CO^2 and cost optimization of reinforced concrete footings over a lime-treated soil using modified simulated annealing algorithm

Optimización de CO^2 y costo de zapatas de concreto reforzado sobre un suelo tratado con cal usando algoritmo de recocido simulado modificado

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Abstract

Introduction– The design of spread footings over a lime-treated soil is studied as an important topic in geotechnical and environmental engineering. With the emergence and use of algorithms, it is possible to solve optimization problems in engineering, leading, for example, to decreased amounts of materials, time, energy, and work.

Objective– This research aims to optimize the CO^2 emission and cost of building spread footings over a treated soil with hydrated lime using the Modified Simulated Annealing Algorithm (MSAA).

Methodology– The parameters for shear strength (cohesion and friction angle) was calculated of a silty soil of the Guabirotuba geological formation of Curitiba (Brazil) stabilized with different lime contents (3, 5, 7 and 9%) at different curing times (30, 90, and 180 days). Then with these parameters, the geometry of the spread footings was optimized with MSAA minimizing the cost and CO^2 emissions of their construction. For the design constraint of the structures the ultimate bearing capacity of the soil was used as criteria, the settlements produced by the service load, and the base safety factor

Results– The results show that most of the problems converge to the same solution for costs and CO^2 emissions without depending on curing time and lime content used, due to the solutions being restricted primarily by the maximum permissible settlements.

Conclusions– With the increase in lime content, the cohesion of the mixtures increased for all curing times studied ant the friction angle had no major variations in relation to the amount of lime administered or to the curing time employed. Costs and carbon dioxide emissions for spread footing construction converge to the same results. In this sense, 9% lime can be avoided, and small percentages of lime (i.e. 3-5%) are appropriated to ground improvement and reduce the costs of this procedure. On the other hand, the MSAA can be designated as a robust algorithm due to having achieved almost equal results and, in some cases, better results compared with other algorithms to solve problems reported in the literature.

Keywords– Lime-soil; multi-objective optimization; modified simulated annealing algorithm; spread footing

Resumen

Introducción– El diseño de cimentaciones sobre suelo tratado con cal se estudia como un tema importante en ingeniería geotécnica y ambiental. Con la aparición y el uso de algoritmos, es posible resolver problemas de optimización en ingeniería, lo que lleva, por ejemplo, a la disminución de cantidades de materiales, tiempo, energía y trabajo.

Objetivo– Esta investigación tiene como objetivo optimizar la emisión de CO^2 y el costo de la construcción de zapatas sobre un suelo tratado con cal hidratada utilizando el Algoritmo Recocido Modificado (MSAA).

Metodología– Se calcularon los parámetros de resistencia al corte (cohesión y ángulo de fricción) de un suelo limoso de la formación geológica Guabirotuba de Curitiba (Brasil) estabilizada con diferentes contenidos de cal (3, 5, 7 y 9%) a diferentes tiempos de curado (30, 90, y 180 días). Luego, con estos parámetros, la geometría de las zapatas se optimizó con MSAA minimizando el costo y las emisiones de CO^2 de su construcción. La capacidad de carga final del suelo, los asentamientos producidos por la carga de servicio y el factor de seguridad de base fueron usados como restricciones de diseño.

Resultados– Los resultados muestran que la mayoría de los problemas convergen a la misma solución para los costos y las emisiones de CO^2 sin depender del tiempo de curado y del contenido de cal utilizado, debido a que las soluciones están restringidas principalmente por los asentamientos máximos permitidos.

Conclusiones– Con el aumento del contenido de cal, la cohesión de las mezclas aumentó para todos los tiempos de curado estudiados y el ángulo de fricción no tuvo variaciones importantes en relación con la cantidad de cal administrada o con el tiempo de curado empleado. Los costos y la emisión de dióxido de carbono para la construcción de zapatas convergentes coinciden con los mismos resultados. En este sentido, se puede evitar el 9% de cal, y pequeños porcentajes de cal (es decir, 3-5%) se destinan a la mejora del suelo y reducen los costos de este procedimiento. Por otro lado, MSAA puede ser considerado como un algoritmo robusto debido a que ha logrado resultados casi iguales y, en algunos casos, mejores resultados en comparación con otros algoritmos para resolver problemas reportados en la literatura.

Palabras clave– Suelo de cal; optimización multiobjetivo; algoritmo de recocido simulado modificado; cimentaciones

I. Introduction

The soil stabilization and ground improvement technique were introduced in geotechnical engineering with the main objective of improving the geotechnical properties of soils to meet the technical specifications required in projects, such as foundation, slopes, and roads, when the soil properties did not meet the technical specifications. For lime-treated soils in the foundation area, the aim is always to improve the parameters of shear strength (friction angle and apparent cohesion) with the objective of increasing the ultimate bearing capacity of the footings, and thus increase the safety factor, decrease the geometry of the footing, and decrease the amount of steel and concrete. When lime is added to clay soils in the presence of water, there are several reactions that lead to the improvement of soil properties. These reactions include cation exchange, flocculation, carbonation, and pozzolanic reaction. Cation exchange occurs between the cations associated with the surfaces of clay particles and the calcium cations of lime, and this exchange is called base exchange; thus, cation exchange between the soil and lime makes the soil more stable [1]. The effect of the exchange and attraction of cations causes the clay particles to aggregate, forming flakes; this process is called flocculation. Flocculation is the main responsible for the modification of the geotechnical properties of fine soils when they are treated with lime [2]. Recent studies show the benefits of adding lime in soils [3], [4] mainly increasing simple compressive strength and indirect traction. The benefits of adding lime also provide decreased plasticity index, compressibility, expansion, and contraction of the soil [5].

Isolated footings are structures used to transmit the loads and moments from the superstructure of a building to the foundation soil. Superficial footings may fail depending on the shear test of the soil that supports it. However, before the occurrence of shear failure in the soil, and even if it does not happen, it is also possible that a superficial foundation is subject to a settlement that is sufficiently large to cause damage on the structure and make it dysfunctional for the purpose for which it was designed [6].

Solving optimization problems of reinforced isolated footings has been an object of studies in the literature for many years. The first authors to propose an optimization for this type of cementation structure were Wang and Kulhawy [7], who used Microsoft Excel Solver to design economic foundations including the optimization of generation of CO^2. Then, Khajehzadeh et al. [8] used the Modified particle swarm algorithm to optimize the cost of retaining walls and isolated footing subjected to axial load and bending moment. The most relevant contribution concerning the optimization of superficial foundations based on the inclusion of design codes was that made by Camp and Assadollahi [9], who used the hybrid big bang-big crunch algorithm BB-BC to optimize both CO^2 emissions and the cost of building foundations subjected to axial loads based on the ACI 318-11 specifications. Finally, Camp and Assadollahi [10] used the BB-BC to optimize of reinforced concrete footings subjected to uniaxial uplift. Optimization algorithms also can be utilized to reach an economical design satisfying all the geotechnical and structural requirements simultaneously. For example, Ahmadi-Nedushan and Varaee [11] and Khajehzadeh et al. [8], [12] used particle swarm optimization; Khajehzadeh and Eslami [13] used a gravitational search algorithm; Yepes et al. [14] utilized simulated annealing; Kaveh and Abadi [15] employed harmony search; Kaveh and Behnam [16] utilized the charged system search algorithm; Sheikholeslami et al. [17] used the hybrid firefly algorithm; Camp and Akin [18] with base shear keys, using big bang\u2013big crunch (BB-BC applied Big Bang Big Crunch, Gandomi et al. [19] employed accelerated particle swarm optimization, firefly algorithm, and cuckoo search; and Gandomi et al. [20] applied differential evolution, evolutionary strategy and biogeography based optimization algorithm. Additionally, despite limited research on concrete retaining wall optimization, there are numerous studies on structural and geotechnical engineering optimization problems, including Sahab et al. [21], Pezeshk and Camp [22] and Das and Basudhar [23]. However, the optimization of footings supported on artificially cemented soils, such as lime, has not been studied in the literature to date.

