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Mechanical Characteristics of Heishan Bentonite for Hazardous Waste Contamination Prevention

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A series of laboratory-based water infiltration tests at room temperature have been conducted to investigate the mechanical characteristics of Heishan bentonite as a potential backfill material. The experiments were performed with an oedometer testing apparatus which facilitates the mechanical loading, the water infiltration, and the deformation measurement. The results show that both swelling pressure-initial dry density and swelling strain-moisture content have an exponential relationship. Moreover, swelling strain dramatically decreases when the applied stress exceeds a reference stress of 100 kpa. Finally, permeability tests were carried on Heishan bentonite specimen and the studied material reaches an impermeable state when the moisture content is larger than 40%. The presented properties certificate that Heishan bentonite can be employed as a backfill material in engineering practice.

Keywords: soil mechanics, heishan bentonite, mechanical behavior, hazardous waste contamination prevention, analytical modeling

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INTRODUCTION

Bentonite has been widely considered as backfill materials in the underground storage of high-level nuclear waste in many countries, because of its low hydraulic conductivity and high swelling capacity (Kanno and Wakamatsu, 1992; Chapman 2006; Chen et al., 2014). In many repository concepts, the backfill material is pre-compacted to a relatively dense state and it is installed in the vicinity of waste canisters (Martin et al., 2006; Romero et al., 2011; Jobmann et al., 2017). The initially unsaturated bentonite can absorb the surrounding fluids to retard the radioactive liquid waste from being transported to the underground water system, and the high swelling capacity imposes sufficient swelling pressure to the adjacent restraints. Therefore, it is critically important to evaluate the swelling behavior of compacted bentonite for the long-term stability of the underground high-level nuclear waste disposal repositories.

In this regard, numerous studies have been carried out to investigate the swelling properties for different types of bentonites (Lloret et al., 2003; Cui et al., 2011; Tang et al., 2011; Wang et al., 2012; Sun et al., 2013; Cui and Si 2014; Ye et al., 2014; Zhang et al., 2021). For example, Komine and Ogata (2003), Komine and Ogata (2004) performed a series of laboratory swelling tests and introduced new equations to quantify the swelling behavior of bentonite for the bentonite/sand mixture. Tanaka and Nakamura investigated the impacts of seawater and temperature on the swelling response of bentonite (Tanaka and Nakamura, 2005). In recent years, many works have been performed on the swelling properties of bentonite using salty water. These researches show that the compacted bentonite is an ideal backfill material in the deep disposal, especially Calcigel in Germany and Kunigel in Japan.

TABLE 1 | Geotechnical properties of bentonite tested.

Property	Value
Specific gravity	2.5
Plastic limit (%)	48.83
Liquid limit (%)	960
PH	8.5
Total specific surface area (m^2/g)	584
Free swelling ratio (%)	528.7
Montmorillonite content (%)	81.6
Cristobalite content (%)	17.4

In China, Gaomiaozi bentonite has been accepted as backfill materials in the deep disposal of high-level radioactive waste. This bentonite is extracted from an open deposit in Gaomiaozi, Inner Mongolia autonomous region, northern China. Regarding Gaomiaozi bentonite, many researches have been conducted using oedometer tests and mockup tests. Xie et al. (2006) performed constant volume tests to study the swelling behavior and the influential factors on swelling behavior. Zhang et al. (2016) studied the swelling characteristics and compared two types of GMZ bentonites. Zhao et al. (2017) investigated the mechanical behavior on wetting-drying cycles and proposed a model based on the concept of the critical swelling-shrinkage state. Recently, Sun et al. (2020) have focused on the swelling characteristics with alkaline chemical conditions to simulate the long-term environment of Chinese repository. Great effort and progress have been made in studying the swelling behavior of different types of bentonites to better understand their mechanical behavior and optimize their engineering applications for nuclear waste disposal.

Engineering uses and industrial demands of bentonites give continued impetus to the study of these materials and a variety of bentonites should be investigated to improve the comprehension of their mechanical properties to better serve the practical engineering. On the basis of geological survey, Heishan bentonite turns out to be the most attractive competitor as a backfill material, because of its large reserves and prominent properties. In the present work, a series of oedomenter tests on Heishan bentonite have been performed for the first time to investigate the swelling behavior as a possible backfill material.

