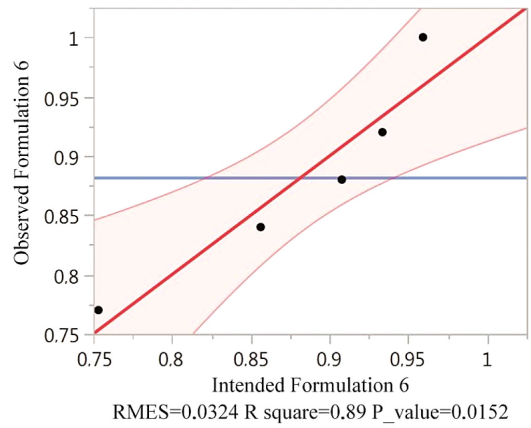

Fig. 9. Correlation between the observed and predicted values for formulation 6

Fig. 9 illustrates the relationship between observed values and predicted values for formulation 6 based on an established model. The red line represents the regression line, while the colored band indicated the model's confidence interval. In Table 5 it is possible to see the coefficients error and tolerance estimation for formulation 6 [10].

Table 5

Coefficients error and tolerance estimation for formulation 6

Estimation of coefficients				
Term	Estimation	Error standard	*t* ration	Probability > [*t*]
Constant	0.95925	0.02115	45.36	<0.0001
Cycle number	–0.008583	0.00171	–5.02	0.0152

The forecasting formula of formulation 6 is as follows

$$Y = 0.95925 - 0.00858333 \cdot CN, \quad (2)$$

where CN – cycle number.

Fig. 10 illustrates the relationship between observed values and predicted values for formulation 8 based on an established model. The red line represents the regression line, while the colored band indicated the model's confidence interval.

In Table 6 it is possible to see the coefficients error and tolerance estimation for formulation 8.

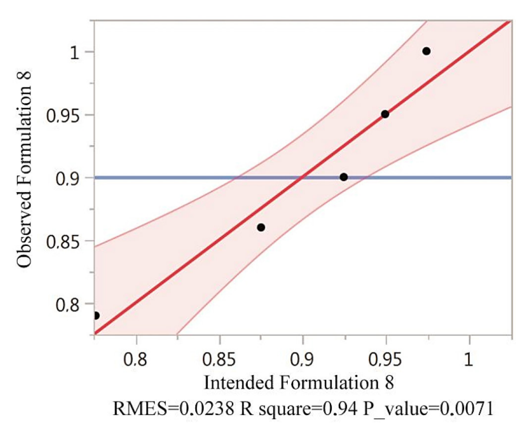

Fig. 10. Correlation between the observed and predicted values for formulation 8

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Table 6

Coefficients error and tolerance estimation for formulation 8

Estimation of coefficients				
Term	Estimation	Error standard	*t* ration	Probability > [*t*]
Constant	0.97425	0.015507	62.82	<0.0001
Cycle number	–0.00825	0.00254	–6.58	0.0152

The forecasting formula of formulation 8 is as follows

$$y = 0.97425 - 0.00825 \cdot CN, \quad (3)$$

where *CN* – cycle number.

The 3D representation of the relationship between the prediction formula concerning formulation 3, 6 and 8 is shown in Fig. 11–13. A generally stable trend is observed with slight parameter variation as the number cycles increases.

This indicates the model maintain relatively consistent performance, demonstrating a good robustness of the prediction model.

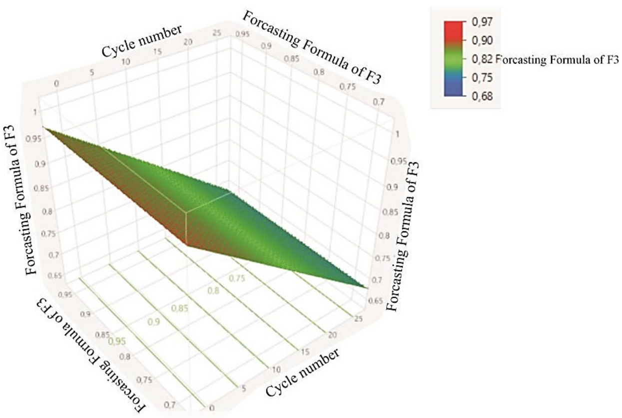

Fig. 11. Evolution of forecast model of formulation 3 according to the number of cycles

