

## Research Article

# Mixture Ratio Design Optimization of Coal Gangue-Based Geopolymer Concrete Based on Modified Gravitational Search Algorithm

Daming Zhang <sup>1,2</sup>, Fangjin Sun <sup>3,4</sup>, Tiantian Liu <sup>5</sup> and Zhonghao Xu <sup>5</sup>

<sup>1</sup>Guangxi Key Laboratory of Embedded Technology and Intelligence, Guilin 541006, China

<sup>2</sup>College of Information Science and Engineering, Guilin University of Technology, Guilin 541006, China

<sup>3</sup>Guangxi Key Laboratory of Geomechanics and Geotechnical Engineering, Guilin University of Technology, Guilin 541004, China

<sup>4</sup>College of Civil Engineering and Architecture, Guilin University of Technology, Guilin 541004, China

<sup>5</sup>College of Civil Engineering, Liaoning Technical University, Fuxin 123000, China

Correspondence should be addressed to Fangjin Sun; e\_dm@163.com

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A green concrete, new type of coal gangue-based geopolymer concrete, was prepared. Coal gangue geopolymer concrete contains many mineral admixtures and alkaline activators; the concrete mixture ratio design has always been a complex problem. The framework of the mix design optimization by the proposed method is established in this work. The paper aims to minimize the economic cost under the premise of ensuring the strength and workability of coal gangue-based geopolymer concrete. Gravitational search algorithm (GSA) has the advantages of faster convergence speed and stronger exploitation performance compared with the traditional optimization algorithms. However, GSA tends to premature convergence and local optimum, with weak search ability. Therefore, chaotic map is introduced in the work here. Gravitational search algorithm was modified based on Chebyshev map in chaotic theory, and the modified equations were derived. The modified algorithm was verified by the calculation of typical functions. And results from traditional GSA and GSA modified by another chaotic mapping, logistic mapping, were compared and the characteristics of different GSA were analyzed and concluded. After that, the mix design of geopolymer concrete based on coal gangue with different strength grades was optimized with the modified GSA. Through analysis of the optimization results, cost variation of different strength grade coal gangue-based geopolymer concrete was revealed. Costs declined significantly; the higher the grades within a certain strength range, the more saved. Therefore, it can be inferred that the modified gravity search method provides a reliable tool for the optimization of mixture ratio of similar geopolymer concrete.

## 1. Introduction

The concept of geopolymer materials was proposed by Frenchman Davidovits in 1978. It is an inorganic polymer with three-dimensional network structure composed of  $AlO_4$  and  $SiO_4$  tetrahedral units, belonging to non-metallic materials. This material has excellent mechanical properties, acid-base resistance, fire resistance, and high temperature resistance. It is possible to replace ordinary Portland cement and it has the characteristics of using mineral waste and construction waste as raw materials. It has applications in building materials, high strength materials, solid nuclear

waste materials, sealing materials, and high temperature resistant materials. Therefore, the optimization of coal gangue-based geopolymer mixture ratio based on modified gravitational search algorithm can not only save construction cost under the condition of ensuring strength and workability, but also maximize the optimization of construction waste and realize the concept of green sustainable.

In recent years, geopolymer materials have become popular materials for scientists and engineers due to their advantages of lower energy consumption, wide sources, and less environmental pollution [1, 2]. They are a kind of green and sustainable development material, which is in line with

the purpose of maximizing the utilization of resources advocated by the state. The main mineral components are silicates or natural silicate of silicate aluminates or solid wastes can be used as raw materials for geopolymers. Coal gangue is the waste discharged during coal mining and processing [3], and its main mineral component is silicate or silicate aluminate. Therefore, it can also be used as a raw material for geopolymers and provides an effective way for the resource utilization of coal gangue.

In the process of concrete configuration, whether the mixture ratio is reasonable or not is directly related to the performance and quality of the concrete. Different from ordinary concrete, many kinds of mineral admixtures and alkaline activator are needed to be added to polymer concrete of coal gangue base, which increases the components of the concrete and strengthens the mutual influence between the components. As a result, the traditional concrete mixture ratio design method has been difficult to apply to the new coal gangue-based geopolymer concrete mixture ratio design. At present, the optimization research on the mixture ratio of geopolymer concrete is very limited, and most of them are based on experimental methods. The commonly used experimental method is response surface method [5–7]. Although these experimental methods have studied the influence of some important components on geopolymer concrete, there are many factors that affect the mixture ratio of geopolymer concrete, and the interaction between various factors, it is very difficult to obtain a general design method of mixture ratio considering the influence of all necessary parameters by experiment method. Therefore, in order to make the coal gangue base geopolymer concrete truly play its “green” and “sustainable” advantages, and extend it to practical projects, it is a work with important theoretical value and engineering application value to study efficient and reliable optimization methods for its mixture ratio design.

Usual metaheuristic optimization algorithms are based on swarm intelligence; from the rise to the present, swarm intelligence algorithms have attracted the attention of many researchers. Some of the nature-inspired algorithms which are most common and widely used are the genetic algorithm (GA) [8], particle swarm optimization (PSO) [9], artificial bee colony algorithm (ABC) [10], and so on. Some of the recently developed and efficient algorithms are sine cosine algorithm (SCA) [11], Harris Hawks optimization (HHO) [12], hybridizing the sine cosine algorithm with grey wolf optimizer (SC-GWO) [13], a modified version of the Salp swarm algorithm called opposition learning and levy-flight search, the algorithm named m-SSA [14], and so on.

In this paper, coal gangue-based geopolymer concrete was first prepared, and its mixture ratio optimization was studied. Based on the gravitational search algorithm, the gravitational search algorithm is modified by chaotic mapping, and the modified gravitational search algorithm formula is derived. The modified gravitational search algorithm is used to optimize the mixture ratio of polymer concrete in coal gangue-based, which provides a reliable optimization method for the mixture ratio design of similar geopolymer concrete.

