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ORIGINAL PAPER

IMPROVEMENT OF EXPANSIVE SOIL BY MICROWAVE IRRADIATION

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ABSTRACT

This paper presents an experimental investigation of the use of microwave irradiation to improve the characteristics of expansive soils. The expansive soil samples were subjected to microwave heating in an industrial microwave oven, and were followed by analysis of the soil characteristics such as the specific gravity, liquid and plastic limit, free swelling ratio, vertical free swelling strain and swelling pressure. X-ray diffraction was also used to determine the mineral composition of the samples. Experimental results showed that the microwave irradiation induces both a rapid increase in the soil temperature and a significant change in the soil mineral content. With the increase in the power level, we observed first an increase in the specific gravity up to a peak, which was followed by a decrease. For the other characteristics such as the liquid and plastic limit, the free swelling ratio, the vertical free swelling strain and the swelling pressure, their values were observed a decrease with the increase in the power level. The change in the soils characteristics could be attributed to the impact of the irradiation on the expulsion of the interlayer structure water and on the change of soil mineral content or structure.

1. INTRODUCTION

Temperature has an important influence on the physical and mechanical properties of soils (Abu-Zreig et al., 2001; Fonseca and Nadimi, 2016). For example, the increase in temperature has a significant impact on soil color, pH value, and water stable aggregates (Terefe et al., 2008). The volume, dry density, saturation, morphology is also changed as the saturated clay soil was exposed to higher temperatures (Chen et al., 2016). In recent years, heat treatment has also been applied as an effective method to improve soil engineering properties (Sun et al., 2016; Liu et al., 2019; Perusomula and Krishnaiah, 2022). However, the traditional heating method suffers from low efficiency and large energy consumption. The application of heating methods to improve soil engineering properties on a large scale has been limited.

With the rapid development of microwave heating technology, many scholars have found that the use of microwave irradiation for material heating provides some advantages, in particular high efficiency and uniform heating process. Thus, microwave heating has shown powerful application advantages in different fields such as mineral processing, solid waste utilization, wastewater treatment (Haque, 1999; Cheng et al., 2021; Wu et al., 2024). The effect of microwave radiation on soil improvement has also been gradually recognized and explored. Hu et al. (2019) found that the microwave heating can improve the mechanical strength and water stability of the weak interlayer of slope. Zhang et al. (2016) showed that the soils contaminated with simulated radionuclide can be successfully vitrified by microwave sintering method.

Expansive soils are worldwide distributed (Thapa et al., 2022). Generally, they are rich in montmorillonite and other strong hydrophilic minerals. Changes in soil moisture conditions can lead to significant changes in its volume change (Abbas et al., 2022), which could cause damages for foundations, slopes, tunnels, etc. (Liu et al., 2022; Mohammad et al., 2022; Sarker and Wang, 2022). Scholars proposed different methods to reduce the expansion potential of these soils such as by adding cement, lime, fly ash and other materials into the soil to improve (Nalbantoğlu, 2004; Seco et al., 2011; Al-Taie et al., 2020; Barman and Dash, 2022; Sahoo and Singh, 2022; Soltani et al., 2022). However, the use of these methods requires additional materials.

It is worth mentioning that some studies have shown that high temperature can reduce the expansion potential of soils (Wang et al., 2008; Estabragh et al., 2016). Microwave irradiation is a fast-heating method,

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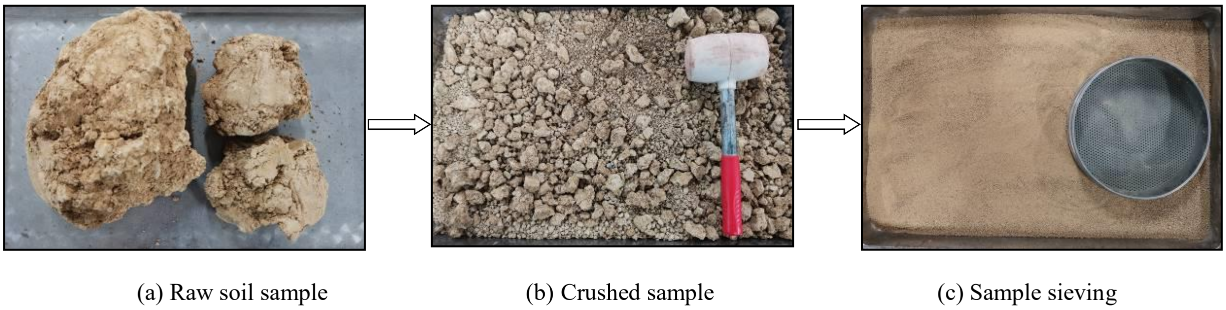

Fig. 1 Pretreatment of soil sample.