The present study aims to calculate firstly, the shear direct parameters of a lime-treated silty soil obtained at 3 curing times: 30, 90 and 180 days. The shear direct parameters data was used to optimize with Modified Simulated Annealing Algorithm (MSAA) the cost and carbon dioxide emissions of steel-reinforced isolated footings over a stabilized soil. The MSAA was recently introduced for solving global optimization problems and is a newly improved version of the simulated annealing (SA) algorithm [24]–[27]. Thus, in the present study was evaluate for the first time the MSAA to solve optimization problems of footings due to its remarkable performance compared to techniques such as Harmony Search, Genetic Algorithms and Particle Swarm Optimization, among others. To that end, this research developed and programmed a procedure in the algorithm for design reinforced concrete footings subjected to vertical and concentric service loads that meet geotechnical limit states and requirements using a modified simulated annealing algorithm

II. Materials and Methodology

The experimental program was divided into three steps: the first was the tests for characterization of soil and lime: grain size distribution was determined according to ASTM D2487 [28], Atterberg limits according to ASTM 4318 [29] and real specific gravity of grains of soil and lime according to ASTM D854 [30]. The second step consisted of molding, curing, and test of specimens subjected to direct shear tests in saturated conditions, and the third step was the design and execution of the optimization tests using the MSAA algorithm based on the results for shear strength at different curing times.

In this research three materials in the first two experimental steps were used: soil, lime, and distilled water. The soil used in this research was collected in the municipality of Fazenda Rio Grande, metropolitan region of Curitiba (Brazil), manually avoiding possible contamination, and sufficient quantity to perform all the tests. The soil is composed, according to the ASTM D2487 [28], of 7.5% of medium sand, 25.9% of fine sand, 57.6% of silt, and 9.3% of clay, as shown in Fig. 1. Table 1 shows the physical properties of the soil, with a plasticity index of 21.3% and a specific gravity of 2.71. According to the Unified Soil Classification System (USCS), the soil is classified as plastic sandy silt (MH). This soil was used previously by Baldovino et al. [4], [31] for soil-lime mixes. The lime used for the study was a dolomitic hydrated lime (CH-III). The CH-III type is one of the most used types of hydrated lime in Brazil. The lime is mainly composed of calcium hydroxide -$Ca(OH)_2$- and magnesium -$Mg(OH)_2$-, produced in the municipality of Almirante Tamandaré (Paraná, Brazil). The retained percentage accumulated in the #200 sieve was 9%, which is in accordance with the Brazilian standard NBR 7175 [32] which specifies that ≤15% of this type of material has to be retained on the #200 sieve. The specific gravity of the lime is 2.39 g/cm^3. To perform all the characterization tests for the soil, for the soil-lime mixtures, and for the molding of specimens distilled water at 25 ± 3°C was used to avoid unwanted reactions and limit the number of variables in the study.

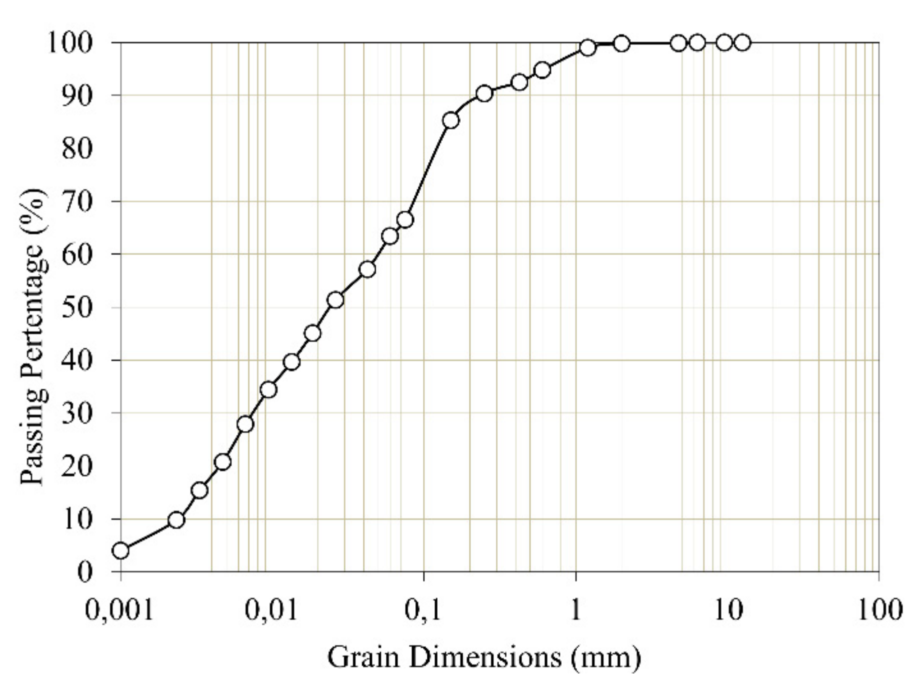

Fig 1. Grain size distribution of soil.
Source: Authors.

Table 1. Physical properties of the soil sample.

Property	Value
Liquid limit	53.1%
Plastic index	21.3%
Specific gravity	2.71
Coarse sand (2.0 mm < φ < 4.75 mm)	0%
Medium sand (0.42 mm < φ < 2.0 mm)	7.5%
Fine sand (0.075 mm < φ < 0.42 mm)	25.9%
Silt (0.002 mm < φ < 0.075 mm)	57.6%
Clay (φ < 0.002 mm)	9.3%
Mean particle diameter (D50)	0.025 mm

Source: Authors.

A. *Definition of molding points, lime contents and curing times*

To define the molding points of this research compaction tests were conducted under standard proctor effort for the soil and for the soil-lime mixtures according to the American standard NBR 7182 [33]. Thus, for the silty soil studied in the standard effort, a maximum dry unit weight value of 13.8 kN/m³ and optimal humidity of 31.0% were obtained as shown in Fig. 2. The lime contents used were defined according to the Brazilian experience [3], [4] from 3 to 9% in relation to the dry mass of the soil. Thus, amounts of lime 3, 5, 7, and 9% were chosen as the molding and study contents. Standard effort of compaction was also conducted for each lime content added (L), which is shown in Fig. 2. With the increase in lime content, the apparent maximum dry specific weight decreases while the optimal humidity increased. This behavior is due to the addition of fine materials (lime) and with a lower density (2.39 g/cm³) with reference to the soil (2.72 g/cm³) that filled the voids between the largest particles of silty soil and led to increase the weight of the solids in the volume per unit. Table 2 shows variation for maximum dry specific weight and optimal humidity for the 3%, 5%, 7%, and 9% lime contents. It is observed that the variation is very small due to the low lime contents used. The soil-lime specimens were molded according to the conditions in Table 2, for the curing times of 30, 90, and 180 days.

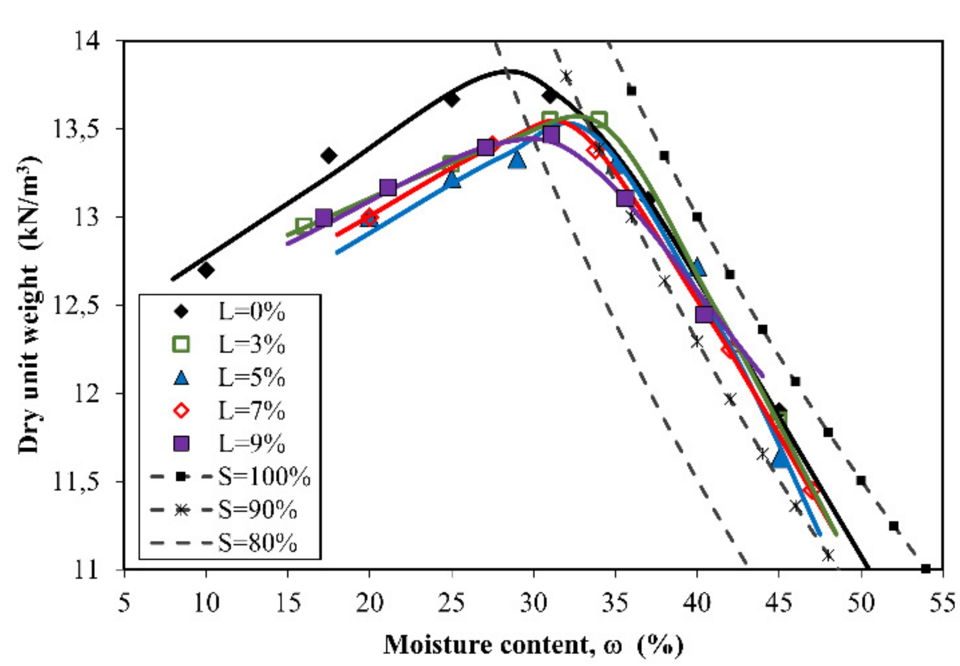

Fig. 2. Compaction curves of soil-lime mixtures.
Source: Authors.