## 2. Preparation of Coal Gangue-Based Geopolymer Concrete

In this paper, coal gangue is used as raw material to prepare coal gangue-based geopolymer concrete. The coal gangue selected for this paper is spontaneous combustion coal gangue from Fuxin area of Liaoning Province. The main chemical components of Fuxin spontaneous combustion coal gangue are  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ , and other elements. The specific chemical components are shown in Table 1.

It can be seen from Table 1 that the main chemical compositions of coal gangue after spontaneous combustion will not change significantly,  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  are still the main components, and the content of  $\text{SiO}_2$  slightly increases.

The process of making geopolymer concrete test blocks is as follows.

- (1) Firstly, sodium hydroxide (SH) solution is mixed with calcium carbonate (CC) powder to generate alkaline excitation powder composed of calcium hydroxide (CH), sodium carbonate (SC), and pirs-sonite (P), which is dried in an oven at  $80^\circ$  for 8 hours.
- (2) Then, crush to a fixed particle size, and finally take the activator powder particle size of less than 0.03 mm powder, as an activator for the preparation of coal gangue-based geopolymer concrete.
- (3) Then, the (spontaneous combustion) coal gangue block is crushed by a sledge hammer, and repeatedly crushed into small particles in a crusher, and sieved to obtain a powder with a particle size of 0.01 mm–0.09 mm.
- (4) Pour sands and stones into the mixer, stir for about 140 s, then pour the coal gangue powder and fly ash, stir for about 20 s, and finally add the dry powder activator powder, with stirring for about 120 s.
- (5) After the final mixing is completed, the geopolymer concrete is poured into the mold, vibrated and compacted, and finally smoothed to make the geopolymer concrete test blocks.

The process and the specimens are shown in Figure 1.

## 3. Optimization of Mixture Ratio of Coal Gangue-Based Geopolymer Concrete

**3.1. Gravitational Search Algorithm.** In the gravitational search algorithm (TGSA), the individual has four attributes: position, inertial mass, active gravity mass, and passive gravity mass. The individual's inertial mass, active gravity mass, and passive gravity mass are all determined by the fitness function of the optimization problem.

Assuming that an individual is defined in an n-dimensional search space, the population consisting of N individuals is  $X = (x_1, x_2, \dots, x_N)$ ,  $i = 1, 2, \dots, N$ , where the position of the  $i$ -th individual, that is, the solution of the problem, can be expressed as  $X_i = (x_i^1, x_i^d, \dots, x_i^n)$ , where  $x_i^d$

TABLE 1: Chemical compositions of coal gangue (%).

|              |                                |                                |                  |      |                  |
|--------------|--------------------------------|--------------------------------|------------------|------|------------------|
| Compositions | SiO <sub>2</sub>               | Al <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | CaO  | MgO              |
| Contents     | 65.09                          | 16.86                          | 2.67             | 2.07 | 1.98             |
| Compositions | Fe <sub>2</sub> O <sub>3</sub> | Na <sub>2</sub> O              | TiO <sub>2</sub> | S    | Loss on ignition |
| Contents     | 6.15                           | 1.64                           | 0.74             | 0.53 | 1.49             |

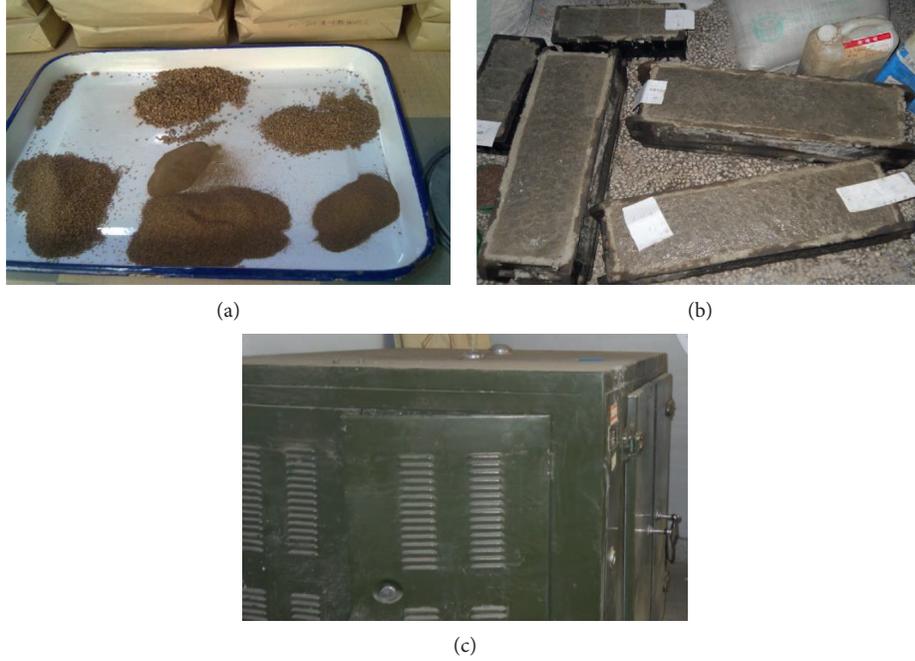


FIGURE 1: Process of making geopolymer concrete. (a) Raw materials for experiment. (b) Coal gangue-based geopolymer concrete. (c) Curing.

represents the position of individual  $i$  in the  $d$ -dimensional space.

In the gravitational search algorithm (GSA), the initial position of the individual is generated randomly. At a certain moment, the universal gravitation between individual  $i$  and individual  $j$  is

$$F_{ij}^d(t) = G(t) \frac{M_{pi}(t) \times M_{aj}(t)}{R_{ij}(t) + \varepsilon} (x_j^d(t) + x_i^d(t)). \quad (1)$$

Among them,  $M_{aj}$  is the active gravity mass related to object  $j$ ,  $M_{pi}$  is the passive gravity mass related to object  $i$ ,  $G(t)$  is the gravitational constant related to time  $t$ ,  $\varepsilon$  is a small constant, and  $R_{ij}(t)$  is the Euclidean distance between two objects  $i$  and  $j$  [14].