MATERIAL

The studied bentonite in this work is mined from Heishan County in Liaoning province, 600 km northeast from Beijing, China. The Heishan bentonite is a gray powder and its main composition is montmorillonite approximately 81.6%. As a calcium-based bentonite, it has a plastic limit 48.83%, liquid limit of 960% and specific gravity of 2.5. **Table 1** summarizes the basic physical properties of the studied material. Prior to preparing the bentonite samples, the studied material is processed through 74 μm sieve, oven-dried for 24 h and stored in a large airtight container for future use in laboratory testing. The bentonites are molded into specimens of 10 mm height and 61.8 mm in diameter under different statically compacted loads and these samples have dry densities of 0.983, 1.081, 1.177, and 1.278 g/cm^3, respectively. A series of tests have been performed on these initial states to investigate the swelling behavior of Heishan bentonite.

METHODS

The oedometer testing apparatus is used in this research and it is illustrated in **Figure 1**. As the main part of the testing device, the oedometer cell consists of three parts, i.e., the mechanical part to apply the vertical loadings (No.5 in **Figure 1**), the infiltration part to allow water moving during wetting paths (No. 1, No. 4, and No. 9) and the monitoring part to measure the vertical deformation during tests (No. 6). In the process of testing, the cutting ring (No. 3) containing the bentonite sample (No. 8) is working with other parts of the oedometer testing apparatus (No. 7) and a series of one-dimensional tests (No. 2) are carried out under various vertical stresses. During the hydration of bentonite samples, the vertical deformation is recorded by the dial gauge for every 2 h. Once the difference of two successive values is small enough (0.01 mm), the current step is completed and water to be added in water carrier continues the following step. **Figure 2** is a summary of varied experimental paths to investigate the hydromechanical behavior of Heishan bentonite.

In this study, the amount of adding water provided by the Standard for geotechnical testing method (GB/T50123-2019) is adopted,

$$\Delta m_w = 0.01 \cdot \rho_d V \cdot \Delta w \tag{1}$$

where, Δm_w is the amount of adding water (g), ρ_d is the initial dry density (g/cm^3), V is the volume of the cutting ring (cm^3) and Δw is the difference between the target moisture content and the initial moisture content of dry soil specimen.

The moisture content of soil specimen is employed to represent hydraulic property and it is defined by,

$$\theta = m_w / m_s \times 100\% \tag{2}$$

where, θ is the moisture content, m_w is the mass of water and m_s is the mass of dry soil.

Swelling Pressure-Dry Density Plot

Swelling pressure is defined as the pressure required to compress the expansive clays back to its original configuration when the specimen is completely soaked. As a backfill material, the swelling pressure is of particular interest because it basically controls sealing properties. The constant-volume swelling pressure experiments have been performed to measure the swelling pressure. In these tests, the impact of initial dry density has been taken into account on the swelling pressure of the studied material.

Figure 3 is aimed at relating the swelling characteristics with the initial dry density of Heishan bentonite. To study the influence of absorbed water on the swelling behavior, the

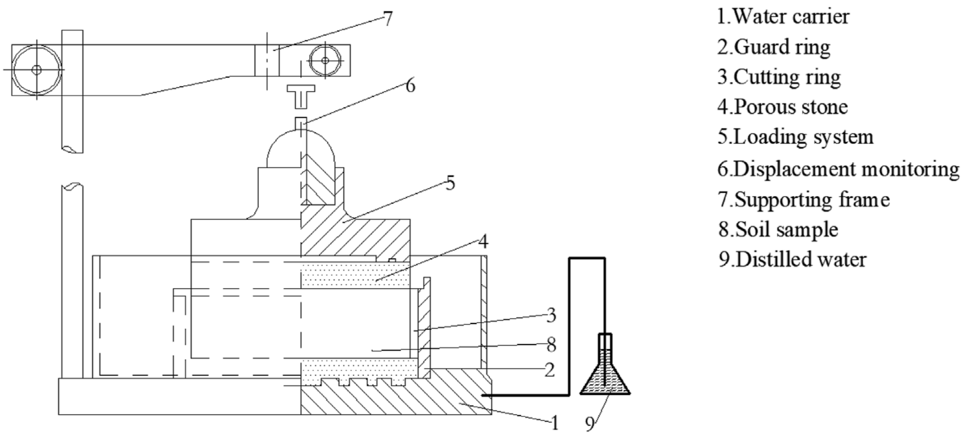

FIGURE 1 | Schematic view of one-dimensional oedometer device.