Table 2. Values of dry unit weight and optimum moisture for the soil-lime mixtures in the compaction with normal energy.

Lime content, L (%)	Dry unit weight (kN/m3)	Optimum moisture (%)
3	13.55	32.5
5	13.51	32.0
7	13.49	31.5
9	13.47	30.0

Source: Authors.

B. *Direct Shear tests*

The direct shear tests were performed following the standard D 3080 [34]. During the tests, normal stresses of 50, 100, 200, and 400 kPa were used. For the direct shear tests, specimens that were 100 mm wide, 100 mm long, and 20 mm thick were molded. The soil was totally dried in a heating chamber, at temperature of 100±5°C, and then divided into evenly distributed portions to be mixed with the different lime contents. The amount of dry lime in relation to the dry weight of the soil sample was added. The soil was mixed with the lime, so the mixture was as homogeneous as possible. Then a percentage of water by weight was added, and this percentage referred to the optimal water content of the molding points. The samples were compressed on the steel mold ensuring the apparent maximum specific weight obtained during the compression tests. The mold volume and the wet mixture weight necessary for each specimen were calculated. Each specimen was compressed into a single layer, statically, ensuring, after molding, the following maximum errors in measurements: (i) Dimensions of width and length of the specimen: ±1 mm; (ii) Dimension of thickness: ±0.5 mm; (iii) Apparent dry specific mass (): ±1%; and (iv) Moisture content (ω): ±0.5%.

The specimens were weighed on a 0.01 g precision scale and their dimensions were measured with a caliper of 0.1 mm error. Then, the specimens were extracted from the steel mold and wrapped in plastic wrap and taken to the wet chamber, at an average temperature of 25°C, to keep the moisture content during the curing time of 29, 89, and 179 days. Before the tests of the specimens, they were left in distilled water for 24 hours, having a total curing time of 30, 90, and 180 days, so at the time of test they were the most saturated possible. For the direct shear strength tests, an ELE International press (Direct Shear Apparatus 220-240V 50/60Hz 1Ph) was used with a maximum capacity of 5 kN, and calibrated rings for axial load with capacities of 4.5 kN. The tests were performed with an automated data collection system, measuring, mainly, the applied force in Newtons, the deformation (with a sensitivity of 0.001 mm), and the test speed (1 mm/s). Right after the tests in the press, the saturation of the specimens was measured as a control parameter, accepting as a minimum a 98% saturation (for undrained condition).

C. *Geotechnical limit states*

For the design of isolated footings as to the geotechnical aspect, two requirements must be met: achieving the base safety factor and not exceeding the permissible settlement value. Fig. 3 shows the general dimensions of an isolated footing: with width L, length B, footing thickness H, height from footing base to ground level D, excavation width L_o + L, excavation length Bo, and column width bcol (assumed as square).

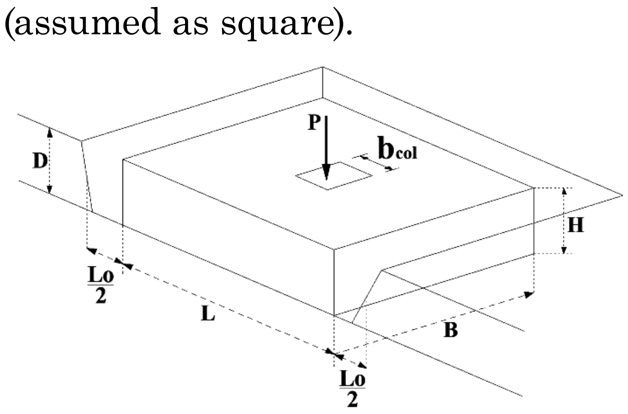

Fig. 3. Spread footing dimensions.
Source: Authors.

The load P is the service load that is transmitted down the column and acts concentrically on the footing area, which produces a uniformly distributed stress *q* over the soil:

$$q=\frac{P+W_f}{BL} \tag{1}$$

Where W_f is the weight of any overload on the footing (including the weight of the footing itself). Thus, the first geotechnical requirement is the limit load capacity of the footing, which is given by the base safety factor and is calculated with the following expression:

$$FS_B=\frac{q_{ult}}{q} \tag{2}$$

Where q_{ult} is the ultimate bearing capacity of the footing, which depends on the geotechnical conditions of the foundation soil and is given by the following Meyerhof's expression [35] for cohesive soils:

$$q_{ult}=cN_cF_{cs}F_{cd}+\gamma DN_qF_{qs}F_{qd}+0.5\gamma BN_\gamma F_{\gamma s}F_{\gamma d} \tag{3}$$

Where γ is the foundation soil specific weight; c is the foundation soil cohesion; N_c, N_q and N_γ are dimensionless bearing capacity factors (being only functions of the foundation soil friction angle – ϕ); F_{cs}, F_{qs} and $F_{\gamma s}$ are shape factors; F_{cd}, F_{qd} and $F_{\gamma d}$ are depth factors, and can be calculated with equations (4)-(16):

$$N_q=e^{\pi\tan\phi}\tan^2\left(\frac{\pi}{4}+\frac{\phi}{2}\right) \tag{4}$$

$$N_\gamma=2\left(N_q+1\right)\tan\phi \tag{5}$$

$$F_{qs}=1+\frac{B}{L}\tan\phi \tag{6}$$

$$F_{\gamma S}=1-0.4\frac{B}{L} \tag{7}$$

$$F_{qd}=1+2\tan\phi(1-\sin\phi)^2U \tag{8}$$

$$F_{qd}=1+2\tan\phi(1-\sin\phi)^2\left[\arctan\left(\frac{D}{B}\right)\right] \tag{9}$$

$$F_{qd}=1+2\tan\phi(1-\sin\phi)^2\left(\frac{D}{B}\right) \tag{10}$$

$$F_{\gamma d}=1 \tag{11}$$

$$F_{cs}=1-\frac{BN_q}{LN_c} \tag{12}$$

Where ϕ is the internal friction angle of the soil. Additionally, Hansen [36] found the following expressions to calculate the F_{cd} shown in Table 3.

Table 3. Fcd Values.

For D/B ≤ 1	and $\phi = 0$	$F_{cd} = 1 + 0.4\left(\frac{D}{B}\right)$	(13)
	and $\phi > 0$	$F_{cd}=F_{qd}-\frac{1-F_{qd}}{N_c \tan\phi}$	(14)
For D/B > 1	and $\phi = 0$	$F_{cd} = 1 + 0.4\arctan\left(\frac{D}{B}\right)$	(15)
	and $\phi > 0$	$F_{cd}=F_{qd}-\frac{1-F_{qd}}{N_c \tan\phi}$	(16)

Source: Authors.

The second geotechnical requirement is that the settlements of the foundation must not exceed the maximum allowable values; thus, the value of the real settlements (δ) were calculated by applying the elastic solution proposed by Poulos and Davis [37] and used in the footing optimization study conducted by Camp and Assadollahi [9] and a second study by Wang and Kulhawy [7]:

$$\delta=\frac{(P+W_f)(1-v^2)}{\beta_z E\sqrt{BL}} \quad (17)$$

Where v is the Poisson's coefficient and E is the module of elasticity of the soil, the form factor β_z is calculated by the following expression of Whitman and Richart [38]:

$$\beta_z= -0.0017\left(\frac{L}{B}\right)^2+0.0597\left(\frac{L}{B}\right)+ 0.9843 \quad (18)$$

D. *Modified simulated annealing algorithm (MSAA)*

Prior to summarizing the characteristics of the Modified Simulated Annealing Algorithm (MSAA), the functioning of the basic Simulated Annealing (SA) is described briefly. SA [39] has been developed from the statistical thermodynamics to simulate the behavior of atomic arrangements in liquid or solid materials during the annealing process. The material reaches the lowest energy level (globally stable condition) as temperature decreases. SA starts with a given state S. Through a single process it creates a neighboring state S' to the initial state. If the evaluation of the S' is smaller than the S, the state S is exchanged by S'. If the evaluation of S' is greater than S, then state is accepted or rejected based on a probabilistic criterion which estimates if design may improve in the next function evaluations. In order to compute probability, a parameter called "temperature" is utilized. Temperature can be a target value (estimated) for the cost function corresponding to a global minimizer. Initially, a larger target value is selected. As the progress of the trial, the target value is reduced based on a cooling schedule [40].