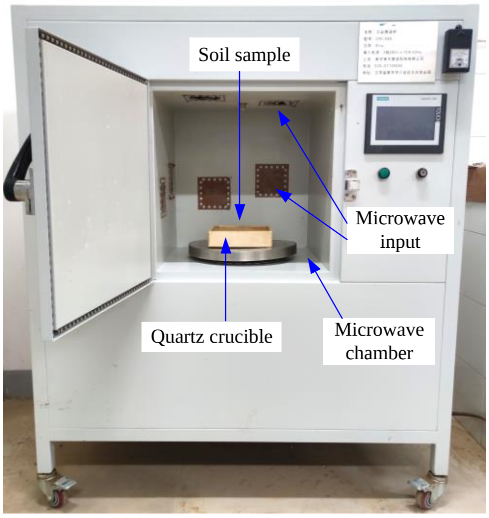

Fig. 2 Microwave oven.

and it is particularly important that the preliminary laboratory test showed that microwave irradiation could be used to treat expansive soil (Yao et al., 2022). But the previous study was limited to the investigation of the influence of the irradiation time on the soil improvement. This paper investigates a new issue of the impact of the microwave irradiation, which is related to the influence of the microwave power level on the properties of the expansive soils. This study will help to select the optimal treatment process to reduce the expansion potential of these soils.

2. MATERIALS AND METHODS

2.1. SAMPLE PREPARATION

The soil samples were collected from an expansive soil layer in a subway station in Hefei. In the laboratory, the raw soil sample was crushed. Coarse particles were removed with a 2 mm sieve (as shown in Fig. 1), then dried at 105 ℃ to constant weight and cooled to the room temperature.

2.2. LABORATORY TESTING PROGRAM

The CM-06S multi-mode industrial microwave oven with a microwave frequency of 2.45 GHz and an adjustable power of 0 ~ 6 kW was used for heating the soil samples. It includes microwave cavity, microwave generator and control system (as shown in Fig. 2). In each microwave irradiation test, a kilogram of soil sample was placed in the microwave oven and heated during 10 minutes under different power conditions (2 kW, 4 kW and 6 kW). The temperature of the soil samples was measured by a handheld infrared thermometer.

After the heating and cooling process, tests were conducted for the determination of the soil of specific gravity, liquid and plastic limit, free expansion ratio and vertical free swelling strain.

The free swell index measures as the augmentation of the soil volume unescorted by extraneous hampering when submerged in water. It is determined as follows:

$$\delta_{ef} = \frac{V - V_0}{V_0} \times 100 \quad (1)$$

δ_{ef} is the free swelling index, V is swelled volume of soil sample after it comes to rest at the bottom of measuring cylinder, V_0 is the free accumulation volume of dry soil.

The vertical free swelling strain tests were performed on the compacted specimens at a dry density of 1.65 g/cm^3 and initial moisture content of 20 %. The prepared specimen with 58 mm in diameter and 20 mm in height, was placed into a rigid mould with an open face at the top, and was then submerged

(a) Raw soil (b) 2 kW (c) 4 kW (d) 6 kW

Fig. 3 Soil sample before and after 10 minutes microwave irradiation (a) Raw soil, (b) 2 kW, (c) 4 kW, (d) 6 kW.

in water. The swelling deformation of the specimen was recorded by a dial indicator until the deformation reached a stable state. It is determined as follows:

$$\varepsilon = \frac{\Delta H}{H_0} \times 100 \quad (2)$$

Where, ε is the vertical free swelling strain, $\triangle H$ is the current swelling deformation (mm), and H_0 is the initial height (mm) of the specimen.