The calculation of gravitational mass and inertial mass can be obtained according to the fitness function of the optimization problem. It is generally assumed that the gravitational mass and inertial mass are equal; then, the inertial mass of each individual  $M_i(t)$  can be expressed as [15]

$$M_{ai} = M_{pi} = M_{ii} = M_i, \quad i = 1, 2, \dots, N,$$

$$m_i(t) = \frac{\text{fit}(t) - \text{worst}(t)}{\text{best}(t) - \text{worst}(t)}, \quad (2)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^N m_j(t)},$$

where  $\text{fit}(t)$  is the fitness value of the individual  $i$  at time  $t$  and  $\text{best}(t)$  and  $\text{worst}(t)$ , respectively, represent the best fitness value and the worst fitness value of all individuals at time  $t$ .

When the objective function is to solve the minimum solution problem [8],

$$\begin{aligned} \text{best}(t) &= \min_{j \in \{1, \dots, N\}} \text{fit}(t), \\ \text{worst}(t) &= \max_{j \in \{1, \dots, N\}} \text{fit}(t). \end{aligned} \quad (3)$$

Finally, the individual's speed and position update formula are as follows:

$$\begin{aligned} v_i^d(t+1) &= \text{rand}_i \times v_i^d(t) + a_i^d(t), \\ x_i^d(t+1) &= x_i^d(t) + v_i^d(t+1). \end{aligned} \quad (4)$$

### 3.2. Modified Gravitational Search Algorithm Based on Chaotic Map

**3.2.1. Typical Chaotic Map.** In solving optimization problems with a high-dimensional search space, the classical optimization algorithms do not provide a suitable solution because the search space increases exponentially with the problem size; therefore solving these problems using exact techniques (such as exhaustive search) is not practical. According to the research content of this paper, here we mainly introduce two typical chaotic mapping models, including logistic mapping and Chebyshev mapping. Among them, logistic mapping is proven to be effective for economic dispatch problem [16]. Chebyshev mapping has higher initial value sensitivity and ambiguity than logistic mapping.

(1) *Logistic mapping.* Logistic mapping can be written as [17]

$$x_{k+1} = \mu x_k (1 - x_k). \quad (5)$$

In the formula,  $\mu$  is the bifurcation parameter,  $x_n \in (0, 1), k \in (0, 4], k$  only takes integer values; when  $k \in (3.5699456 \dots, 4]$ , the logistic mapping enters the chaotic interval. When  $k = 4$ , it is called a full mapping.

(2) *Chebyshev mapping.* Assuming that  $n$  is an integer and  $x$  is a variable in the interval  $[-1, 1]$ , Chebyshev mapping  $T_n$  is expressed as [18]

$$T_n(x) = \cos(ncos^{-1}x). \quad (6)$$

When  $n \geq 2$ , the Chebyshev mapping is in a chaotic state. Since the mapping in the interval  $[-1, 1]$  is unchanged during the process of  $T_n: T_n = ([-1, 1]) \rightarrow [-1, 1]$ , the Chebyshev mapping is chaotic for all integers of  $n \geq 2$  in the interval  $[-1, 1]$ ; at the same time, it also shows that Chebyshev mapping has chaotic boundedness.

This paper will focus on the gravitational search algorithm based on Chebyshev mapping modification, because the Chebyshev mapping has higher initial value sensitivity and ambiguity than logistic mapping. Later in this paper, logistic mapping and Chebyshev mapping are used to modify the gravitational search algorithm and the results are compared to further explain the advantages and disadvantages of logistic mapping and Chebyshev mapping.

**3.2.2. Modifying the Gravitational Search Algorithm Based on Chaotic Map.** Suppose to consider the following minimize value problem:

$$\text{Minimize } f(x) = f(x_1, x_2, \dots, x_n). \quad (7)$$

The constraint condition is

$$L_i \leq x_i \leq U_i, \quad i = 1, 2, \dots, n. \quad (8)$$

Among them,  $f: \mathfrak{R}^n \rightarrow \mathfrak{R}$  represents the objective function and is continuously differentiable; that is, it has solutions for  $n$  design variables  $x_i$ ;  $L_i$  and  $U_i$  are the upper and lower limits of the variables  $x_i$ .

If  $S$  represents the search space in the interval  $[L_i, U_i]$  and the chaotic function is in the interval  $[0, 1]$ , in order to use the chaotic function, the following linear mapping is defined between the chaotic variable  $\delta_i$  and the design variable  $x_i$ :

$$\delta_i = \frac{x_i - L_i}{U_i - L_i}. \quad (9)$$

The steps of the modified gravitational search algorithm based on chaotic mapping are as follows:

- (1) Set any initial value of chaotic mapping  $0 < \delta_i < 1$ , set initial design variable  $x_i^j = \delta_i^0 (U_i - L_i) + L_i$ , iteration count  $k = 1$ , object function value  $f^* = f(x^0)$ .
- (2) Map chaotic variable  $\delta_i$  to the interval of  $[L, U]$ ; that is,

$$x_i^j = \delta_i^j (U_i - L_i) + L_i. \quad (10)$$

- (3) Calculate the fitness value of each particle  $x_i$  in the  $k$ -th iteration; update the gravity constant.
- (4) When solving the minimum value problem, using formulas (7) and (8), the mass of each particle is calculated according to the calculated fitness.
- (5) According to formulas (11) and (12), the velocity and position of each particle in the  $k$ -th iteration are calculated; that is,

$$v_i^d(k) = \text{rand}_i \times v_i^d(k-1) + a_i^d(k-1), \quad (11)$$

$$x_i^d(k) = x_i^d(k-1) + v_i^d(k). \quad (12)$$

- (6) Use Chebyshev chaotic mapping calculation to determine the calculation variable of the  $(k+1)$ -th iteration

$$\beta_{k+1}^j = \cos(k \cos^{-1}(\beta_k)). \quad (13)$$

Among them,  $k$  is iteration times,  $\beta_0$  is the initial condition of chaotic mapping, and the mapping interval is  $[-1, 1]$ .

