Study on changing the dielectric constant and radar reflection of foamed polyurethane by adding graphite

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Abstract. Polyurethane is often used for filling and plugging in engineering. However, it is difficult to detect the restoration effect by GPR. For the convenience of detection, graphite was added into polyurethane to change its dielectric constant. Five ratios were designed to measure the dielectric constant under dry and wet conditions. The dielectric constant of polyurethane under dry and wet conditions and the relationship between graphite dosage and detection frequency were obtained. The reflection coefficient of polyurethane-air interface to electromagnetic wave is calculated. The reflection coefficient is increased due to the addition of graphite. According to the results of GPR forward modeling, the filling body can be imaged, and the filling effect can be distinguished obviously.

1. Introduction
Polyurethane (PU) is a kind of high polymer grouting material widely used in dams, highways, tunnels and other projects because of its rapid expansion, solidification and anti-seepage characteristics. However, because the dielectric constant of foamed polyurethane is similar to that of air, it is difficult to distinguish the filling degree by GPR when the cavity is not filled completely. Therefore, it is proposed that adding additive to polyurethane can change its dielectric constant, so as to facilitate the identification of ground penetrating radar.

The dielectric constant of polymer grouting material is an important electromagnetic characteristic index, which is related to the chemical composition and physical structure of polymer. It reflects the radiation, scattering, absorption and transmission of electromagnetic wave by polymer. When the electromagnetic wave is used for nondestructive testing of grouting effect, it directly affects the effect of detection and analysis.

There are a few experimental research results on dielectric properties of non-aqueous reactive polymer grouting materials represented by two-component foamed polyurethane at home and abroad. Cao Kaidong et al. studied the structure and dielectric properties of polyurethane elastomer, such as
volume resistivity, dielectric constant and dielectric loss, by comparing different kinds of polyols and isocyanates [1]. Some industries from the technical needs, chemical synthesis has special requirements of dielectric constant polymers [2, 3]. In Engineering, Meng Meili et al. Studied the dielectric properties of specimens with different densities at different frequencies and analyzed the relationship between dielectric properties and mechanical properties [4]. However, there are few researches on how to improve the detection effect by adding some material to change its dielectric constant. Referring to the water tracer used in dam leakage analysis [5], this paper mainly studies the method of adding graphite powder in polyurethane to change its dielectric constant, in order to improve the GPR detection effect of polyurethane filled cavity.

2. Dielectric constant test of polyurethane added graphite

2.1 Principle and method of dielectric constant measurement

The relative permittivity is a physical parameter that characterizes the dielectric properties or polarization properties of dielectric materials. Its value is equal to the ratio of the capacitance measured with the measured material as the medium and the vacuum as the medium in capacitors of the same size. As shown in Figure 1, the parallel plate capacitor for measurement and its circuit diagram are shown. Measure the capacitance C1 of the parallel plate capacitor in vacuum and the capacitance C2 when it is full of medium, then the relative permittivity of the medium is $\varepsilon_r = C_2 / C_1$.

![Figure 1. Parallel plate capacitor for measurement and its circuit diagram](image)

2.2 Making polyurethane specimen added graphite

(1) Prepare the mold with the same size as required, and the mold size is 20cm × 20cm × 2cm cuboid. According to the requirements of different material volume ratio, the test pieces with different material content volume ratio are made. In this test, powdered graphite is added, and the volume ratio of the test pieces is 0:100, 1:100, 3:100, 5:100, 7:100, 9:100, and 10:100. Each group made 3 specimens, a total of 21 specimens.

(2) In the process of making test pieces, polyurethane A and B are poured into two glass beakers according to the ratio of 1:1, and then graphite powder with the required proportion is added into the two beakers respectively. After fully mixing, they are transferred to the mixing container for stirring and mixing. After fully mixing, the materials are transferred to the mold in time, and the mold is closed. Proper exhaust gas is discharged during the foaming process. When the foam is solidified above 20min, open the mold and remove the finished specimen.
(3) Fb306-JLG integrated AC circuit tester was used to measure the sample, and the measuring frequency was 1kHz ~ 10kHz. The dielectric constant of the sample was recorded at different frequencies.

(4) Immerse the specimen in water (20 ± 1 °C) for 24h, take out and dry the surface of the specimen, measure the specimen again at 1kHz ~ 10kHz, and record the dielectric constant of the specimen at different frequencies after immersion. The indoor humidity is 60% and the temperature is 20 ± 2 °C.