The swelling pressure designates the pressure that prevents a soil sample from expansion. Zero swell tests were conducted on the compacted specimens with the dry density of 1.65 g/cm^3 and initial moisture content of 20 % to evaluate the effect of the microwave irradiation on the soil swelling pressure. A specimen with 61.8 mm in diameter and 20 mm in height was placed in the standard consolidation cell and water was added. The soil expansion due to soaking was prevented by applying small convenient load increments. The swelling pressure was defined as the final load divided by the cross-section of the specimen.

3. RESULTS AND ANALYSIS

3.1. MINERAL CONTENT

A ten minutes microwave treatment of the soil samples using 2 kW, 4 kW and 6 kW showed that the surface temperature of the samples reached 268 ℃, 470 ℃ and 950 ℃ respectively. Figure 3 shows the influence of the microwave power on the morphology of soil samples. The raw soil sample is yellowish brown. With the increase in the microwave power, the soil sample gradually becomes dark and brick red. This change results from the impact of the microwave irradiation on the physical and chemical properties of soils, such as the oxidation of iron minerals to form hematite (Fe_2O_3) (Han et al., 2017; Geng and Sun, 2018).

At the same time, we can also see that some particles in the soil sample have become coarser especially when heated at 6 kW for 10 minutes (as shown in Figure 3(d)), which is mainly due to the sintering of some fine particles at high temperature (Inna et al., 2022). That is, with the increase of temperature, along with the evaporation of crystal water in clay minerals and the destruction of layered structures, new mineral phases are formed. When the temperature is higher (over 900 °C), the fusible component in the clay begin to melt and the vitreous liquid phase appears to bind the non-fusible particles together (Yao et al., 2022).

The mineral content of soil samples before and after microwave irradiation was analyzed by X-ray diffraction (XRD). Figure 4 shows the XRD diffraction patterns of the soil samples. The results are summarized in Table 1. It can be seen that the mineral components of the soil sample mainly include montmorillonite, illite, quartz, feldspar, hematite, etc. With the increase in the microwave power, we observe a decrease trend in the content of montmorillonite and quartz, while an increasing trend in the content of illite, feldspar and hematite. Experimental results indicate that high temperature induced physical and chemical changes in the soil samples such as oxidative decomposition of some minerals.

Table 1 Main mineral content of soil samples after microwave irradiation / %.

Microwave power	Samples No.	Mineral content				
		Montmorillonite	Illite	Quartz	Feldspar	Hematite
0kW	Sample 1	29.2	22.5	23.5	18.9	5.9
	Sample 2	33.1	26.3	17.3	19.5	3.8
2kW	Sample 1	27.6	32.6	19.6	15.6	4.6
	Sample 2	28.1	31.6	16.8	16.7	6.8
4kW	Sample 1	26.8	31.2	17.4	17.7	6.9
	Sample 2	24.8	30.6	19.8	16.9	7.9
6kW	Sample 1	21.3	32.4	17.2	20.2	8.9
	Sample 2	21.7	33.5	15.4	21.3	8.1

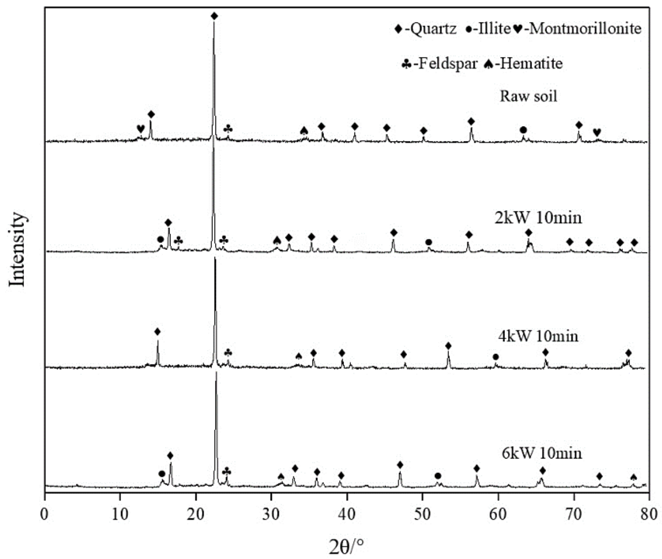

Fig. 4 Influence of the microwave power on the XRD patterns of soil samples.