- (7) Update the  $(k+1)$ -th iteration speed and position of the particles:

$$v_i^d(k+1) = \beta_{k+1} \text{rand}_i \times v_i^d(k) + a_i^d(k), \quad (14)$$

$$x_i^d(k+1) = x_i^d(k) + v_i^d(k+1).$$

- (8) Estimate the new adaptation value of the new variable  $x_i^d(k+1)$ , and continue the calculation of the above steps until the termination condition is satisfied.

The flow of the modified gravitational search algorithm based on chaotic mapping is shown in Figure 2.

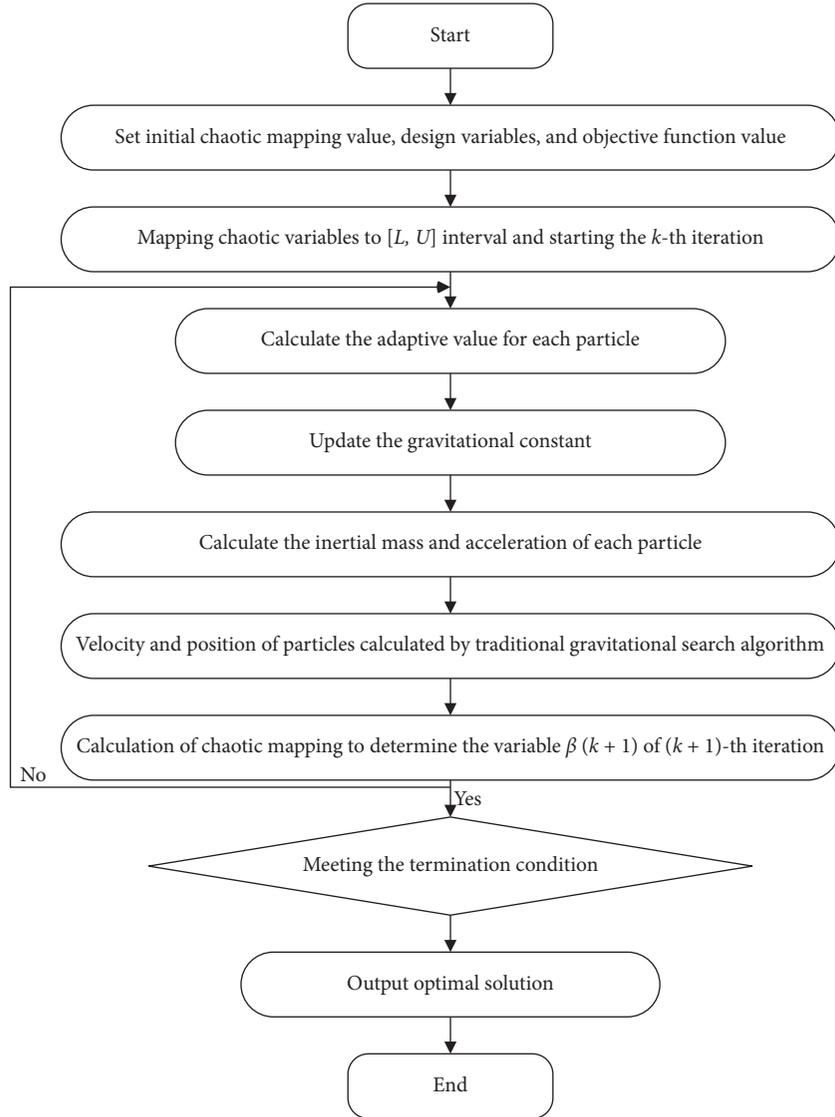


FIGURE 2: Flowchart of improved gravity search algorithm based on chaotic mapping.

#### 4. Simulation Experiment and Analysis

In order to validate the algorithms based on chaotic mapping, five typical test functions are selected for test verification.

Among them,

$$f_1(x) = \sum_{i=1}^n x_i^2. \quad (15)$$

Searching range is  $[-100, 100]^n$ ;

$$f_2 = \sum_{i=1}^{n-1} \left[ 100(x_{x+1} - x_i^2)^2 + (1 - x_i)^2 \right]. \quad (16)$$

Searching range is  $[-30, 30]^n$ ;

$$f_3(x) = \frac{1}{4000} \sum_{i=2}^n (x_i)^2 - \prod_{i=1}^n \cos \frac{x_i}{\sqrt{i}} + 1. \quad (17)$$

Searching range is  $[-600, 600]^n$ ;

$$f_4(x) = \sum_{i=1}^n (x_i^2 - 10 \cos(2\pi x_i) + 10). \quad (18)$$

Searching range is  $[-5.12, 5.12]^n$ ;

$$f_5(x) = \left( \frac{1}{500} + \sum_{i=1}^{25} \frac{1}{j + \sum_{i=1}^2 (x_i - a_{ii})^6} \right)^{-1}. \quad (19)$$

Searching range is  $[-65.53, 65.53]^n$ .

$f_1(x)$  and  $f_2(x)$  are single peak high-dimensional functions,  $f_3(x)$  and  $f_4(x)$  are multi-peak high-dimensional functions,  $f_5(x)$  is peak low-dimensional functions, and  $n$  represents dimension. The results are compared using the traditional gravitational search algorithm (TGSA) and the modified gravitational search algorithm based on chaotic mapping (CGSA), respectively. Optimization calculation and performance comparison are made for the gravitational

search algorithm of two different chaotic mappings, logistic and Chebyshev, recorded as CGSA (L) and CGSA (C), respectively.