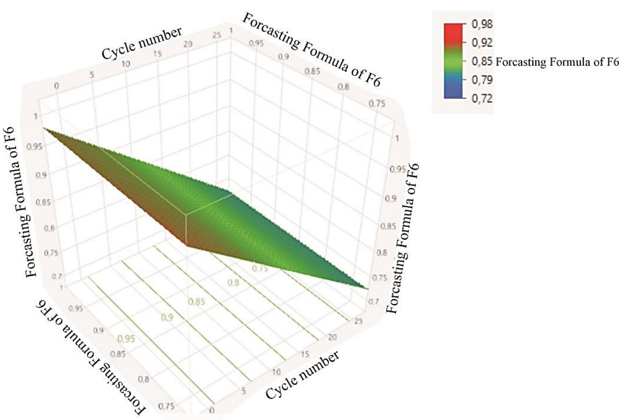

Fig. 12. Evolution of forecast model of formulation 6 according to the number of cycles

Fig. 14 shows the predicted response variation according to cycle's number for eight formulations. Each graph represents a trend curve (black line) accompanied by its uncertainty area (blue band representing the confidence interval). The numerical values on the left of each subplot represent the predicted mean (in red) as well as its 95% confidence interval (in blue).

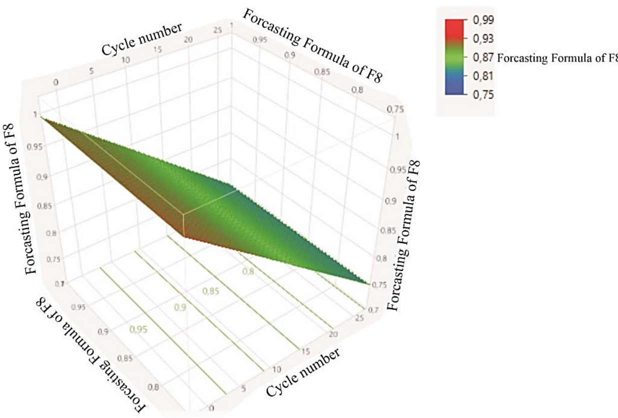

Fig. 13. Evolution of forecast model of formulation 8 according to the number of cycles

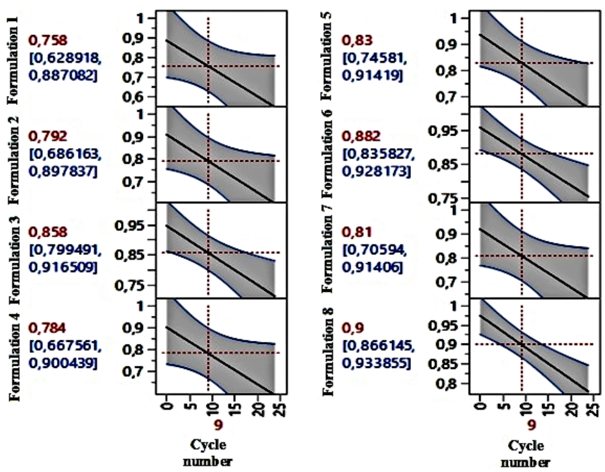

Fig. 14. Forecast profiler

After 180 days of cure, the endogenous state's original values are used to standardize the results. The relative compressive strength of the different formulations decreases as a function of the number of cycles. The three formulations 1, 2, and 3 show a near equal decline over 0 and 6 wetting-drying cycles. It is obvious that the curve's shapes vary depending on the formulation starting in the sixth cycler: for formulation 1, the relative compressive strength continues to decrease significantly as a function of the number of cycles, i. e., by 41%. However, for the other formulations, a slight decrease in the relative compressive strength is observed between the sixth and twenty-fourth cycles. The relative compressive strength of the soil mix decreases by 21 to 41% between the third and twenty-fourth cycles, regardless of the cement dosage.

3.2. Effect of cement dosage on relative compressive strength

Monitoring of a relative compressive strength (f_c) evolution as a function of cement dosage is presented in the following figures, for all formulations Fig. 15–17.

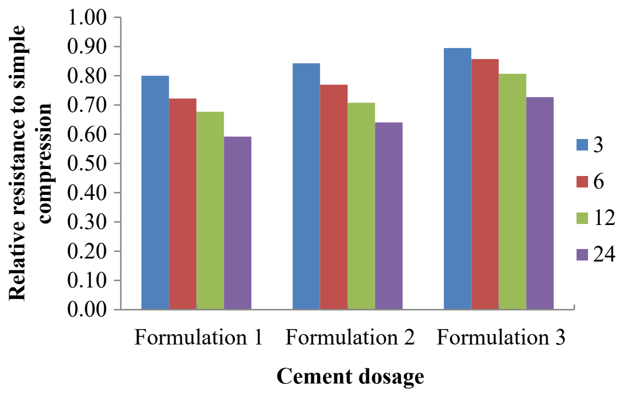

Fig. 15. Evolution of the relative resistance to simple compression as a function of the cement dosage for a fine particles rate of 25%