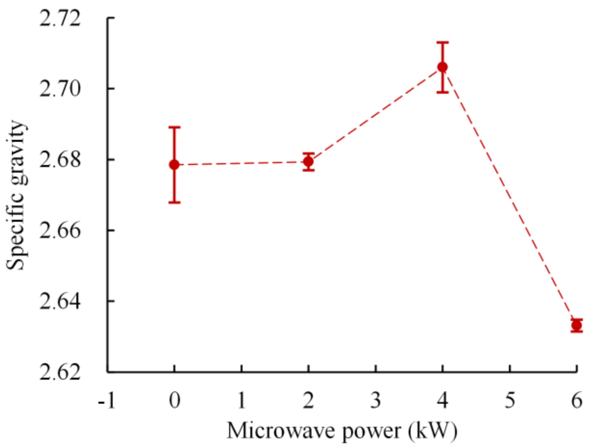

Fig. 5 Influence of the microwave power on the specific gravity.

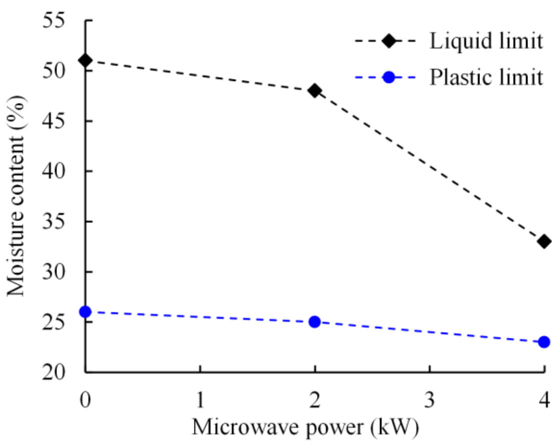

Fig. 6 Influence of the microwave power on the liquid and plastic limits.

3.2. SPECIFIC GRAVITY

The specific gravities of the samples after irradiation for 10 minutes are shown in Figure 5. The average specific gravity of the raw soil sample is 2.678. It increased to 2.679 and 2.706, respectively after irradiation at 2 and 4 kW, and then decreases to 2.634 at 6 kW. In the initial stage, due to the low microwave power the soil sample temperature is relatively low (268 ℃), and the specific gravity has hardly increased. The sample temperature reached 470 ℃ under the microwave power at 4 kW. As the temperature increases, the adsorbed water in the soil particles evaporated and the bound water escaped, resulting in a significant increase in the specific gravity of the soil sample. During the test with the microwave power 6 kW, the soil sample temperature raised rapidly to 950 ℃. During this process, changes in some mineral components led to a decrease in specific gravity. As mentioned above, during the sintering process at high temperatures, some clay particles may melt, resulting in the formation of components with low specific gravity.

3.3. LIQUID AND PLASTIC LIMIT

The liquid and plastic limits of soil samples are shown in Figure 6. It can be seen that the liquid and plastic limit of soil samples have decreased after microwave irradiation at 2 kW and 4 kW, especially the liquid limit. After the microwave power reaches 6 kW, the soil samples have the characteristics of cohesionless coarse grained soil (as shown in Fig. 4), and it is impossible to measure the liquid and plastic limit. This is mainly because some clay minerals are sintered under microwave irradiation. Microwave sintering has proved to be an efficient method for soil treatment (Zhang et al., 2016). The above results show that the temperature of the soil sample reaches 950 ℃ after 6 kW irradiation, which is high enough to cause a series of significant changes in the soil sample.

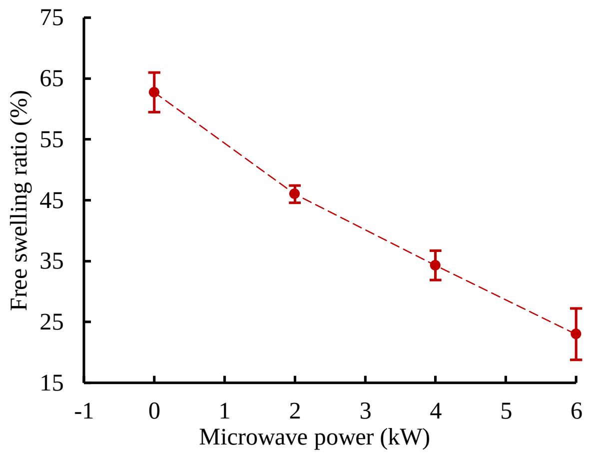

Fig. 7 Influence of the microwave power on the samples' free swelling ratio.