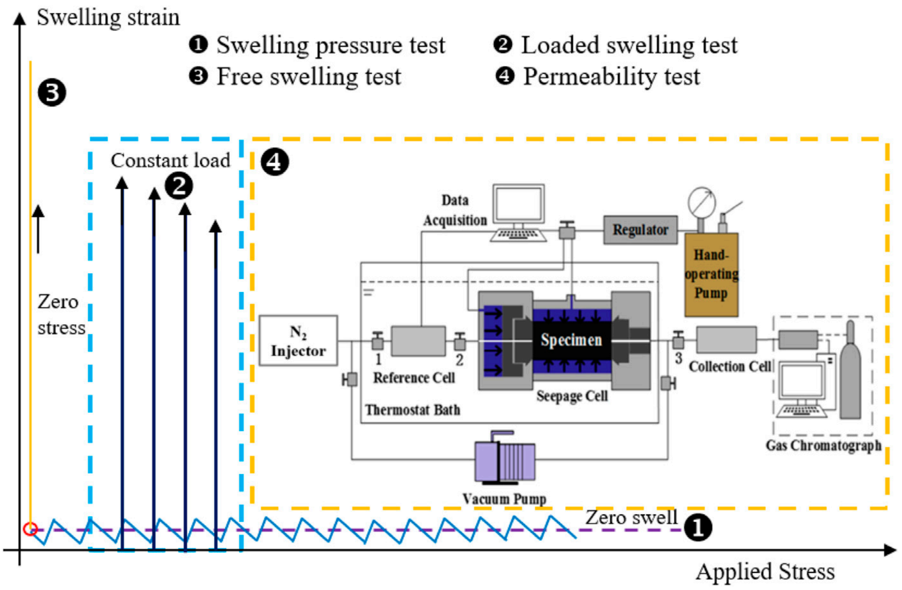

FIGURE 2 | Stress path of various experimental methods.

relationship between the swelling pressure and the water absorption is presented in **Figure 3**. Based on the plotted relationship between different dry density and swelling pressure, the swelling pressure increases exponentially as the initial dry density increases and the amount of absorbed water also amplifies the swelling pressure. Apart from attributing material swelling to the mineral phases, the pore water is exclusively attached to the swelling behavior of studied bentonite. Therefore, the initial dry density and the water absorption are key factors to affect the swelling behavior of Heishan bentonite.

As a result, the swelling pressure at different dry densities for Heishan bentonite can be calculated by the following empirical formula,

$$P_e = a \cdot \exp\left(b \cdot \rho_d\right) \tag{3}$$

where, P_e is the swelling pressure (kPa), ρ_d is initial dry density (g/cm^3), a and b are model constants presented in **Figure 3**.

Swelling Strain-Elapsed Time Plot

To determine the swelling characteristics of Heishan bentonite under the condition of different loadings, swelling strain is employed in this work and it is defined as follows:

$$\varepsilon_{\mathrm{exp}} = \frac{Z_1 - Z_2}{h_0} \times 100\% \tag{4}$$

where $\varepsilon_{\mathrm{exp}}$ is the swelling strain, Z_1 is the deformation of the specimen at the current loading stage, Z_2 is the deformation at the

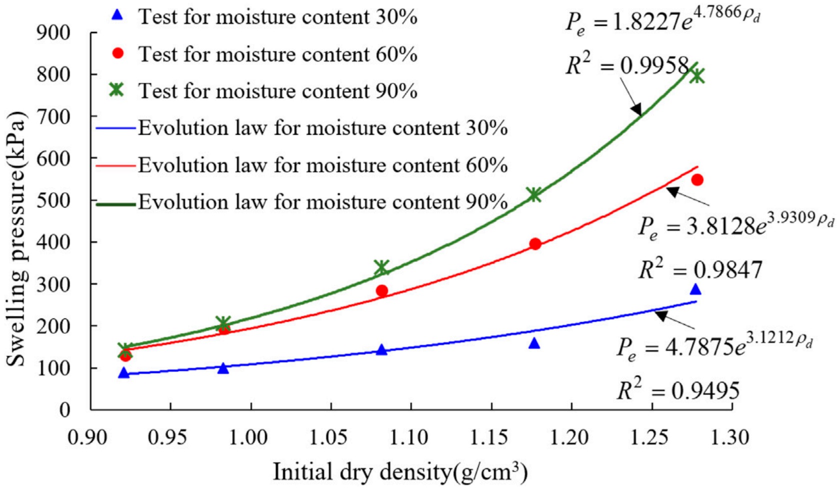

FIGURE 3 | Relationship between swelling pressure and initial dry density for different moisture contents.