Run 25 times for each benchmark test function, and count the average value, optimal value, and standard deviation. Among them, the dimension of  $f_1(x) - f_4(x)$  is 30, the dimension of  $f_5(x)$  is 2, the maximum number of iterations is 1000,  $G_0 = 100$ , and  $\alpha = 20$ . The results of the two algorithms are compared as shown in Table 2.

It can be found that for different functions,  $f_1(x) - f_5(x)$ , gravitational search algorithm based on chaotic Chebyshev mapping (CGSA (C)) is better than gravitational search algorithm based on chaotic logistic mapping (CGSA (L)) and traditional gravitational search algorithm (TGSA) in both optimization speed and accuracy. It can be found that for different functions,  $f_1(x) - f_5(x)$ , CGSA (C) is better than CGSA (L) and TGSA in both optimization speed and accuracy. The mean and standard deviations after multiple optimizations are better. Take  $f_1(x)$  as an example; the mean optimized by CGSA (C) improved 3 orders in magnitude compared with that by CGSA (L), and improved 11 orders in magnitude compared with that by TGSA. Meanwhile, the convergence speed is faster than that optimized by CGSA (L) and TGSA. This is also the reason why the sequence generated by Chebyshev mapping is superior to logistic mapping in chaotic performance.

The convergence curves of traditional gravitational search algorithm (TGSA), gravitational search algorithm based on chaotic logistic mapping (CGSA (L)), and gravitational search algorithm based on chaotic Chebyshev mapping (CGSA (C)) for the above five functions are also given to compare the optimization process. As shown in Figure 3, one of the 25 running results is selected.

As can be seen from Figure 3, compared with the traditional gravitational search algorithm (TGSA), the global convergence speed of the modified gravitational search algorithm based on chaotic mapping (CGSA) is significantly improved, and the optimization performance is also significantly improved; in the modified gravitational search algorithm based on chaotic mapping (CGSA), the convergence speed and optimization performance of CGSA (C) are higher than those of CGSA (L). It shows that, in this paper, a modified gravitational search algorithm based on chaotic Chebyshev mapping can achieve better results.

## 5. Optimization of the Mixture Ratio of Coal Gangue-Based Geopolymer Concrete

In this section, the gravitational search algorithm modified by Chebyshev chaotic mapping is used to optimize the mixture ratio of coal gangue-based geopolymer concrete. Under the premise of ensuring the strength and workability of geopolymer, the economic cost is minimized and the project cost is reduced.

**5.1. Objective Functions.** The main components of coal gangue-based geopolymer concrete are coal gangue, fly ash, sodium silicate (water glass), sand, stone, water, cement,

TABLE 2: Comparison of optimized results from standard testing functions.

| Functions | Statistical data   | TGSA        | CGSA (L)    | CGSA (C)    |
|-----------|--------------------|-------------|-------------|-------------|
| $f_1(x)$  | Mean               | $3.301E-16$ | $2.452E-19$ | $2.452E-21$ |
|           | Optimal value      | $2.026E-16$ | $1.103E-19$ | $1.103E-21$ |
|           | Standard deviation | $1.411E-16$ | $2.877E-19$ | $2.877E-21$ |
| $f_2(x)$  | Mean               | 26.433      | 19.751      | 12.342      |
|           | Optimal value      | 25.302      | 8.459       | 5.221       |
|           | Standard deviation | 16.453      | 1.246       | 0.678       |
| $f_3(x)$  | Mean               | 4.427       | 2.235       | 1.055       |
|           | Optimal value      | 3.012       | 0.043       | 0.024       |
|           | Standard deviation | 1.254       | 0.848       | 0.457       |
| $f_4(x)$  | Mean               | 17.842      | 10.366      | 8.822       |
|           | Optimal value      | 13.474      | 2.478       | 1.175       |
|           | Standard deviation | 3.675       | 1.551       | 1.046       |
| $f_5(x)$  | Mean               | 5.765       | 0.137       | 0.0975      |
|           | Optimal value      | 4.038       | 0.0839      | 0.0622      |
|           | Standard deviation | 2.654       | 0.257       | 0.164       |

high-efficiency water-reducing agent, and other materials. The amount of each of the above materials is expressed as  $x_1, x_2, \dots, x_8$ , and the unit price of each materials is  $y_1, y_2, \dots, y_8$ . Then, the cost function of coal gangue-based geopolymer concrete can be expressed as

$$C = \sum_{i=1}^8 y_i x_i. \quad (20)$$

Here, the optimization objective is to minimize the cost function.

**5.2. Constraint Conditions.** The constraint conditions of the algorithm include not only the concrete performance requirements that are selected as the constraint conditions in the above flexible modeling, but also the water-binder ratio, concrete bulk density, sand rate, and the upper and lower limits of the amount of various raw materials. These limits are generally determined by experience.

- (1) The value constraint of component dosage of each material:

$$x_{\min} \leq x_i \leq x_{\max}, \quad i = 1, 2, \dots, 8, \quad (21)$$

where  $x_{\min}$  and  $x_{\max}$  are the upper and lower limits of  $x_i$ , respectively, and  $x_i$  is the amount of the above materials.

- (2) Water-binder ratio value constraints:

$$\frac{0.30 \leq x_6}{x_1 + x_2 + x_7 \leq 0.45}. \quad (22)$$

In the formula,  $x_6/(x_1 + x_2 + x_7)$  is the ratio of water to cementing materials (cement and mineral admixture).