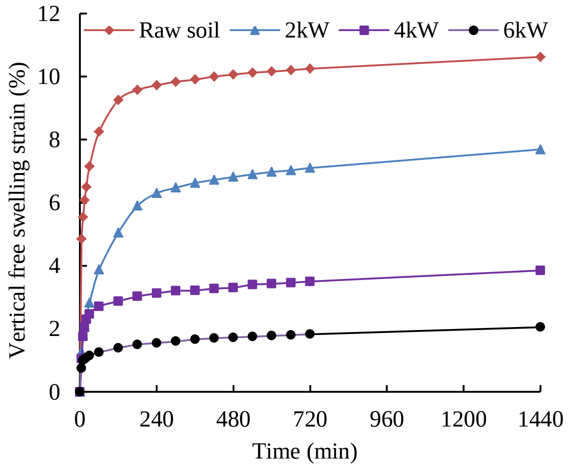

Fig. 8 Vertical free swelling tests on samples subjected to different microwave power.

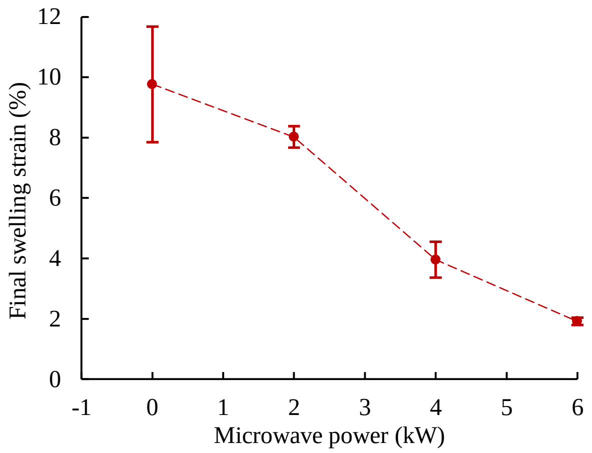

Fig. 9 Influence of the microwave power on the final free swelling.

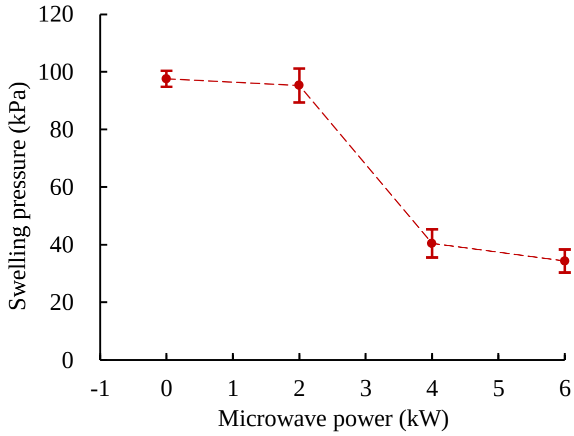

Fig. 10 Influence of the microwave power on the swelling pressure.

3.4. FREE SWELLING RATIO

The free expansion ratio of soil sample is shown in Figure 7. It can be seen that the free swelling ratio of the initial soil sample is about 62.7 %, which indicates a medium expansive soil. After irradiation for 10 minutes at 2 kW, 4 kW and 6 kW, the average free swelling ratios of the soil samples decreased to 46.0 %, 34.3 % and 23.0 %, respectively. This indicates that microwave heating can significantly reduce the free swelling ratio of expansive soil in a short period of time, and as the microwave power increases, the free swelling ratio decreases.

3.5. VERTICAL FREE SWELLING STRAIN

Figure 8 shows the results of vertical free swelling tests. It can be seen that the swelling process has basically the same trend: a rapid free swelling, which is followed by a moderate swelling. However, the microwave power has an important influence on the amount of the free swelling. The swelling deformation of the raw soil sample increases rapidly within 60 minutes, then increases slowly, and only slightly after 240 minutes. The time for the rapid swelling of soils sample subjected to microwave irradiation decreased with the increase in the power level. For example, the swelling deformation of soil sample treated at 6 kW power increased rapidly within 10 minutes, and only a slight increase followed.