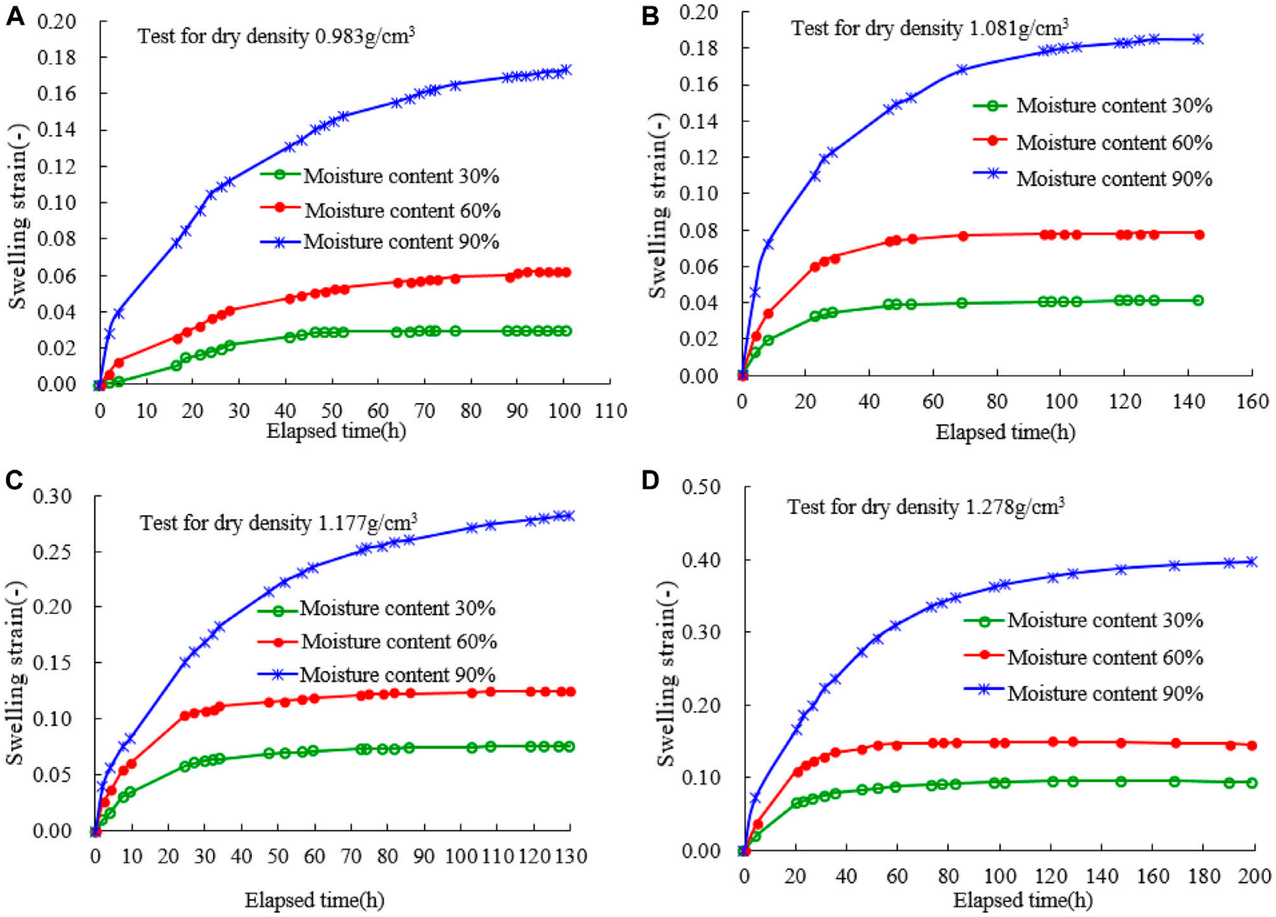

FIGURE 4 | Variation of swelling behavior with initial dry density at the constant applied stress of 50 kPa.

