

# Non-Contact Terahertz Inspection of Water Content in Concrete of Infrastructure Buildings

Tadao Tanabe<sup>1</sup>, Tomoya Kanai<sup>1</sup>, Kenta Kuroo<sup>1</sup>, Tomoya Nishiwaki<sup>2</sup>,  
Yutaka Oyama<sup>1</sup>

<sup>1</sup>Department of Materials Science, Graduate School of Engineering, Tohoku University, Sendai, Japan

<sup>2</sup>Department of Architecture and Building Science, Graduate School of Engineering, Tohoku University, Sendai, Japan

Email: tadao.tanabe.b1@tohoku.ac.jp

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## Abstract

Concrete is the most widely used for construction materials in the world. Water content of concrete is an important parameter in terms durability of concrete structures. Terahertz (THz) waves, for which concrete is a porous and absorbable material, have been studied in order to establish a new non-contact inspection technology for maintenance of concrete structures. In this study, THz transmittance and reflectance of concrete in drying process were measured with a 60 GHz GUNN diode and absorption coefficient is analyzed for concrete with various water contents. It is shown that quantitative detection below 10% is possible for the water content at surface area of concrete.

## Keywords

Concrete, Water Content, Terahertz Wave, Noncontact Inspection

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## 1. Introduction

### 1.1. Terahertz Waves and Applications

Terahertz (THz) waves are electromagnetic waves in the frequency range between approximately 0.1 and 10 THz, which is just the middle of the radio wave and the light wave. Therefore, THz wave has both of characteristics as represented by transparency of radio wave to non-polarized substance and good reflectivity to metal of light wave.

1 THz corresponds to quantum energy of about 4.1 meV, which is relatively as low as one hundred thousandth of X-ray. Hence, it is safe for human body. THz waves are expected as non-destructive evaluation. Our group has created a database of THz permeability characteristics for industrial materials, and successfully

constructed non-destructive THz diagnosis of building blocks [1], insulated copper cable [2], hot-dip galvanized steel sheet and banknotes [3]. Furthermore, the energy of a THz wave corresponds to molecular interactions such as hydrogen bonding, van der Waals interactions and lattice interactions. The lattice interaction is affected by a mechanical deformation of polymer. THz spectroscopy can be used for non-destructive diagnosis of mechanical deformation in polymers [4]. By other researchers, the non-destructive THz imaging inspection has been applied to space-shuttle ceramic style bonded state [5], tablet surface defect analysis [6], in the medical field, non-destructive inspection of cancer cell [7].

In this study, we report the non-contact inspection of water content inside the concrete by sub-THz waves which are relatively low frequency in the THz band. Water has a large absorption in the THz frequency region. THz wave has a high sensitivity in detecting water in concrete. Based on quantitative relation between THz absorption coefficient and water content, which is measured in this study, non-destructive THz inspection is available for water content in concrete of infrastructure buildings itself. THz wave generator and detector are recently developed with small size.

## 1.2. Concrete

From the Roman period, concrete is widely used in our lives such as buildings, bridges, dams due to its good mechanical properties, durability, workability, and accessibility with low economical cost. To establish a sustainable society, the durability of concrete structures with proper maintenance work becomes more and more important. When constructing a new concrete, it is not obtaining strength from the beginning. It obtains strength by hydration reaction by mixing cement and water in casting. In case that enough water is not provided at the early hydration stage, concrete has risks of insufficient strength and durability due to rough microstructure. Moreover, corrosion of reinforcing steel bars of concrete structure is strongly affected by the presence of water. Therefore, it is important to measure the water content at concrete structures.

As a traditional inspection method for the water content in concrete, a high frequency capacitance measurement method is available now [8] [9] [10]. In this method, an alternating current of 20 MHz is passed through the sample, and its dielectric constant change is measured as the water amount. The dielectric constant of various materials is 10 or less when air is 1, but water is 80, so the apparent dielectric constant greatly increases when water is contained. Therefore, if the relation between water and dielectric constant is obtained beforehand, the water content of the sample can be calculated by measuring the dielectric constant. Although this method can inspect water content, it has disadvantage such as contact method and necessary of sample information, for example specific gravity and thickness. Therefore, in this study, we describe a contactless method to measure water content of concrete by using THz waves.