SA starts with an initial solution chosen randomly in the search space and compares it with another solution that is also stochastically selected in the search space, which affects the algorithm when there are highly dimensional and modal functions, generating longer searches and suboptimal solutions. In addition, the probability of accepting an inadequate solution is in a range between 0 and 1, which at initial temperatures may lead the algorithm to accept a large number of lower quality solutions (increasing the risk of getting stuck in a local optimal).

The MSAA [25] is a newly improved version of the Simulated Annealing (SA) algorithm with three modifications. Firstly, a preliminary exploration is realized to choose the starting point of search. Secondly, the transition from the start point to the new point is done by search step. Thirdly, the range of probability of accepting a worse solution is reduced. The modifications allow the algorithm to maintain a balance between intensification and diversification during a search. Intensification (exploitation) aims to identify the best solution and select during the process a succession of best solutions. Diversification (exploration) ensures, usually by randomization, that the algorithm explores the search space efficiently.

1) *Preliminary Exploration*

In this phase the algorithm performs a scan in the search space and is given by the following matrix:

$$X_{PxN}=I_{PxN}X_{L}+rand_{PxN}\ \ X_{U}-X_{L} \tag{19}$$

Where P is the number of points (states) that are desired in the search space; is the number of dimensions of the problem; I_{PxN} is the identity matrix of size PxN; X_L is the lower limit of the problem; X_U is the upper limit of the problem and $rand_{PxN}$ is the matrix of random numbers (pure randomness) between 0 and 1 of size PxN.

To start the optimization process with MSAA, all points generated with (19) are evaluated in the objective function of the problem and the smallest value (in the case of searching the minimum value of the function) is chosen as the starting point of the search.

2) *Search Step*

From the starting point determined in the preliminary exploration step, a search step is generated in order to determine the neighboring state. This step depends on a Radius (R) of action that gradually decreases as the temperature of the system decreases. The transition from starting point to the new point (search step) is performed by the addition of random numbers that are between [-R, R]. This enables the algorithm to execute a global exploration at high temperatures and a local exploration at low temperatures, providing a balance between the exploration and exploitation of the algorithm. The radius is updated as follows:

$$R_{i+1}=R_{i}\cdot\alpha \tag{20}$$

Where R_i is the initial radius, and α is the radius reduction coefficient.

3) *Probability of acceptance*

In the MSAA, the probability of acceptance of a worse solution is given by:

$$P=\frac{1}{1+e^{\left(\Delta f/_{T}\right)}} \tag{21}$$

Where P is the probability of accepting the new state; is the difference of the evaluations of the function for each state; Δf is the temperature of the system, and is the Euler number. This probability is in a range between 0 and 0.5, allowing the algorithm to have a lower range of acceptance of worse solutions. The Pseudocode of MSAA is as follow:

Setting initial temperature ($T_{initial}$)
Setting final temperature (T_{final})
Setting maximum number of perturbations at the same temperature (np_{max})
Generate Initial Solution (S) chosen by the preliminary exploration eq. (19) $T = T_{final}$
While ($T > T_{final}$) do //Temperature Cycle
For np = 1 to np_{max} //Metropolis Cycle
Generate S' by search step eq. (20)
Obtain difference (Δf) between S' and S
If ((Δf) ≤ 0) then
Accept S'
else
$P = \frac{1}{1 + e^{\left(\Delta f / T\right)}}$ eq. (21)
If (random(0, 1) < P) then
Accept S'
end If
end If
end For
Decrease T by cooling function $T_{k+1} = T_k \cdot \alpha$
end while
Shown best solution (S_{best})

4) *MSAA Spread footing design parameters*

Numerical results indicate that a population of 100 (preliminary exploration); initial temperature $T_{initial}$ = 10; final temperature $T_{final} = 1 \times 10^{-3}$; maximum number of perturbations np_{max} = 2000; cooling function $T_{k+1} = T_k \cdot \alpha$; attenuation coefficient α = 0.8; and search step R = 2 are adequate to provide good results.

To estimate the general performance of the MSAA, each benchmark design problem was run independently 100 times. While the number of runs is arbitrary, it should be adequate to provide reliable statistics on the general quality of the solutions and the convergence of the MSAA. It is also important to note that all presented MSAA designs are feasible. The algorithm was coded in MATLAB.

E. *CO_2 and cost optimization*

An example of isolated footings was originally developed by Wang and Kulhawy [7] and then used by Camp and Assadollahi [9]. Wang and Kulhawy [7] used Microsoft Excel Solver as optimization tool with the use of continuous variables to find the smallest monetary value for the construction of footings, then authors Camp and Assadollahi [9] optimized the same example with the aid of Big Bang-Big Crunch (BB-BC) using discrete and continuous variables, in addition they added the ACI 318-11 requirements for the structural calculation of the footing of the same example finding the smallest footing geometry that achieves the smallest possible construction costs and the lower CO_2 emissions. The present study took as reference the example used by the two researches to minimize cost and CO_2 emissions in isolated footings supported over soil treated with different lime contents at different curing times with the aid of the MSAA, taking into account the importance of having this type of study for cities such as Curitiba-Brazil, since the soils of the region most times cannot be employed as support for foundations.

The design of cost optimization for the construction of footings for lime-treated soil is defined as:

$$f_{cost} = C_e V_e + C_f A_f + \xi C_r M_r + \frac{f_c}{f_{c\,min}} C_c V_c + C_b V_b \qquad (22)$$

Where C_e is the unit cost of excavation, C_f is unit cost of the formwork, C_r is the unit cost of reinforcing steel, C_c is the unit cost of concrete, C_b is the unit cost of earth filling. The design of CO_2 emission optimization for the construction of footings for lime-treated soil is defined as:

$$f_{CO_2}=E_eV_e+E_fA_f+\xi E_rM_r+\frac{f_c}{f_{c\,min}}E_cV_c+E_bV_b \qquad (23)$$

Where E_e is the unit emission of excavation, E_f is the unit emission of the formwork, E_r is the unit emission of the reinforcement, ξ is a factor scale that gives the reinforcement steel term a magnitude comparable to that of other terms, and $f_{c\,min}$ is the minimum allowable strength of concrete. The excavation volume V_e, formwork area A_f, and reinforcing steel weight are calculated, respectively, as:

$$V_e=(B+B_o)(L+L_o)D \qquad (24)$$

$$A_f = 2H(B+L) \qquad (25)$$

$$M_r=mV_c \qquad (26)$$

Where m is a proportionality coefficient taken by Camp and Assadollahi [9] and Wang and Kulhawy [7] as 29.67 kg/m³. Thus, the concrete volume V_c is calculated as:

$$V_c = BLH - V_r \qquad (27)$$

Where V_r is the reinforcing steel volume (considering the specific mass of steel as 7,850 kg/m³). When $H \geq B$ there is no earth filling over the foundation and the compressed volume of the earth filling V_b is calculated as:

$$V_b=[(B+B_o)(L+L_o)-BL]D \qquad (28)$$

If H is not greater than or equal to B, the compressed volume of the earth filling is defined as:

$$V_b= V_e- BLH+b_{col}l_{col}(D-H)] \qquad (29)$$

Where l_{col} is column length. Using the weighted aggregation approach, the multi-objective fitness function is defined as:

$$f_{multi} = \zeta f_{cost} + (1-\zeta)f_{CO_2} \qquad (30)$$

Where ζ is a weighting factor that varies from 0 to 1. Table 3 presents the unit cost values and the unit CO_2 emission values in the isolated footing construction process reported by Wang e Kulhawy [7].

TABLE 3. UNIT COST AND CO_2 VALUES.

Input parameter	Unit	Symbol	Value
Cost of excavation	\$/m³	Ce	25.16
Cost of concrete formwork	\$/m²	Cf	51.97
Cost of reinforcement	\$/kg	Cr	2.16
Cost of concrete	\$/m³	Cc	173.96
Cost of compacted backfill	\$/m³	Cb	3.97
CO_2 emission for excavation	kg/m³	Ee	13.16
CO_2 emission for concrete formwork	kg/m²	Ef	14.55
CO_2 emission for reinforcement	kg/kg	Er	3.02
CO_2 emission for concrete	kg/m³	Ec	224.05
CO_2 emission for compacted backfill	kg/m³	Eb	27.20

Source: Authors.