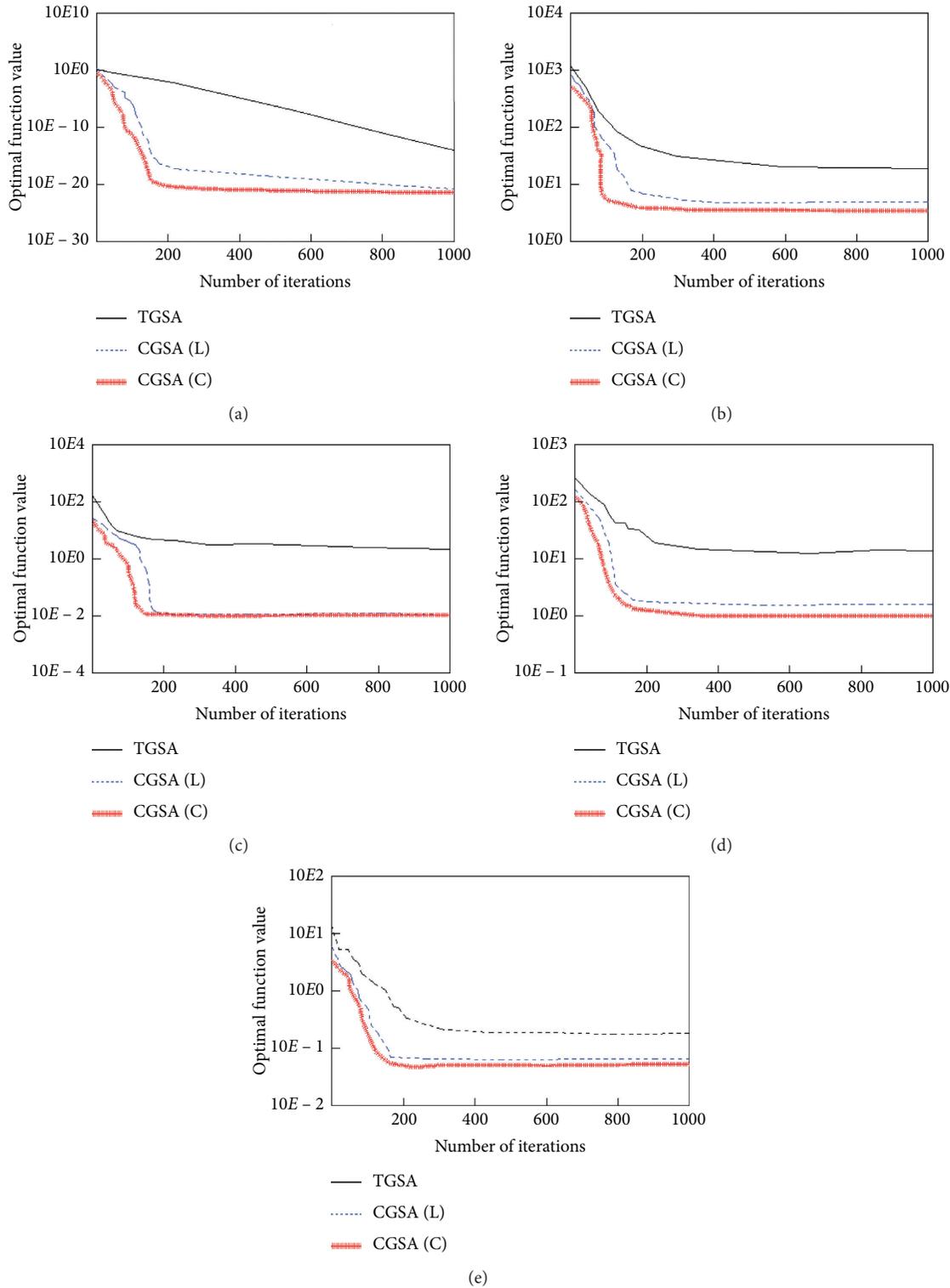


FIGURE 3: Convergence curves of different functions. (a)  $f_1(x)$  convergence curves. (b)  $f_2(x)$  convergence curves. (c)  $f_3(x)$  convergence curves. (d)  $f_4(x)$  convergence curves. (e)  $f_5(x)$  convergence curves.

(3) Sand rate value constraints:

$$0.30 \leq \frac{x_4}{x_4 + x_5} \leq 0.36. \quad (23)$$

(4) Constraints on the amount of cementitious materials:

$$350 \leq x_1 + x_2 + x_7 \leq 500. \quad (24)$$

(5) Constraints on volume of material:

$$\sum_{i=1}^8 \frac{x_i}{\rho_i} + 10\alpha - 1000 = 0, \quad (25)$$

where  $\rho_i$  is the density of each material ( $i = 1, 2, \dots, 8$ ) and  $\alpha$  is the air content of concrete, when no air-entraining agent is added,  $\alpha = 1$ .

(6) Constraints of the percentage of high-efficiency water-reducing agent in cement consumption:

$$0.008 \leq \frac{x_8}{x_9} \leq 0.014. \quad (26)$$

(7) The dosage constraint of fly ash:

$$0.3 \leq \frac{(x_1 + x_2)}{x_7} \leq 0.45. \quad (27)$$

(8) The strength value constraint of geopolymer concrete.

Here, the relationship between the water-binder ratio and the strength of concrete preparation is used, which incorporates the admixture activity index in the mix ratio design. The relationship between water-binder ratio and concrete strength can be expressed as follows:

$$A \cdot \left( -0.4952 + \frac{5.514x_6}{x_1 + x_2 + x_7} \right) \cdot \alpha_a \cdot f_{ce} \cdot \left( \frac{x_1 + x_2 + x_7}{x_6} - \alpha_b \right) - f_{cu,k} + 1.645\sigma \geq 0, \quad (28)$$

where  $A$  is the activity index of the mineral admixture;  $f_{cu,k}$  is the standard value of the cubic compressive strength of concrete;  $f_{ce}$  is the actual strength of cement;  $\sigma$  is the standard deviation of concrete strength;  $\alpha_a$  and  $\alpha_b$  represent the regression coefficient in JGJ55-2000 "Design Regulations for Mixture Ratio of Ordinary Concrete."

**5.3. Mixture Ratio Optimization of Coal Gangue-Based Geopolymer Concrete.** In this section, coal gangue-based geopolymer concrete is activated using alkaline activator agent water glass (sodium silicate). The market prices of raw materials are shown in Table 3.