## 2. Materials and Methods

### 2.1. Measurement Sample

**Figure 1** shows photograph of the concrete test sample. As the measurement sample, a concrete sample prepared with following mix proportion; 32 MPa of the design strength, 0.62 of the water/cement ratio, 15 cm of the target slump, 273 kg/m<sup>3</sup> of the unit cement content, and 4.5% of the target air content. Crushed stone is used as coarse aggregate and sand is used as fine aggregate. The diameter of sample is 30 mm and the thickness of the sample is cut to 7 mm and 13.5 mm. When this sample leave at the condition of concrete including water up to the maximum, the mass varied like **Figure 2**. And this mass change was considered to be the evaporation of water and the water content at the measurement time was calculated by

$$u = \frac{m - m_0}{m_0} \times 100 \quad (1)$$

which  $u$  is water content,  $m$  is mass at measurement and  $m_0$  is mass at dry condition. In this study, transmittance and reflection intensity measurements were carried out for the concrete as a function of water content.

### 2.2. THz Transmittance and Reflection Measurement

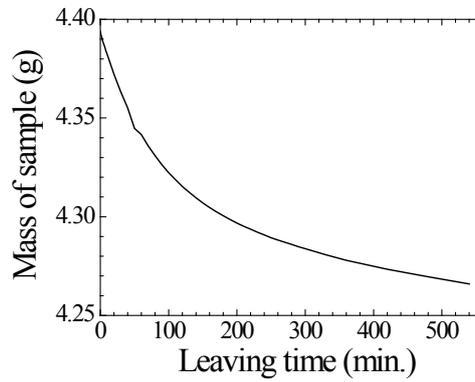
A schematic diagram of the transmittance and reflection measurement system is shown in **Figure 3**. A 60 GHz GUNN diode is used for the THz source. Since the light source is continuous wave, it has sufficient and steady intensity. Hence, we did not use the lock-in amplifier. The generated THz waves are collimated by a Teflon lens and then focused on the surface of sample by Teflon lens. The beam diameter of the light source is an ellipse with a width of 28 mm and a length of 26 mm. The transmitted and reflected THz waves from the sample are collected by Teflon lens, and the transmitted and reflected waves are detected by a Schottky barrier diode, respectively. In this study, we set the sample with maximum water content into the optical system and measured the transmittance and reflection and intensity as a function of leaving time.

## 3. Results and Discussion

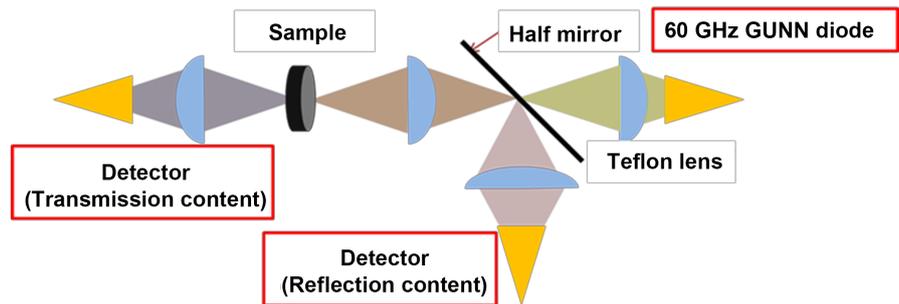
Using the transmittance and the reflectance obtained by this measurement, the absorption coefficient was calculated by



**Figure 1.** Photographs of the concrete test sample.



**Figure 2.** Mass change of concrete by leaving.

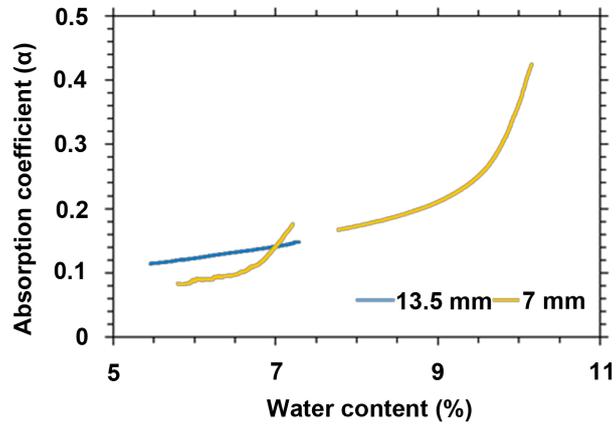


**Figure 3.** The optical schematic system of THz transmittance and reflection measurement.

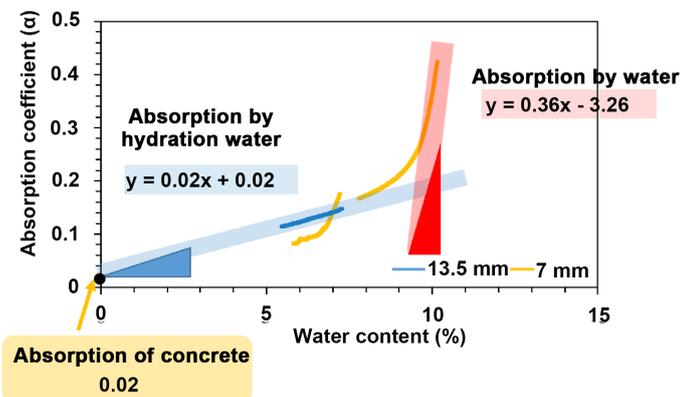
$$\alpha = -\frac{\ln\left(\frac{T}{100-R}\right)}{x} \tag{2}$$