F. *Restrictions*

The design of safe and stable isolated footings requires meeting certain geotechnical conditions related with the maximum load capacity and the permissible settlements in the soil defined by Equations (3) and (17), respectively. The amount of reinforcing steel is a percentage of the geometry and weight of the footing due to experimental calculations as reported by Wang and Kulhawy [7]. In the original example of Wang and Kulhawy [7] they used Vesic's theory [41] to calculate the ultimate bearing capacity of foundations over noncohesive soils, for the present study Meyerhof's theory [35] was used for cohesive silty soil. Thus, the geotechnical constraints due to the safety of the base and settlements are given by the following expressions:

$$FS_B \geq FS_{Bdesign} \quad (31)$$

$$\delta \leq \delta_{design} \quad (32)$$

where $FS_{Bdesign}$ and δ_{design} are the base safety factors and the maximum settlement required, respectively.

III. Results and Discussions

A. *Results of the direct shear strength tests*

Table 5 presents the results of the direct shear strength tests conducted under saturated conditions for the samples cured with 30, 90, and 180 days. The shear strength envelope followed the following form (33):

$$\tau = c+\sigma \tan(\phi) \quad (33)$$

Where τ is the shear force in the specimen, c is the cohesion, and σ is the normal stress applied to the specimen during the test. For all results, the mixtures studied showed cohesion and friction angle. To determine the Mohr-Coulomb envelope, 4 normal stresses (50, 100, 200, and 400 kPa) were applied. According to the results, it can be observed that cohesion increases with the increase in lime content except in 90 days of curing time, where the cohesion of soil-lime mixture with 9% of lime is 39.3 kPa which is much smaller than those of soil-lime mixtures with 5% and 7% of lime (i.e., 51.5 and 61.5 kPa), which means that there is more development of cohesion between the grains when the lime reacts with the water in the voids.

Table 4. Results of direct shear tests

Curing time	Lime content (%)	Cohesion (kPa)	Angle of internal friction (degree)	R^2
30	3	24.8	27.6	0.97
	5	39.4	28.4	0.98
	7	53.0	29.9	0.97
	9	53.2	30.0	0.99
90	3	31.7	31.3	0.99
	5	51.5	30.2	0.96
	7	61.5	25.1	0.94
	9	39.3	36.0	0.98
180	3	37.3	24.6	0.97
	5	42.1	26.3	0.99
	7	20.2	36.8	0.98
	9	52.9	32.3	0.99

Source: Authors.

The direct shear tests were performed under saturated conditions. The saturation values of the samples after being tested were 98% of saturation, leading to the conclusion that suction is not an analysis variable in the test. In 30 days of curing time, the cohesion of the soil-lime mixtures went from 24.8 kPa with 3% of lime to 53.2 kPa with the addition of 9% of lime (an increase of 115%). In 90 days of curing time, the mixtures went from a cohesion of 31.7 kPa with 3% of lime to reach a cohesion of 61.5 kPa with 7% of lime (an increase of 94%). Finally, in 180 days of curing time, the mixtures went from a cohesion of 37.3 kPa with 3% of lime to 52.9 kPa with 9% of lime (an increase of 42%). However, employing 7% of lime, the cohesion of mix decreases to 20.2 kPa due to development of internal friction angle was higher compared to other mixes (i.e. 36.8°).

Table 4 also shows that the friction angle values of the mixtures increased: 9%, 15%, and 30% increase for 30, 90, and 180 days, respectively. Thus, the mixtures showed no increase in friction angle with curing time: 29°, 30.7°, and 30° for 30, 90, and 180 days of curing time, respectively. The results for the fitness of the shear strength envelopes (coefficients of determination, R^2) show that the calculated values have high acceptance (R^2 between 0.94 and 0.99).

B. *Optimizing an example reported in the literature*

To validate the MSAA for the solution of optimization problems of foundations, a benchmark problem reported by [7] and [9] were developed with the input parameters shown in Table 5. The problem was approached with continuous variables as presented in Table 6 for the optimization of both cost and CO_2 emissions. The exercise is constrained by a safety factor of 3 and maximum settlements of 25 mm. The strength parameters of the input soil correspond to sand (c = 0 kPa) with a high friction angle (ϕ = 35). On the other hand, the height from footing base to ground level D was limited from 0.5 to 2.0 m. The standard deviation was used to measure the accuracy and stability of the method. It is said that a heuristic optimization method is stable and accurate if its standard deviation is low. The algorithm can be catalogued as robust when it is applied to different problems and presents efficient accuracy. In this work, each run of the algorithm was made 1,000 times and the value of the function, the worst value of the function, the mean, and the standard deviation of the values are reported. For continuous variable formulations, $\xi = 1$ and $fcmin = fc$ are applied, producing an identical fitness as the one presented by [7] and [9].

Table 5. Input parameters for standard example

Input parameter	Unit	Symbol	Value
Internal friction angle of soil	Degree	ϕ	35
Unit weight of soil	kN/m3	γs	18.5
Poisson ratio of soil	-	v	0.3
Modulus of elasticity of soil	MPa	E	50
Applied vertical force	kN	P	3000
Over excavation length	m	Lo	0.3
Over excavation width	m	Bo	0.3
Thickness of footing	m	H	0.6
Factor of safety for bearing capacity	-	FS	3
Maximum allowable settlement	mm	δ	25

Source: Authors.

Table 6. Design variables standard example - continuous variables

Design variables	Unit	Lower bound	Upper bound
B	m	0.01	5.0
L	m	0.01	5.0
D	m	0.50	2.0

Source: Authors.

Table 7 shows the results for the optimization of the example reported in the literature and also being compared with [7] and [9] for both cost and CO_2 emissions. As seen, the differences are insignificant between the optimization results (i.e., cost and CO_2 emission) obtained by [7] and [9]. Although L and B dimensions change, the area of the foundation is practically maintained. On the other hand, the MSAA requires fewer the number of analyses (2000 analyses for Cost and 2000 analyses for CO_2) than [9] (10207 analyses for Cost and 10958 analyses for CO_2) to converge the optimal solution. Furthermore, the MSAA is always more stable than [9] through the best value of standard deviation. By comparing the results obtained with the MSAA, it can be mentioned that as to the objective function of the cost decreases by US$0.01 (1,086.00- US$ 1,085.99) the value of [7] and by US$0.16 (1,086.15-US$1,085.99) the result of [9]. On the other hand, by comparing the optimization of the CO_2 function with the MSAA, the value obtained was 0.13 kg less than the value reported with the use of the BB-BC (1119.40-1119.53 kg).

Table 7. Designs for standard example (continuous variables)

Design variables	Wang and Kulhawy [7]	BB-BC COST [9]	BB-BC CO_2 [9]	MSAA COST	MSA CO_2
B (m)	1.86	1.87	2.09	1.63	2.27
L (m)	2.30	2.30	2.10	2.56	1.97
D (m)	1.38	1.37	1.26	1.48	1.17
Excavation (m^3)	7.75	7.72	7.20	8.17	6.82
Concrete formwork (m^2)	5.00	5.00	5.03	5.03	5.09
Reinforcement (kg)	76.16	76.26	78.12	74.28	79.61
Concrete (m^3)	2.57	2.57	2.63	2.50	2.68
Compacted backfill (m^3)	5.18	5.15	4.57	5.67	4.14
Design objetive	$1086	$1086.15	1119.53 kg	$1085.99	1119.40 kg
Secundary objetive	-	1122.15 kg	$1087.32	1122.22 kg	$1091.36
Average fitness	-	$1087.88	1124.23 kg	$1088.43	1119.93 kg
Std. Dev. Fitness	-	$1.35	3.80 kg	$1.52	0.27 kg
Average no. analyses	-	10207	10958	2000	2000

Source: [7], [9].

The MSAA can be considered as a robust optimization algorithm, as it found equal or better values than those reported by other authors, who worked with the standard problem made in this work. Thus, Fig. 4 presents the convergence of the optimization of the standard problem for costs and carbon dioxide emissions of footing construction. It is noted that during the convergence of costs the algorithm achieved a decrease of US$85 in 20 cycles and in the convergence of CO_2 it decreased 14 kg in approximately 14 cycles.