2.3 Dielectric constant test results and discussion

The dielectric constants of 42 polyurethane specimens with different graphite content and before and after soaking in water were measured, and the relative dielectric constant of each specimen in the frequency range of 1kHz~10kHz was measured. The relationship between dielectric constant of polyurethane specimen and frequency is shown in Fig. 2 and Fig. 3.

![Figure 2. Relationship between dielectric constant of polyurethane mixture and frequency](image)

It can be seen from the figure that the dielectric constant of polyurethane mixture in the frequency range (1kHz ~ 10kHz) is 1 ~ 2. The dielectric constant of polyurethane mixture with the same graphite content decreases with the increase of frequency, but the decreasing range becomes smaller. The reason is that polyurethane belongs to high molecular polymer, and its molecular structure is chain type. Under the action of external electric field, it will produce polarization phenomenon, and the polarization between molecules is limited due to the existence of chain bonds. When the frequency increases, the unidirectional duration of the electric field shortens, the polarization is insufficient, the degree of polarization is small, and the charge induced by polarization is less, so the dielectric constant decreases with the increase of frequency.
Figure 3. Relationship between dielectric constant of polyurethane mixture and frequency after soaking

The relationship between the dielectric constant and graphite content of polyurethane mixture at the same frequency and the average frequency is shown in Fig. 4 and Fig. 5.

The foamed polyurethane can be regarded as a mixture, which is composed of cured polyurethane film and air. After adding graphite, it is composed of three parts, both of which are gas-solid two-phase mixture. In wet state, considering the water factor, it is composed of four parts, which are gas, solid and liquid combination.

Figure 4. Relationship between dielectric constant of polyurethane mixture and graphite content
Figure 5. Relationship between dielectric constant of polyurethane mixture and graphite content after soaking.

It can be seen from the figure that at the same frequency (1kHz), the dielectric constant of polyurethane mixture increases with the increase of graphite volume percentage. The dielectric constant of pure polyurethane is 1.2 at 1kHz. When the volume percentage of graphite is 10%, the dielectric constant increases to about 2, with an increase of 67%. In the frequency range (1kHz ~ 10kHz), the average increase of dielectric constant of polyurethane mixture is 60% when the volume percentage of graphite is 10%, which indicates that adding graphite to polyurethane foam can improve the dielectric constant of the mixture.

The reason is that the dielectric constant of graphite is 12-15. Under the action of external electric field, the polarization degree of graphite is greater than that of polyurethane, which increases the dielectric constant of the mixture. With the addition of powder, the porosity of the polymer decreases, the influence of air on the mixture decreases, and the dielectric constant increases.

Compared with Fig. 4 and Fig. 5, it can be seen that the dielectric constant of polyurethane mixture in wet state is higher than that in dry state at the same frequency. With the increase of graphite volume percentage, the increase of dielectric constant is greater. When the volume percentage of graphite is 10%, the polyurethane mixture reaches 36. In addition to the graphite itself and its effect on porosity, the water absorption of polyurethane is enhanced by the filling of graphite particles. The dielectric constant of water is 81, so the dielectric constant increases greatly.

There are many dielectric constant models of mixtures, including linear model, root mean square model and Rayleigh model. The polyurethane with graphite is more complex. In order to facilitate interpolation estimation, the fitting equation with graphite addition is given in Fig. 4 and Fig. 5, which can be used for reference. The test also shows that the addition of graphite has no significant effect on the engineering properties of polyurethane.
3. Influence on radar wave reflection

3.1. Ground penetrating radar detection principle

Ground penetrating radar (GPR) is commonly used in engineering detection, including the filling of polyaminase. It transmits high-frequency electromagnetic waves ($n \times 10^6 \sim n \times 10^9$Hz) to the underground through the antenna. When the electromagnetic waves meet the interfaces of different media, they will be reflected. The reflected waves return to the ground surface and are received by the receiving antenna (as shown in Figure 6). At this time, the radar host records the two-way travel time difference $t$ of electromagnetic wave from transmitting to receiving. Because the propagation velocity $V$ of electromagnetic wave in the underground can be determined by the known medium, the depth of underground abnormal body can be calculated by formula $Z = \frac{vt}{2} = \frac{ct}{2\sqrt{\varepsilon}}$. According to the arrival time of the reflected wave and the propagation velocity of the electromagnetic wave in the medium, the depth of the interface is determined. At the same time, the nature of the target is determined according to the shape, intensity and change of the reflected wave.