Among them, ordinary Portland cement, grade 42.5, fine aggregate modulus of fineness is 2.80, and slump is 140–180 mm.

Based on the above data, traditional gravitational search algorithm, modified gravitational search algorithm based on chaotic Chebyshev mapping, and modified gravitational search algorithm based on logistic mapping were used to optimize the mixture ratio of coal gangue-based geopolymer concrete based on 28d strength. In order to compare with the optimized mixture ratio, the initial mixture ratio under different strength (referring to the strength of ordinary concrete) without optimization is given here, which is determined by the experiment. The results are shown in Table 4. The economic cost of coal gangue-based geopolymers with different strength levels before optimization is shown in Table 5.

The mixture ratio and economic cost of coal gangue-based geopolymers optimized with traditional gravitational search algorithm are listed in Tables 6 and 7, respectively. The mixture ratio and economic cost of coal gangue-based geopolymers with different strength grades optimized by modified gravitational search algorithm based on chaotic

logistic mapping are shown in Tables 8 and 9, respectively. The mixture ratio and economic cost of coal gangue-based geopolymers with different strength grades optimized by modified gravitational search algorithm based on chaotic Chebyshev mapping are shown in Tables 10 and 11, respectively.

In this paper, by analyzing Tables 6–11 and comparing with Tables 4 and 5, it can be found that, after using the traditional gravitational search algorithm and the gravitational search algorithm of different mappings proposed to optimize the mixture ratio of coal gangue-based geopolymer concrete with different strength grades, the economic cost is significantly reduced. However, the economic costs of modified gravitational search algorithm based on chaotic Chebyshev mapping and modified gravitational search algorithm based on logistic mapping are significantly lower than those of the traditional gravitational search algorithm optimization results. After analysis, compared with before optimization, the economic cost of gravitational search algorithm optimization based on chaotic Chebyshev mapping and logistic mapping has been effectively reduced, and the economic cost of coal gangue-based geopolymers with different strength grades has been saved by an average of about 17.74% and 11.65%, respectively, indicating that the gravitational search algorithm of chaotic Chebyshev mapping is better than that of Logistic mapping. And, within the experimental range, the higher the intensity level, the higher the cost savings after optimization.

The reason why gravitational search algorithm with chaotic Chebyshev mapping outperformed the one with logistic mapping lies in the fact that, compared with logistic mapping, Chebyshev mapping is more sensitive to initial values, and in terms of Lyapunov index, Lyapunov index of Chebyshev mapping is larger than that of logistic mapping.

TABLE 3: The market prices of raw materials (yuan/ton).

| Raw materials                                  | Prices (yuan/ton) | Density (kg/m <sup>3</sup> ) |
|--|-------------------|------------------------------|
| Ordinary Portland cement                       | 320               | 3100                         |
| Coal gangue                                    | 300               | —                            |
| Fly ash  | 30                | —                            |
| Polycarboxylate high performance water reducer | 4500              | —                            |
| Water glass                                    | 3200              | —                            |
| Pebble   | 350               | 2684                         |
| River sand                                     | 45                | 1589                         |

TABLE 4: Mix design of different strength grades coal gangue-based geopolymer concrete (before optimization).

| Strength grades | Cement (kg/m <sup>3</sup> ) | Fly ash (kg/m <sup>3</sup> ) | Coal gangue (kg/m <sup>3</sup> ) | Sand (kg/m <sup>3</sup> ) | Pebble (kg/m <sup>3</sup> ) | Water reducing agent (kg/m <sup>3</sup> ) | Water glass (kg/m <sup>3</sup> ) |
|-----------------|-----------------------------|------------------------------|----------------------------------|---------------------------|-----------------------------|---|----------------------------------|
| C30             | 314                         | 154                          | 486                              | 765                       | 902                         | 5.7                                       | 94.5                             |
| C35             | 330                         | 188                          | 452                              | 736                       | 865                         | 6.1                                       | 131.8                            |
| C40             | 365                         | 221                          | 435                              | 703                       | 821                         | 6.4                                       | 152.3                            |
| C45             | 402                         | 258                          | 417                              | 664                       | 785                         | 6.8                                       | 157.9                            |
| C50             | 434                         | 287                          | 383                              | 639                       | 738                         | 7.1                                       | 171.4                            |

TABLE 5: Cost of different strength grades coal gangue-based geopolymer concrete (yuan/m<sup>3</sup>) (before optimization).

| Strength grades | C30    | C35    | C40    | C45    | C50    |
|-----------------|--------|--------|--------|--------|--------|
| Economic costs  | 206.52 | 234.05 | 256.29 | 278.71 | 298.34 |

TABLE 6: Mix design optimization of different strength grades coal gangue-based geopolymer concrete based on traditional GSA.

| Strength grades | Cement (kg/m <sup>3</sup> ) | Fly ash (kg/m <sup>3</sup> ) | Coal gangue (kg/m <sup>3</sup> ) | Sand (kg/m <sup>3</sup> ) | Pebble (kg/m <sup>3</sup> ) | Water reducing agent (kg/m <sup>3</sup> ) | Water glass (kg/m <sup>3</sup> ) |
|-----------------|-----------------------------|------------------------------|----------------------------------|---------------------------|-----------------------------|---|----------------------------------|
| C30             | 287.42                      | 202.26                       | 421.46                           | 716.64                    | 858.64                      | 4.20                                      | 63.6                             |
| C35             | 298.38                      | 252.64                       | 366.72                           | 689.49                    | 812.67                      | 4.20                                      | 94.7                             |
| C40             | 321.55                      | 341.62                       | 357.86                           | 662.91                    | 810.74                      | 4.30                                      | 88.2                             |
| C45             | 385.31                      | 379.52                       | 396.53                           | 602.42                    | 686.78                      | 4.90                                      | 96.4                             |
| C50             | 402.93                      | 431.68                       | 339.71                           | 607.53                    | 665.48                      | 5.10                                      | 101.3                            |