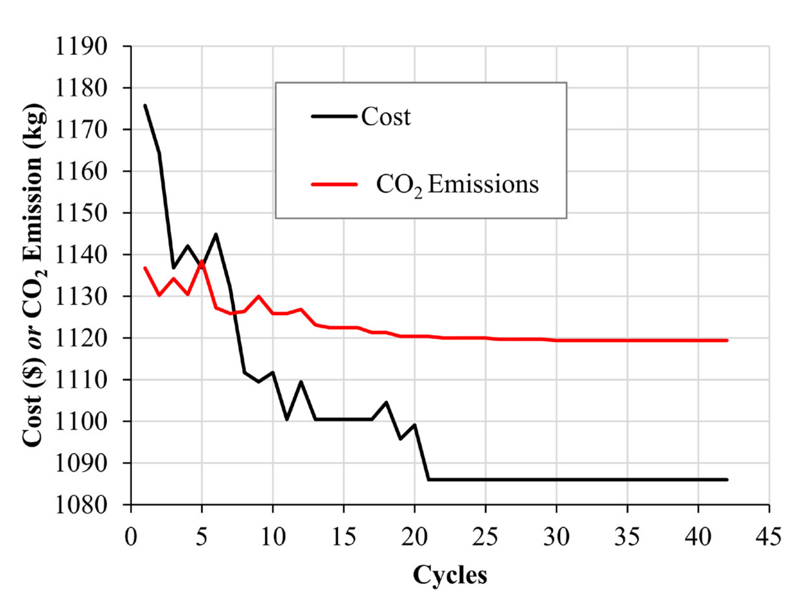

Fig. 4. Convergence of the standard problem.
Source: Authors

C. *Optimizing isolated footings over lime-treated soils*

After the MSAA was validated with a standard example reported in the literature, it was proceeding to optimize problems with the design of footings supported over soil-lime with the shear strength parameters shown in Table 4. The problems were approached with the input parameters shown in Table 8 and with the continuous variables shown in Table 6.

Table 8. Input parameters for standard example lime-soil

Input parameter	Unit	Symbol	Value
Internal friction angle of soil	Degree	ϕ	Table 4
Coesion	kPa	c	Table 4
Unit weight of soil	kN/m3	γs	15
Poisson ratio of soil	-	v	0.3
Modulus of elasticity of soil	MPa	E	50
Applied vertical force	kN	P	3000
Over excavation length	m	Lo	0.3
Over excavation width	m	Bo	0.3
Thickness of footing	m	H	0.6
Factor of safety for bearing capacity	-	FS	3
Maximum allowable settlement	mm	δ	25

Source: Authors.

For 30 days of curing time, a series of 1,000 runs of the MSAA was made using as objective function the cost and CO_2 emissions. The designs for each lime content and type of objective function are presented in Table 9. For the cost function and for the lime contents from 3 to 9% it was obtained minimum construction cost of US$933.10 for L = 7% and a maximum cost of US$951.20 for L = 3%. For the CO_2 function values between 933.27 kg and 933.64 kg with L = 9% and L = 3% were obtained, respectively. The secondary objective functions for each lime content are also shown in Table 9. It is noted that the values of the secondary results also converge on the main objective solutions.

Table 9. Designs for lime-soil treated with 30 days of curing

Design variables	L = 3%		L = 5%		L = 7%		L = 9%	
	Cost	CO_2	Cost	CO_2	Cost	CO_2	Cost	CO_2
B (m)	2.24	2.24	2.00	2.00	2.00	2.00	2.00	2.00
L (m)	2.24	2.24	2.17	2.17	2.17	2.17	2.17	2.17
D (m)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Excavation (m^3)	3.23	3.23	2.84	2.84	2.84	2.84	2.84	2.84
Concrete formwork (m^2)	5.38	5.38	5.01	5.01	5.01	5.01	5.01	5.01
Reinforcement (kg)	3.01	3.01	2.61	2.61	2.61	2.61	2.61	2.61
Concrete (m^3)	89.32	89.32	77.36	77.36	77.36	77.36	77.36	77.36
Compacted backfill (m3)	0.22	0.22	0.24	0.24	0.24	0.24	0.24	0.24
Design objective	$951.20	933.64 kg	$951.11	933.34kg	$951.10	933.27kg	$951.12	933.27kg
Secondary objective	933.39 kg	$951.44	933.28 kg	$951.17	933.27 kg	$951.10	933.29 kg	$951.12
Average fitness	$ 951.56	$934.00	$ 951.23	$933.34	$ 951.15	$933.32	$ 951.37	$933.40
Std. Dev. Fitness	$0.26	0.21 kg	$0.12	0.20 kg	$0.03	0.05 kg	$0.23	0.11 kg

Source: Authors.

Fig. 5 shows the convergence of the optimization of the designs of footings over soil treated with lime contents of 5, 7 and 9%. The convergence of the optimization of the designs with 3% of lime is shown in Fig. 6. It is noted that all the values converge on the same result after 30 cycles for both cost and CO_2 (i.e., in this number of cycles the MSAA finds the overall optimum result). Table 10 shows the results of the designs for footings supported on soil-lime cured for 90 days. On average, the values of the cost optimization results are consistent at US$951 for both the objective functions and secondary functions. Fig. 7 shows the graphs for the convergence of the cost optimizations for lime contents of 3, 5, 7, and 9%, while Fig. 8 shows the convergences of the CO_2 optimizations for the same lime contents (3-9%). It is noted that for costs, a reduction of US$35 in the result was achieved after 30 cycles in the MSAA, and for CO_2 a reduction of 40 kg in the result was achieved after 20 cycles.

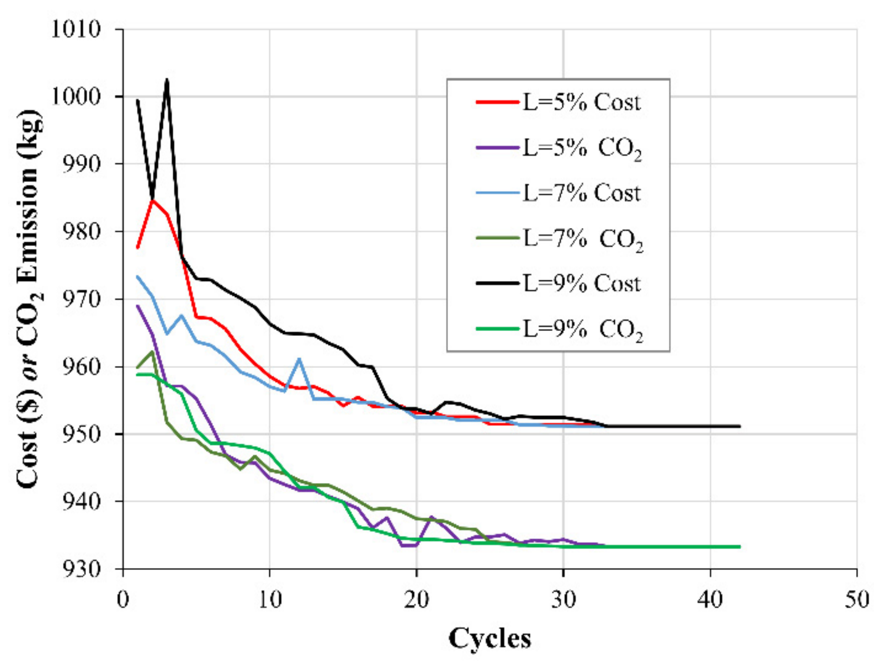

Fig. 5. Convergence history of spread footing (cost and CO_2 optimization) for lime (5, 7 and 9%) -soil cured with 30 days.
Source: Authors.