The final vertical swelling strain of soil samples immersed for 24 h decreased with the increase in the microwave power as shown in Figure 9. Under irradiation at 2 kW, 4 kW and 6 kW, the soil final swelling strain decreased by 27.6 %, 63.8 % and 80.7 %, respectively. Overall, the trend of final swelling strain changing with microwave power is similar to the trend of free swelling ratio.

3.6. SWELLING PRESSURE

Figure 10 shows the variation of soil swelling pressure with microwave power. The swelling pressure of the specimens decreases with the increase in the microwave power. The treatment at 2 kW has a small impact on the soil swelling pressure, while the treatment power of 4 and 6 kW reduced the soil swelling pressure by about 59 % and 65 %, respectively. The decreasing trend of swelling pressure with microwave power is consistent with the law of swelling deformation mentioned above.

4. DISCUSSION

The swelling characteristics of expansive soil when encountering water mainly lie in the presence of a large amount of hydrophilic clay minerals such as montmorillonite, which have the high capacities of water-absorbing swelling and water-loss shrinking (Abbas et al., 2022). In the sample composition of this study, it can be seen that the proportion of montmorillonite exceeds 20 %, which is a typical expansive soil. The main reasons for the changes in the properties of soil samples after microwave radiation are two aspects: water loss and changes in mineral composition during the heating process.

The experimental results indicate that microwave irradiation can cause an increase in soil temperature. Under the same irradiation time, the temperature of soil samples increases with the increase of microwave power. In the low-temperature stage, the changes in soil samples are mainly related to water loss, but their composition and particle structure do not change obviously. When encountering water again, the soil sample still exhibits significant swelling characteristics. Some studies showed that montmorillonite loses interlayer bound water between 100 ℃ and 200 ℃, while illite removes adsorbed water and interlayer water before 300 ℃ (Mohammad et al., 2022; Inna et al., 2022). In this experiment, the temperature of the soil sample heated at a power of 2 kW for 10 minutes was only 268 ℃. Under this temperature, the adsorbed water in the soil sample evaporates, and interlayer bound water also escapes. There are no significant changes in composition and particle structure, therefore the specific gravity, liquid plastic limit, and expansion behavior of the soil sample change little.

As the microwave power increases, we can observe a rapid increase in sample temperature. As mentioned above, after heating at 4 and 6 kW power for 10 minutes, the soil sample temperature reaches 470 and 950 ℃. Within this temperature range, mineral decomposition and lattice structure changes, etc., will occur. For example, it has been shown that the OH groups (dehydroxylation) in montmorillonite can be removed at 400–800 °C (Rodrigo et al., 2011), and illite was also dehydroxylated at 400-700 °C (Jiang et al., 2008). The structure of montmorillonite and illite was destroyed after dehydroxylation, and consequently they lost their expansive characteristics. And at 573 ℃, there is a distinct phase transition in the quartz structure, where a transition from phase α to phase β occurs (Geng and Sun, 2018). It is also worth noting that at high temperatures, clay particles will be sintered. The structure of clay minerals such as montmorillonite is damaged after these processes, and can no longer absorb water and restore the original structure. This results in changes in specific gravity, liquid limits and plastic limits, as well as significant reductions in swelling characteristics. In general, the result shows that the microwave irradiation could be effective in the improvement of expansive soils.

5. CONCLUSIONS

This paper presented an experimental investigation about the use of the microwave irradiation in improving the engineering properties of expansive soils. The main conclusions of this study are as follows:

1. The microwave irradiation induces a rapid augmentation of the soil sample temperature; this augmentation increases significantly with the increase in the microwave power.
2. With the increase in the microwave power level, the soil specific gravity increases first and then decreases, while the other properties (liquid and plastic limit, free swelling ratio, vertical free swelling strain and swelling pressure) decrease continuously.
3. The high temperature induced by microwave irradiation induce physical, chemical and mechanical changes in the properties of expansive soils. Especially at high microwave irradiation power, soil swelling behaviors were significantly reduced. Therefore, this technology can be used as an effective method to improve expansive soils.

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