![Figure 6. Working principle of ground penetrating radar](image)

3.2 Reflection coefficient

In the process of electromagnetic wave propagating to underground medium, the reflected wave and transmitted wave will be produced when different wave impedance interfaces are encountered. The phenomenon of reflection and transmission follows the law of reflection and transmission. The energy of the reflected wave depends on the reflection coefficient $R$. The mathematical expression of the reflection coefficient is as follows

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}$$

(1)

Where $\varepsilon_1$ and $\varepsilon_2$ represents the relative permittivity on both sides of the reflective interface. According to formula (1), the reflection coefficient of electromagnetic wave depends on the difference of relative permittivity between the two sides of the reflection interface. The larger the difference of dielectric constant is, the clearer the radar waveform is. Generally, $|R| \geq 0.1$, it is possible to analyze and identify the image effectively, which is the necessary prerequisite for GPR detection.
3.3 Reflection coefficient of polyurethane filling to radar wave
In the polyurethane filling project, the relative dielectric constant values of relevant media are shown in Table 1.

| medium              | Dielectric constant | medium              | Dielectric constant |
|---------------------|---------------------|---------------------|---------------------|
| air                 | 1.0                 | water               | 81                  |
| Clay (dry)          | 4~10                | Clay (wet)          | 10~30               |
| Polyurethane (dry)  | 1.2                 | Polyurethane (wet)  | 3.6                 |

According to the above data, it is assumed that there is a hole in the underground medium, surrounded by clay, and its reflection coefficient is 0.333-0.691. When the hole is filled with polyurethane, the reflection coefficient is 0.292 ~ 0.667, which can meet the detection requirements. When the cavity is partially filled, the reflection coefficient of the filled and unfilled interface is 0.045. The reflection coefficient of the filled and unfilled interface is 0.310. It can be seen that when the cavity is partially filled and above the groundwater level, the reflection coefficient is very small and difficult to detect.

If graphite is added into polyurethane, its relative dielectric constant and reflection coefficient will change. Table 2 shows the reflection coefficient of 1kHz electromagnetic wave under different graphite dosage. In the dry state, the reflection coefficient of the filled and unfilled interface is 3.76 times of the original, and greater than 0.1, which is helpful to distinguish the degree of polyurethane filling in the cavity.

| Graphite: Polyurethane | 0:100 | 1:100 | 3:100 | 5:100 | 7:100 | 9:100 | 10:100 |
|------------------------|-------|-------|-------|-------|-------|-------|--------|
| Dry state              | 0.045 | 0.083 | 0.099 | 0.117 | 0.121 | 0.159 | 0.169 |
| Wet state              | 0.298 | 0.519 | 0.528 | 0.588 | 0.618 | 0.669 | 0.715 |

4. Forward modeling of ground penetrating radar detection of filling effect
GPR MAX software is used in GPR forward modeling, which is a numerical simulation software of GPR forward modeling based on FDTD algorithm and PML boundary absorption condition. The Yee element of FDTD is used to solve the three-dimensional Maxwell equations. The propagation law of electric field and magnetic field and their distribution in the medium space are calculated recursively in time step. Finally, the forward simulation maps of GPR under different medium conditions are obtained.

4.1. Forward modeling of polyurethane filled and unfilled interface
The model is shown in Figure 7. The model area is 4m×2.5m×0.1m, and the grid step size is \( \Delta x = \Delta y = \Delta z = 0.01 \text{m} \). Therefore, the whole model can be regarded as a two-dimensional model. The first layer of the model is a dielectric layer with a thickness of 0.5m, which is used to reserve space for transmitting and receiving antennas. The second layer is the air medium layer with a thickness of 1m.
and a relative dielectric constant of $\varepsilon_1 = 1$, conductivity $\sigma_1 = 0$. The third layer is filled polyurethane layer with a thickness of 1m and a relative dielectric constant of $\varepsilon_2 = 1.2$, conductivity $\sigma_2 = 0.001$. The model uses Ricker wavelet with 400MHz antenna center frequency, the initial position of transmitting antenna is (0.2, 2.0), the initial position of receiving antenna is (0.25, 2.0), and the antenna step size is 0.05m. The time window $t$ is set to $3 \times 10^{-8}$s, and the calculation step is 70.