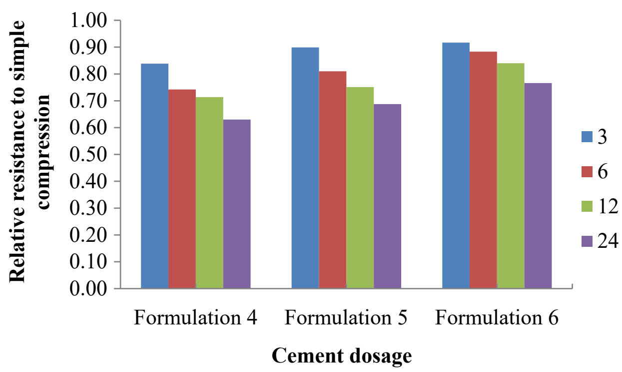

Fig. 16. Evolution of the relative resistance to simple compression as a function of the cement dosage for a fine particles rate of 10%

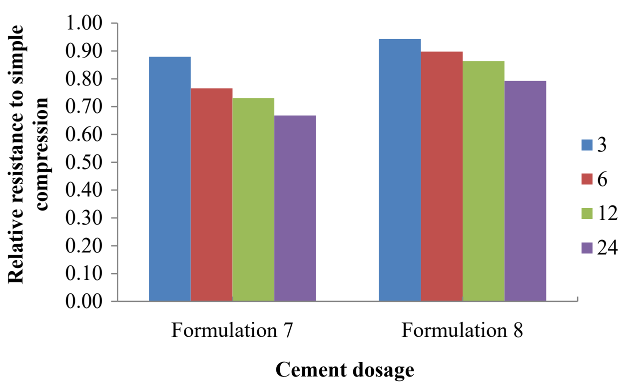

Fig. 17. Evolution of the relative resistance to simple compression as a function of the cement dosage for a fine particles rate of 5%

The obtained results show that the relative compressive strength increases as a function of cement dosage for all formulations, with an increase ranging from 18 to 25% for the different formulations, regardless of the number of wetting-drying cycles.

3.3. Effect of fine particle dosage on relative compressive strength

The evolution of relative compressive strength (f_c) as a function of fine particle dosage is shown in Fig. 18–20.

The obtained results show the increasing effect of relative resistance for a minimum percentage of particles for the whole case of cement dosage, the increase in resistance is approximately 23%.

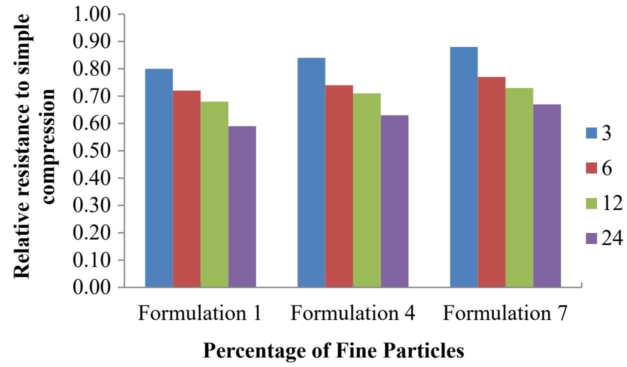

Fig. 18. Evolution of a relative resistance to simple compression as a function of fine particles percentage for 200 kg/m^{3}cement dosage

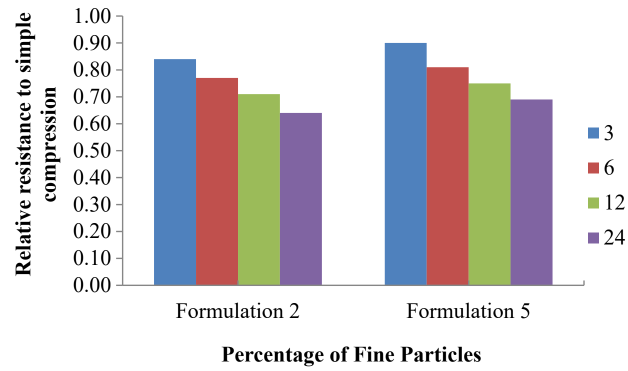

Fig. 19. Evolution of a relative resistance to simple compression as a function of fine particles percentage for 250 kg/m^3 cement dosage

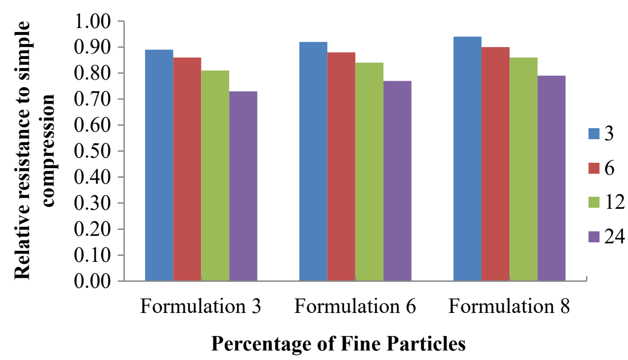

Fig. 20. Evolution of a relative resistance to simple compression as a function of fine particles percentage for 300 kg/m^3 cement dosage