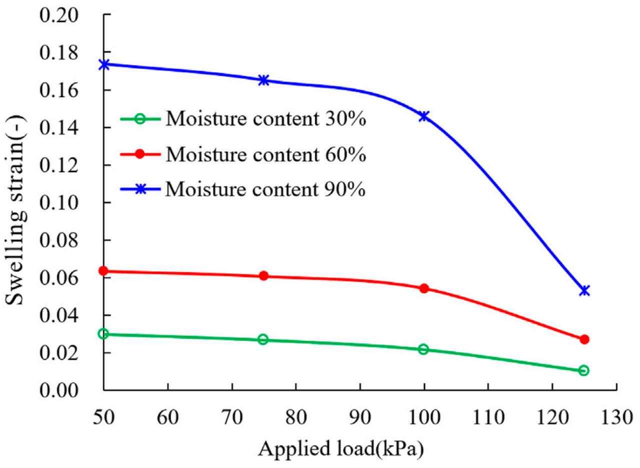

FIGURE 5 | Variation of swelling behavior with vertical stress at the constant initial dry density of 0.983 g/cm^3.

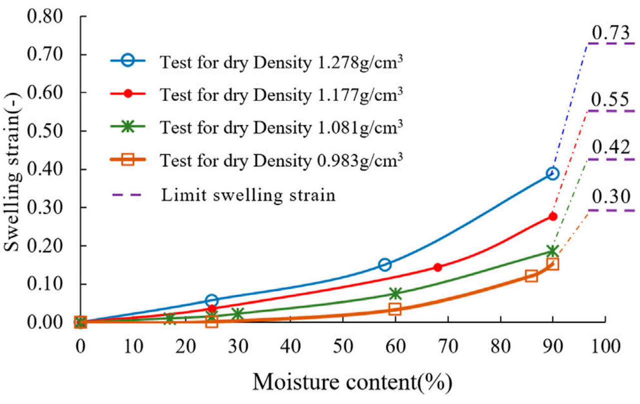

FIGURE 6 | Variation of swelling behavior with moisture content at the constant applied stress of 50 kPa.

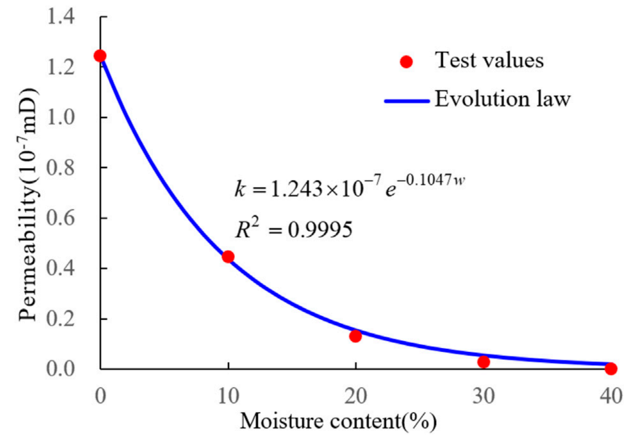

FIGURE 7 | Relationship between permeability and moisture content.

beginning of the current loading stage, and h_0 is the initial height of the specimen.

Constant applied stress and varied initial dry density. The mobilization of swelling strain with passage of time is illustrated in **Figure 4** for the studied material. Taking test results at the constant applied stress of 50 kPa for instance, the curves demonstrate a distinct change in both the shapes of curves and the mobilized swelling strain for different moisture contents. For various initial dry densities (0.983, 1.081, 1.177, and 1.278 g/cm^3), the increase of swelling strain is rapid at the earlier stage of tests and the curve of swelling strain tends progressively flatter with the elapsed time.

Constant dry density and varied vertical stress. To study the impact of applied stress on the swelling behavior of Heishan bentonite, typical tests of swelling behavior with different vertical stresses are carried out. **Figure 5** plots the curves of swelling strain with the elapsed time under different vertical stresses of 50, 75, 100, and 125 kPa. For the initial dry density of 0.983 g/cm^3, it is obvious that the swelling strain decreases with the increase of vertical stress. When the vertical stress in inferior to a reference stress p_c, swelling strain varies relatively small. However, the swelling strain has a dramatic reduction as the vertical stress exceeds p_c value and it indicates the bentonite expansion occurs in micro-structural level leading to a dense state of the studied sample.