**Figure 7.** Forward modeling of polyurethane filled and unfilled interface

If the third layer is filled with dry graphite polyurethane, the relative dielectric constant is changed to $\varepsilon_2 = 2$, other parameters remain unchanged. Run the software to get the model1. Out file, and use the Matplotlib module to get the forward radar image. The forward radar images of polyurethane filled with graphite and polyurethane are shown in Figure 8.

**Figure 8.** Forward modeling results of filled and unfilled interface detected by GPR

By comparing (a) and (b), it can be seen that the air polyurethane interface cannot be recognized by radar when filled with pure polyurethane. When filled with graphite polyurethane, a transverse radar wave can be seen at 10ns, which is the reflection wave of air graphite polyurethane interface. Therefore, the recognition of air polyurethane interface can be improved by adding graphite into polyurethane.
4.2. Forward modeling of polyurethane filled and unfilled interface in underground cavity

In order to analyze the radar detection effect of polyurethane filled and unfilled interface in the cavity, GRP Max was used to establish the numerical model of underground cavity. The model is shown in Figure 9. The model area is 4m × 2.5m × 0.01M, and the grid step size is \( \Delta x = \Delta y = \Delta z = 0.01M \). Therefore, the whole model can be regarded as a two-dimensional model. The first layer of the model is a dielectric layer with a thickness of 0.5m, which is used to reserve space for transmitting and receiving antennas. The model set the whole underground as clay layer, with a thickness of 2M and a relative permittivity of \( \varepsilon_0 = 8 \), conductivity \( \sigma_0 = 0.0001 \). A rectangular cavity with the size of 2m × 1m is set at the buried depth of 0.5m. The upper half is air medium with a thickness of 0.5m; the lower half is filling layer with a thickness of 0.5m. The relative permittivity and conductivity of polyurethane and graphite polyurethane are as described above.

![Figure 9. Forward modeling of polyurethane filled underground cavity](image-url)

The forward simulation results are shown in Figure 10. Comparing the two figures (a) and (b), we can see that a strong reflection wave at 1.2ns in figure (a) is the interface between air and clay, and a slightly weak reflection wave at 2ns is the interface between polyurethane and clay, so we can judge the size range of rectangular holes. In figure (b), in addition to the location of the hole, there is a shear wave at 1.6ns. According to the position of the filled and unfilled interface, it can be seen that this is the interface between air and dry graphite polyurethane. When the hole is filled with pure polyurethane, the interface can not be distinguished from figure (a). It can be seen that when the underground cavity is filled with graphite polyurethane, the filled and unfilled interface can be identified by GPR forward modeling, and the results are consistent with the calculation of reflection coefficient.
5. Conclusion
Polyurethane foam materials are more and more used in engineering, and its filling effect often needs to be detected in engineering. In order to meet the needs of engineering, the experimental study of changing the dielectric constant of polyurethane was carried out, and its influence on radar wave reflection was analyzed, and the detection results were forward simulated.

The main conclusions are as follows
(1) The dielectric constant of polyurethane is small, and the dielectric constant of graphite is 12-15. Adding graphite can effectively change the dielectric constant of the mixture. The dielectric constant of polyurethane mixture increases with the increase of graphite volume percentage, and the average increase is 60% at 1kHz.

(2) For polyurethane mixture, the dielectric constant in wet state is higher than that in dry state.

(3) In the test range, the dielectric constant of polyurethane mixture decreases with the increase of frequency, but the decreasing range becomes smaller.

(4) It is difficult to distinguish the interface between polyurethane and air in engineering detection. The reflection coefficient of electromagnetic wave increases greatly with the increase of dielectric constant after adding graphite. When the graphite content is 10% of the volume of polyurethane, it can meet the basic requirements of GPR.

(5) The forward modeling software is used to simulate the radar detection in the underground cavity filled with polyurethane. The results show that the interface between polyurethane and air presents a distinguishable image after adding graphite, while the interface between air and pure polyurethane cannot be recognized.

In hydraulic and traffic engineering, polyurethane mixture is often used as filling material. The research results can provide the basis for radar wave nondestructive testing. It provides a new technical way for the detection of complex working conditions.

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