TABLE 7: Cost of different strength grades coal gangue-based geopolymer concrete based on traditional GSA (yuan/m<sup>3</sup>).

| Strength grades | C30    | C35    | C40    | C45    | C50    |
|-----------------|--------|--------|--------|--------|--------|
| Economic costs  | 189.37 | 218.92 | 238.28 | 251.31 | 275.75 |

TABLE 8: Mix design optimization of different strength grades coal gangue-based geopolymer concrete based on logistic mapping.

| Strength grades | Cement (kg/m <sup>3</sup> ) | Fly ash (kg/m <sup>3</sup> ) | Coal gangue (kg/m <sup>3</sup> ) | Sand (kg/m <sup>3</sup> ) | Pebble (kg/m <sup>3</sup> ) | Water reducing agent (kg/m <sup>3</sup> ) | Water glass (kg/m <sup>3</sup> ) |
|-----------------|-----------------------------|------------------------------|----------------------------------|---------------------------|-----------------------------|---|----------------------------------|
| C30             | 265.32                      | 189.58                       | 412.65                           | 704.47                    | 826.21                      | 3.50                                      | 58.8                             |
| C35             | 276.43                      | 237.37                       | 346.75                           | 676.42                    | 823.67                      | 3.70                                      | 89.4                             |
| C40             | 310.21                      | 312.23                       | 353.62                           | 647.18                    | 807.55                      | 3.80                                      | 90.3                             |
| C45             | 353.73                      | 380.84                       | 347.73                           | 606.47                    | 678.66                      | 4.30                                      | 94.6                             |
| C50             | 362.26                      | 424.21                       | 314.57                           | 595.46                    | 642.35                      | 4.40                                      | 96.5                             |

TABLE 9: Cost of different strength grades coal gangue-based geopolymer concrete based on Logistic mapping optimization (yuan/m<sup>3</sup>).

| Strength grades | C30    | C35    | C40    | C45    | C50    |
|-----------------|--------|--------|--------|--------|--------|
| Economic costs  | 180.32 | 203.81 | 220.24 | 231.68 | 242.62 |

TABLE 10: Mix design optimization of different strength grades coal gangue-based geopolymer concrete based on Chebyshev mapping.

| Strength grade | Cement<br>(kg/m <sup>3</sup> ) | Fly ash<br>(kg/m <sup>3</sup> ) | Coal gangue<br>(kg/m <sup>3</sup> ) | Sand<br>(kg/m <sup>3</sup> ) | Pebble<br>(kg/m <sup>3</sup> ) | Water reducing agent<br>(kg/m <sup>3</sup> ) | Water glass<br>(kg/m <sup>3</sup> ) |
|----------------|--------------------------------|---------------------------------|-------------------------------------|------------------------------|--------------------------------|--|-------------------------------------|
| C30            | 256.61                         | 186.34                          | 408.24                              | 707.63                       | 834.31                         | 3.10   | 54.4                                |
| C35            | 264.45                         | 229.77                          | 357.08                              | 694.86                       | 818.23                         | 3.30   | 84.2                                |
| C40            | 294.65                         | 304.98                          | 334.95                              | 636.22                       | 804.35                         | 3.30   | 86.6                                |
| C45            | 334.46                         | 363.78                          | 352.38                              | 597.60                       | 698.65                         | 3.80   | 91.3                                |
| C50            | 348.50                         | 407.66                          | 310.56                              | 578.30                       | 654.68                         | 4.20   | 94.9                                |

TABLE 11: Economic cost optimization of different strength grades coal gangue-based geopolymer concrete based on Chebyshev mapping optimization (yuan/m<sup>3</sup>).

| Strength grades | C30    | C35    | C40    | C45    | C50    |
|-----------------|--------|--------|--------|--------|--------|
| Economic costs  | 176.49 | 195.53 | 214.47 | 225.40 | 234.79 |

It shows that, for chaotic extent, Chebyshev mapping is better than logistic mapping. In addition, Chebyshev mapping has sharper peak value and zero autocorrelation sidelobe, and its cross-correlation function curve has similar stochastic noise flatness and sound correlation characteristics; it suggests that spread spectrum sequences produced by Chebyshev mapping have better strong anti-interference ability.

## 6. Conclusions

Under the premise of ensuring the strength and workability of geopolymers, from the perspective of reducing the cost of geopolymers, this paper uses chaotic mapping to modify the intelligent optimization algorithm-gravity search method and derives the revised gravitational search algorithm. The research has the following findings:

- (1) Based on the practical application of the engineering, in response to the call of maximizing the utilization of resources advocated by the state, the gravitational search algorithm of chaotic Chebyshev mapping and logistic mapping is used to optimize the mixture ratio of coal gangue-based geopolymer concrete, which not only saves the engineering cost, but also makes the coal gangue-based geopolymer concrete processing technology more mature, making full use of the potential resources of coal gangue.
- (2) It is found that, after using the modified gravitational search algorithm based on chaotic mapping to optimize the mixture ratio of coal gangue-based geopolymers concrete with different strength levels, the economic cost was significantly reduced, and the optimization result of chaotic Chebyshev mapping was better than logistic mapping. Within the experimental range, the higher the intensity level, the higher the cost savings after optimization.
- (3) The optimized mixture ratio of coal gangue-based geopolymer concrete with different strength grades is obtained by using the modified gravitational search method, economic costs decreased significantly. After analysis, economic costs of gravitational

search algorithm optimized based on chaotic Chebyshev mapping and logistic mapping are effectively; the economic costs of coal gangue-based geopolymers concrete with different strength grades are saved by about 17.74% and 11.65%, respectively. And in the experimental range, the higher the strength grade, the higher the cost savings after optimization.

- (4) The modified gravitational search algorithm improves the optimization speed and saves a lot of time, which provides an efficient and reliable research method for the optimization of mixture ratio and economic cost saving of similar geopolymers concrete.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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