Swelling Strain-Moisture Content Plot

The amount of adding water is calculated according to **Eq. 1** and the wetting path under a constant vertical stress of 50kpa is performed on the studied material. **Figure 6** experimentally demonstrates the relationship between the moisture content and the swelling behavior of Heishan bentonite. In this plot, the swelling strains of several moisture contents have been tested and the swelling strain exponentially increases with the moisture content. To investigate the maximum swelling strain of each initial dry density, the soil specimen is wetted until it cannot absorb water and the limit swelling strain is portrayed in **Figure 6**. For different initial dry densities in this work, the limit swelling strain of Heishan bentonite varies from 0.3 to 0.73.

Permeability-Moisture Content Plot

As a potential backfill material, low permeability is required to evaluate the sealing efficiency of the bentonite barrier. To study this property, the experimental testing system based on Darcy's law is developed and it mainly consists of a N_2 injector, a reference cell, a seepage cell, and a collection cell as shown in **Figure 2**. The soil specimen is firstly vacuumed and the confining pressure is imposed on the specimen. N_2 is injected into the reference cell under pressure and the seepage test starts when the pressure in reference cell is stable. The collection cell is employed to measure the flow rate of injected gas and the permeability is defined by

$$k = \frac{2\cdot\mu\cdot p_2\cdot L\cdot Q}{\left(p_1^2 - p_2^2\right)\cdot A} \tag{5}$$

where, p_1 and p_2 are the upstream and downstream pressure, A is the cross-sectional area, μ is the viscosity of N_2, L is the length of the specimen and Q is the flow rate.

Figure 7 describes the relationship between soil permeability and moisture content and an empirical expression is proposed to simulate the fore-mentioned relationship,

$$k = k_0 \cdot \exp(-\lambda \cdot \theta) \tag{6}$$

where, k_0 is the permeability of soil specimen at the dry state (mD), θ is the moisture content and λ is a constant.

In **Figure 7** we can find that the soil permeability is exponential reduction with the moisture content increasing. When the moisture content reaches 40%, the permeability of bentonite barrier is so dense that no gas can be collected in collection cell. This suggests that Heishan bentonite has a relatively low permeability under an enough pressure and a proper moisture content.

CONCLUSION

A series of swelling pressure tests, loaded swelling tests, free swelling tests and permeability tests have been conducted on Heishan bentonites and the experimental results allow the following conclusion to be drawn.

1) swelling pressure-initial dry density relationship.

The swelling pressure of the studied material exponentially increases with the initial dry densities rising, and this value is greatly influenced by the amount of absorbed water during wetting. The proposed empirical formula is able to estimate the swelling pressure because of the small fitting tolerance.

2) Swelling strain-elapsed time relationship.

Under the condition of constant applied stress and varied initial dry density, swelling strain increases rapidly at the earlier stage of tests and then it tends progressively flatter with the elapsed time. The higher moisture content, the larger is the swelling strain. In case of constant initial dry density and varied vertical stress, swelling strain reduces significantly when the vertical stress exceeds the reference stress and it can be explained that the bentonite expansion occurs in micro-structural level under a relatively large vertical stress.

3) Swelling strain-moisture content relationship.

The swelling strain increases with the moisture content mounting and its relationship abides by an exponential law. The limit swelling strain is investigated when the soil sample cannot absorb more water and this value varies from 0.3 to 0.73 for different initial dry densities.

4) Permeability-moisture content relationship.

The bentonite permeability is exponential reduction with the increase of moisture content and the soil specimen becomes impermeable when the moisture content is larger than 40%. This suggests that Heishan bentonite has a relatively low permeability and Heishan bentonite can be employed as a backfill material in the future.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

J-HX contributed to conception and design of the study. KL wrote the whole draft of the manuscript and carried out statistical analysis. K-MS and S-CZ performed the experimental tests. All authors contributed to the submitted manuscript.

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Conflict of Interest: Author J-HX is employed by POWERCHINA Huadong Engineering Corporation Limited and Zhejiang Huadong Engineering Consulting Corporation Limited.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.