3.4. Discussion

The determination coefficient R^2 = 0.87, 0.882 and 0.94 of Fig. 12, 13, 16, respectively shows a good predictive capability of the model, explaining 87%, 88.2% and 94% the variability in the observed data. The *RMSE* = 0.0411, 0.0324, and 0.0238 of Fig. 8–10, respectively, indicate a low average error between predicted and observed values, which confirm the model's accuracy. Furthermore, the *p*-value = 0.02, 0.0152 and 0.0071 of Fig. 10, 13, 14, respectively, which are all inferior to 0.05; demonstrates the statistical significance of the relationship between the variables. Thus, the model developed for formulation 3, 6 and 8 exhibit good predictive validity and a statistical correlation between experimental results and estimated values

The numerous results and conclusions obtained from this research highlight the significance of carrying out a compressive parametric research at the laboratory level, in order to facilitate the efficient and less expensive design of soil-mixing columns.

Throughout the lifespan soil-mixing columns our research shows how crucial the proportion of fine particles in the soil and the cement dosage are over the course of soil-mixing column's life.

This work was conducted in a single region of Amizour, in Bejaia province. The extension of the research area may lead to other results, depending on characteristics of the existing soils.

The various results obtained highlighted the influence of fine particles percentage and cement dosage on performance and durability of soil-mixing columns.

To better understand the influence of environmental phenomena (temperature, rising water, humidification-drying cycle, etc.) on the lifespan and performance of a soil-mixing column, it is necessary to consider:

– expanding the research area to cover as many soil types as possible;
– researching the effect of different grain size distributions (e. g., continuous, coarser, or finer);
– determining the influence of soil composition (type of aggregates) on the lifespan of soil-mixing columns.

The results obtained in this research pertain to a single research area; therefore the various conclusions are limited to this area. These results allow to predict the behavior of a soil mixing column under the effect of aging, which enables to conduct an optimal research and reduce the construction cost without compromising the safety of the structures.

Although this research demonstrated that the aging process influences the unconfined compressive strength of a soil mixing column, it has some limitations, including the limited research area and the fact that the parametric analysis was restricted to a single mechanical parameter (unconfined compressive strength). Future research could therefore delve deeper into this topic by exploring the influence of different particle size distributions (e. g., continuous or coarser) on the performance of soil mixing columns. The nature of the aggregates (silico-calcareous or calcareous), the clay (illite or even montmorillonite in varying proportions), and even the binder (e. g., CEMIII with less slag, or binders other than Portland cement) would also be worth investigating.

4. Conclusions

1. The research of the effect of the number of wetting-drying cycles on relative compressive strength shows that it decreases by approximately 41% between 3 and 24 cycles, regardless of the cement content. Among the tested formulations, formulation 8 has the highest average value (0.94), followed by formulations 6 (0.89) and 3 (0.87), indicating superior performance or stability. Conversely, formulations 1 and 4 show lower average values, suggesting reduced performance or increased sensitivity to cycles.

2. The research of the effect of cement dosage on relative compressive strength shows that it increases by approximately 18 to 25% with increasing cement dosage for all formulations.

3. The research of the effect of the percentage of fine particles on the relative compressive strength shows that it decreases by about 23% with an increase in the percentage of fine particles.

Conflict of interest

The authors declares that they have no conflict of interest in relation to this research, including financial, personal, authorship or other, which could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating the submitted paper.

Authors' contributions

Farouk Menari: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review and editing, Visualization; ***Sabah Moussaoui***: Validation, Writing – original draft, Writing – review and editing; ***Mourad Belgasmia***: Validation, Writing – original draft, Writing – review and editing; ***Khelifa Abbeche***: Writing – review and editing.

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✉***Farouk Menari,*** *PhD Student, Department of Civil Engineering, University of Batna 1, Batna, Algeria, e-mail: menarifarouk@yahoo.fr, ORCID: https://orcid.org/0009-0000-4758-307X*

Sabah Moussaoui, *Associate Professor, Civil Engineering Research Laboratory-Sétif, Department of Civil Engineering, Setif 1 University – Ferhat Abbas, Sétif, Algeria, ORCID: https://orcid.org/0000-0002-8641-089X*

Mourad Belgasmia, *Professor, Civil Engineering Research Laboratory-Sétif, Department of Civil Engineering, Setif 1 University – Ferhat Abbas, Sétif, Algeria, ORCID: https://orcid.org/0000-0003-1409-0281*

Khelifa Abbeche, *Professor, Department of Civil Engineering, University of Batna 1, Batna, Algeria, ORCID: https://orcid.org/0009-0006-2476-6408*

✉*Corresponding author*