which  $T$  is transmittance,  $R$  is reflectance and  $x$  is width of sample [11]. The relationship between the absorption coefficient and the water content in each sample is shown in **Figure 4**. For 7 mm thickness, we prepared two samples with different water content. From this result, it can be seen that the absorption coefficient increases with increase of the water content in both samples. It shows that the absorption of THz waves increases as the amount of water increases, but as shown in **Figure 5**, the absorption coefficient rapidly increases around 10% water content. In the lower water content region, the change in the absorption coefficient is slight, which is attributed to hydrated water in concrete. The absorption coefficient at 0% water content is that of dry concrete itself. In the high water around 10%, the absorption coefficient changes rapidly, which is assigned to free water [12] [13]. Assuming that the amount of change in absorption coefficient per 1% water content as the sensitivity in this study, which is slope in **Figure 5**, the sensitivity with hydrated water is 0.02 and the sensitivity with water is 0.36. The possibility of measuring the quantitative water content inside the concrete by THz wave is up to 10%.

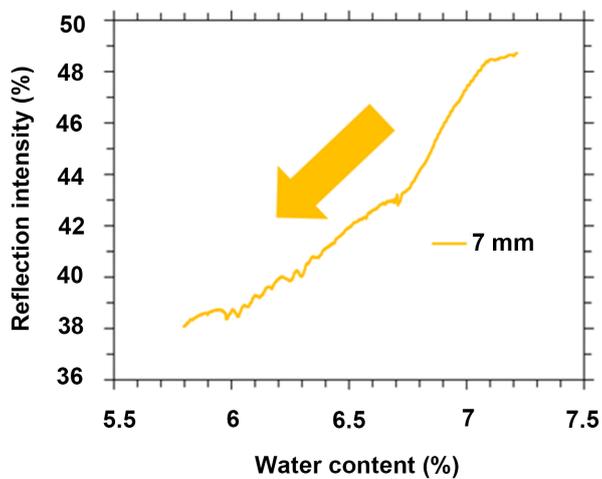
Since it is difficult to measure the transmission wave from the sample in the field measurement, we consider the quantitative detection possibility using only



**Figure 4.** Relationship between water content and absorption coefficient.

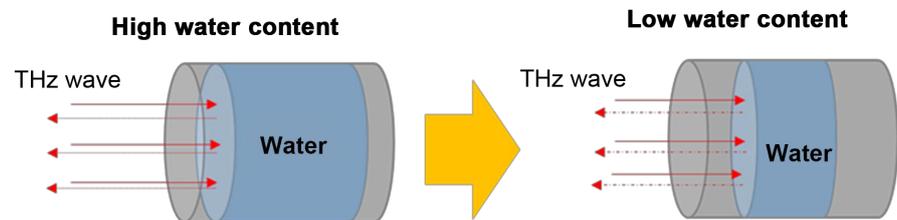


**Figure 5.** Relationship between thickness and sensitivity.



**Figure 6.** Reflection intensity from the concrete of 7 mm thickness.

the reflected wave. The measurement result of the reflection intensity from the concrete when the thickness is 7 mm is shown in **Figure 6**. In this result, as the water content decreases, the reflection intensity decreases. This is because the



**Figure 7.** Difference in reflection behavior due to moisture content.

water evaporates from the surface, the THz wave penetrates deeper and the absorption of the THz wave by the concrete becomes larger. From **Figure 5**, the absorption of THz waves increases by increasing the water content, but the reason for the opposite result is that because the water evaporates from the surface, the THz wave penetrates deeper and the absorption of the THz wave by the concrete becomes larger like **Figure 7**. This result showed the possibility of measuring the distribution of water inside the concrete.

#### 4. Conclusion

For concrete with 0 - 10 water contents, absorption coefficient was measured using 60 GHz emitter at room temperature. The absorption coefficient increases slowly with increasing water content up to 10%. This feature can be taken as evidence for hydrated water in concrete. Above 10%, the absorption coefficient increases steeply, which is attributed to free water. The water content can be measured below 10% at surface area of concrete.

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