Table 10. Designs for lime-soil treated with 90 days of curing

Design variables	L = 3%		L = 5%		L = 7%		L = 9%	
	Cost	CO_2	Cost	CO_2	Cost	CO_2	Cost	CO_2
B	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
L	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17
D	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Excavation (m^3)	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84
Concrete formwork (m^2)	5.01	5.01	5.01	5.01	5.01	5.01	5.01	5.01
Reinforcement (kg)	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61
Concrete (m^3)	77.36	77.36	77.36	77.36	77.36	77.36	77.36	77.36
Compacted backfill (m^2)	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Design objective	$951.12	933.30kg	$951.60	933.30kg	$951.17	933.30kg	$951.38	933.30kg
Secondary objective	933.29 kg	$951.13	933.63 kg	$951.13	933.34kg	$951.17	933.56kg	$951.13
Average fitness	$ 951.24	$933.43	$ 951.43	$933.51	$ 951.26	$933.54	$ 951.56	$933.45
Std. Dev. Fitness	$0.12	0.11 kg	$0.13	0.10 kg	$0.12	0.18 kg	$0.15	0.10 kg

Source: Authors.

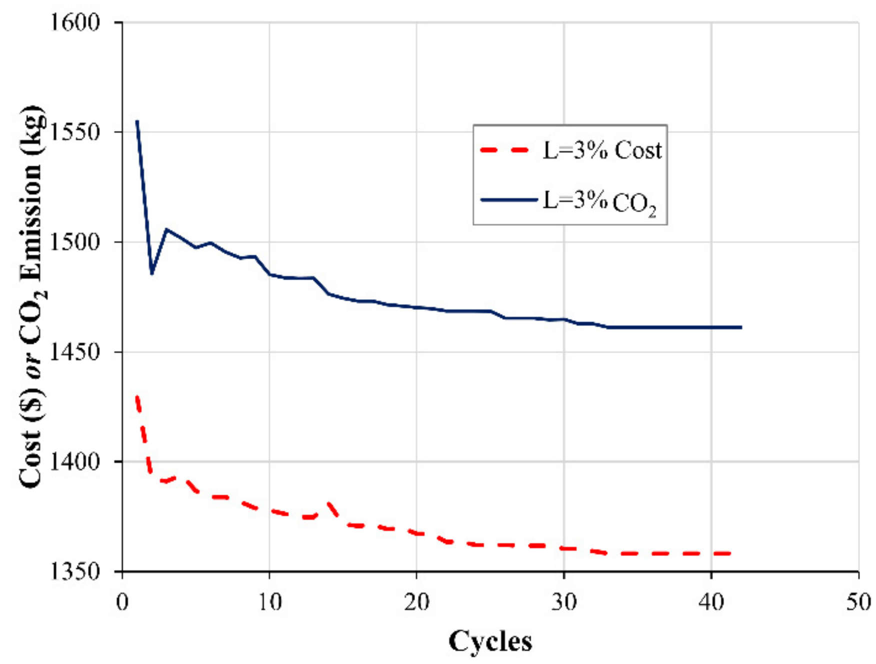

Fig. 6. Convergence history of spread footing (cost and CO2 optimization) for lime (L=3%) -soil cured with 30 days

Source: Authors.

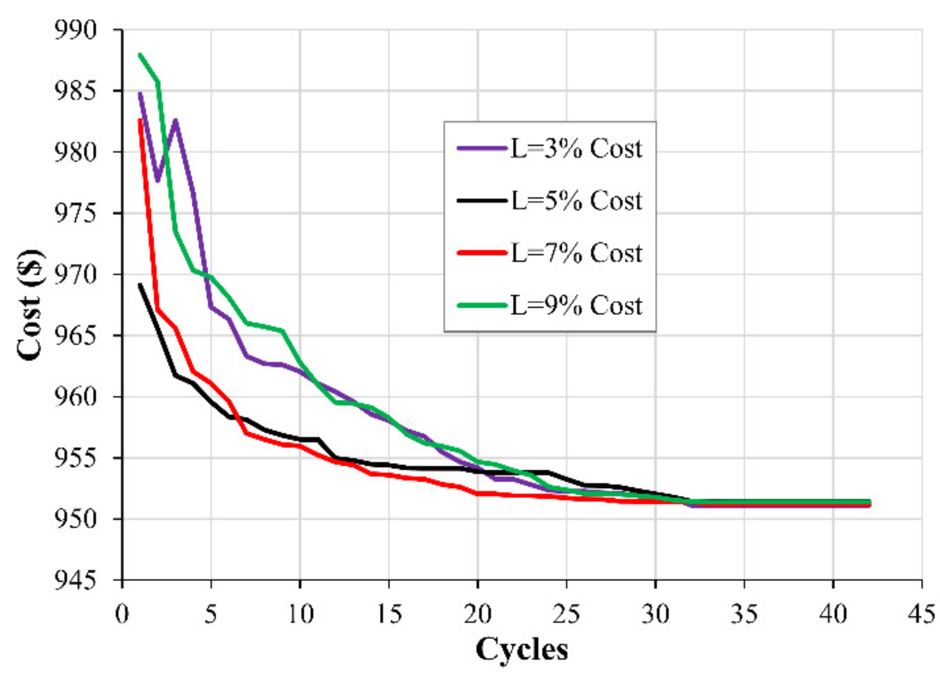

Fig. 7. Convergence history of spread footing (cost optimization) for lime-soil cured with 90 days.
Source: Authors.

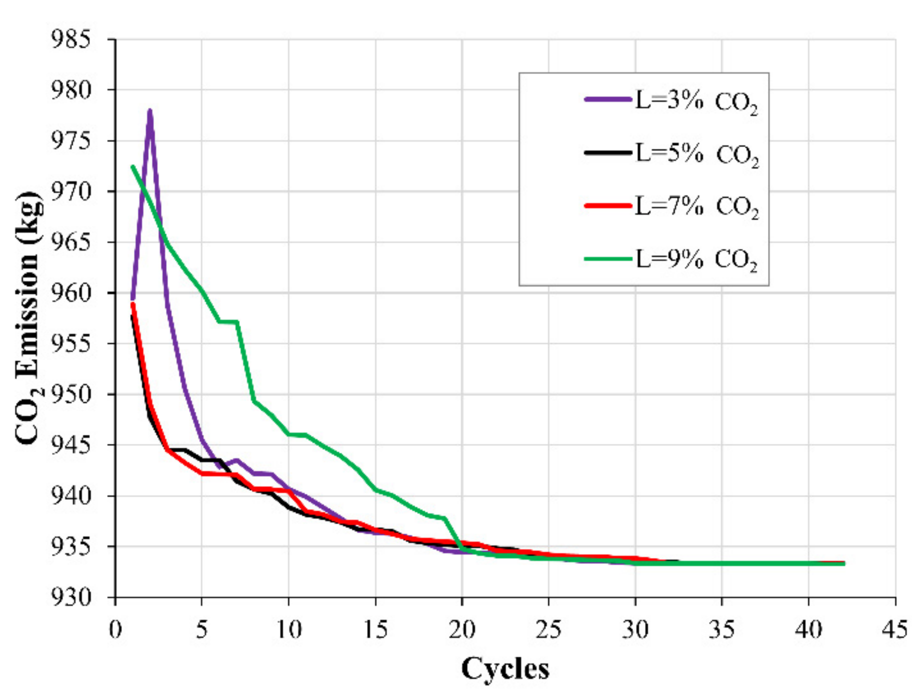

Fig. 8. Convergence history of spread footing (CO_2 Emission optimization) for lime-soil cured with 90 days.
Source: Authors.

Table 11 shows the results of the designs of footings supported over soil-lime cured for 180 days. It is noted that for all the optimizations and for all the lime contents of 3.5 and 9% the results converged. The cost optimization values were US$951.20, US$951.43, and US$951.13 for 3, 5, and 9% lime, respectively. For 7% lime, a result of US$1,669.23 for cost was obtained. The convergence of the designs for 3, 5, and 9% lime and 180 days of curing time are shown in Fig. 9. It is noted that after 35 cycles the results for the cost and CO_2 functions converge on the same result. While the convergence of the designs for 7% lime optimizing cost and CO_2 are shown in Fig. 10. For the 1,000 runs made for 180 days of curing time, the results of 7% lime did not converge with the results of 3, 5, and 9% lime, and the optimization values of 7% were higher than those of the other lime contents due to the low cohesion and high friction angle, where the MSAA worked in the limit load capacity and in the maximum settlement of 25 mm.

Table 11. Designs for lime-soil treated with 180 days of curing

Design variables	L = 3%		L = 5%		L = 7%		L = 9%	
	Cost	CO_2	Cost	CO_2	Cost	CO_2	Cost	CO_2
B	2.00	2.00	2.00	2.00	2.52	2.52	2.00	2.00
L	2.17	2.17	2.17	2.17	2.53	2.52	2.17	2.17
D	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Excavation (m^3)	2.84	2.84	2.84	2.84	3.99	3.98	2.84	2.84
Concrete formwork (m^2)	5.01	5.01	5.01	5.01	6.06	6.05	5.01	5.01
Reinforcement (kg)	2.61	2.61	2.61	2.61	3.83	3.81	2.61	2.61
Concrete (m^3)	77.36	77.36	77.36	77.36	113.50	113.05	77.36	77.36
Compacted backfill (m^3)	0.24	0.24	0.24	0.24	0.16	0.17	0.24	0.24
Design objective	$951.20	933.64 kg	$951.43	933.34 kg	$1669.53	1822.94 kg	$951.13	933.88 kg
Secondary objective	933.39 kg	$951.44	933.63 kg	$951.17	1823.49 kg	$1669.06	934.39 kg	$933.88
Average fitness	$ 951.56	$934.00	$ 951.78	$934.62	$1670.28	$1824.65	$ 953.03	$951.67
Std. Dev. Fitness	$0.26	0.21 kg	$0.36	0.20 kg	$0.67	1.09 kg	$0.63	0.30 kg

Source: Authors.

Analyzing results reported in Table 9, Table 10 and Table 11, costs and carbon dioxide emission for spread footing construction converge to the same results. In this sense, 9% lime can be avoided, and small percentages of lime (i.e. 3-5%) are appropriated to ground improvement and reduce the costs of this procedure. In addition, curing time period can be reduced to 30 days. Compaction effort increase the durability of the ground and promote the gain of strength [31].

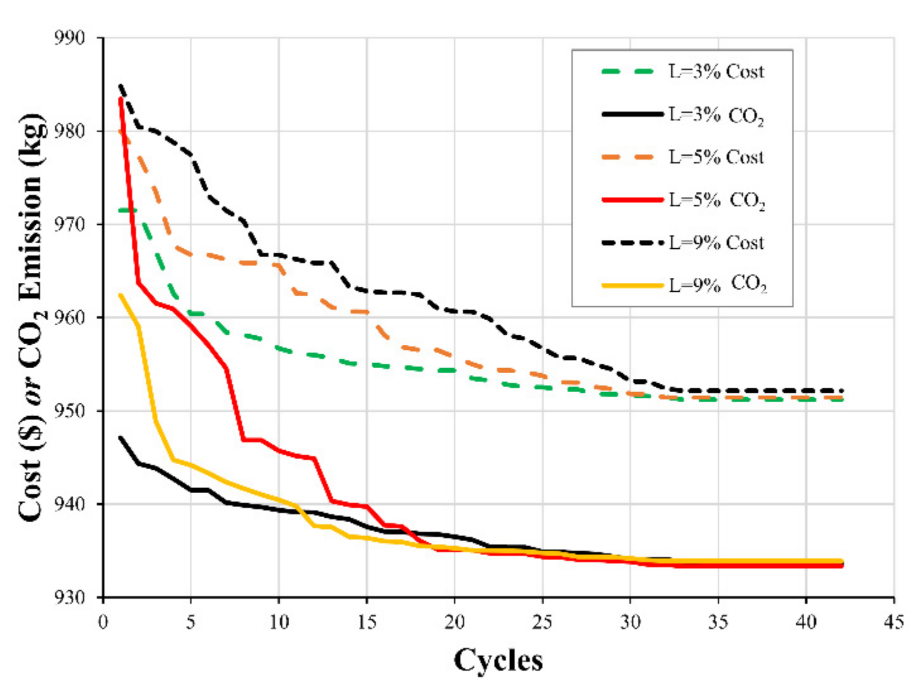

Fig. 9. Convergence history of spread footing (cost and CO² optimization) for lime (3, 5 and 9%) -soil cured with 180 days
Source: Authors.

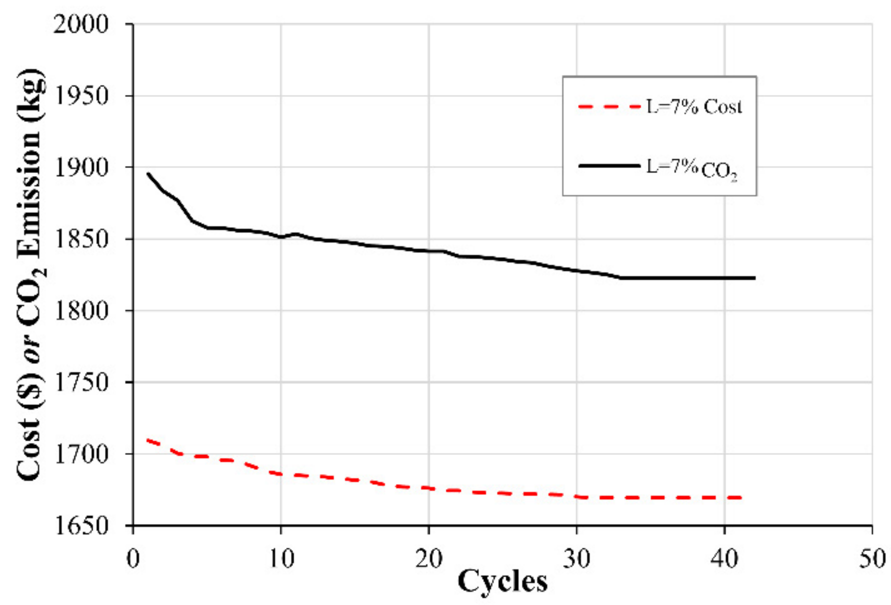

Fig. 10. Convergence history of spread footing (cost and CO_2 optimization) for lime (L = 7%) -soil cured with 180 days.
Source: Authors.

For the purpose of analysis, during the optimization of the problems in the MSAA, most of them converged on the same result except for L = 3% at 30 days of curing time and L = 7% at 180 days of curing time, for both cost and CO^2 emissions. Thus, the mean values of US$951 and 933 kg were found for most lime contents. Equations 11 and 33 delimitated these results, with the value of 25 mm of settlement becoming the universal limiting factor of the exercises proposed in this research. The load capacity of the foundations increased with the increase in cohesion and friction angle (3). Finally, it can be mentioned that the best analysis time was 30 days of curing time, any lime content can be chosen (except for 3% and 7% at 30 and 180 days, respectively), and the best results for cost and CO_2 were US$951 and 933 kg, respectively. The comparison of the economically optimized design with the conventional designs shows that the savings in the construction cost could be up to 30%, but the economically optimized design may vary by location [7]. The E and ϕ can be values that significantly affect site design variables. Thus, all depend, and independent variables must be study individually.

IV. Conclusions

According to the results and the analysis in this study, the following conclusions can be considered:

- With the increase in lime content (from 3% to 9%), the cohesion of the mixtures increased for all curing times studied (from 24.8 kPa using 3% lime at 30-days to 61.5 kPa using 7% lime at 90-days curing). In addition, the friction angle had no major variations in relation to the amount of lime administered or to the curing time employed. On average, the internal angle remained at 30 degrees to 7% and 9% lime.
- Lime at 9% is a higher content, it would produce additional costs in the ground improvement and not environmentally friendly for stabilization but is the more efficient content to reach the best strength values. In order to avoid 9% lime, results demonstrate 3% and 5% produces an acceptable requirement for foundation purposes.
- Regarding the convergence capability, the MSSA algorithm generally performed better than Camp and Assadollahi [9]. In the benchmark problem, the MSAA required a much less number of analyses to achieve the global optimal solution. This indicates that the MSAA is very effective for a speedy escape from local optima trapping. The MSAA required 2000 analyses for Cost and 2000 analyses for CO_2 and Camp and Assadollahi [9] required 10207 analyses for Cost and 10958 analyses for CO_2 to converge the optimal solution.
- The MSAA can be designated as a robust algorithm due to having achieved almost equal results and, in some cases, better results compared with other algorithms to solve problems reported in the literature.

- Success was achieved in optimizing the cost and CO_2 emissions with the MSAA and in finding mean results of US$933 and 951 kg for the cost and CO_2 emission, respectively. Regardless of curing time and lime content most of the results converged on the same values, is that the main constraint is the maximum permissible settlements of 25 mm.

Acknowledgments

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