Theoretical Analyses and Experimental Research on Transmission of Electromagnetic Wave Passing through Concrete Materials Surface

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Abstract: Simplified theoretical model of electromagnetic wave propagation on concrete materials surface is established first by only considering the normal incidence case. In order to investigate the impact of concrete component to the wave transmission, concrete materials specimens with different composite were casted, which were tested by electromagnetic pulse testing method. Study shows that the transmission rate is only relevant with the concrete materials relative dielectric parameter. The greater relative dielectric constant, the smaller transmission rate in materials surface is. Among all this concrete casting components, unit volume water content has the most obvious influence on transmission rate. To change the transmission rate of electromagnetic wave, it is necessary to control the unit volume water content in concrete materials design process.

1. Introduction

At present, electromagnetic radiation pollution has become a threat to human survival following air pollution, noise pollution, water pollution and becomes the fourth major pollution sources. Concrete as building materials has been largely used in civil engineering. The study to transmission of electromagnetic wave passing through concrete materials surface has important practical significance to prevent the hazards of electromagnetic radiation on human health and the prevention of electromagnetic radiation due to communication interruption, data leakage, and electronic instruments dysfunction. When electromagnetic wave passing through concrete materials, some of it will be reflected in the surface called reflected wave and turn back to the original space, the rest part will enter the concrete inner materials continuing transmission, known as transmitted wave, the proportion of transmitted wave in the incident electromagnetic wave defined as transmission rate which is an parameter to evaluate the absorbing wave capacity of materials. In order to reduce interference and influence of external electromagnetic waves on the indoor and electronic equipment, transmitted wave must be declined in the concrete surface making the surface reflection of electromagnetic wave as large as possible; while in some other cases, transmitted wave must be strong enough to provide adequate wireless signal strength coverage. The one same thing of the two conditions is the controlling of transmitted wave proportion, named transmission rate. In this study, simplified theoretical model of electromagnetic wave propagation on concrete materials surface is analyzed by only considering the normal incidence case. Theoretical formula was deduced to show that the transmission rate has no relationship with electromagnetic waves incident frequencies. Thus, research can be focus on how concrete materials components influence the transmission proportion. Experiment is carried out by casting concrete
specimens with different components under laboratory condition using electromagnetic pulse test. The conclusions can be guidelines in concrete materials design considering absorbing wave or reflecting wave.

2. Theoretical analysis
The relationship between transmission rate and concrete electromagnetic parameters is determined by a simplified model analysis of considering only the normal incidence of electromagnetic wave. When electromagnetic wave travel from air to concrete at concrete surface, the normal incident wave will be divided into two parts of transmitted wave and reflected wave, the transmitted wave will propagate in the inner space of concrete. $\varepsilon_0$ and $\mu_0$ are dielectric constant and magnetic permeability air medium, $\varepsilon_i$ and $\mu_i$ are dielectric constant and magnetic permeability of concrete materials, amplitude transmittance of transmitted wave is denoted as $\tau_i$, in this case, In formula (1), $\eta_0$ and $\eta_i$ are wave impedance of air medium and concrete materials.

$$\tau_i = \frac{2\eta_i}{\eta_i + \eta_0} \quad (1)$$

for air medium,

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \quad (2)$$

for concrete materials,

$$\eta_i = \sqrt{\frac{\mu_i}{\varepsilon_i}} / \sqrt{1 - j \frac{\sigma_i}{\omega \varepsilon_i}} \quad (3)$$

In formula (3), $j \sigma_i / \omega \varepsilon_i$ can be ignored because medium consuming angle tangent value of concrete materials is small, so, formula (3) can be simplified as

$$\eta_i = \sqrt{\frac{\mu_i}{\varepsilon_i}} / \sqrt{\omega \sigma_i} \quad (4)$$

In formula (4), $\varepsilon_i$ and $\mu_i$ are relative dielectric constant and relative magnetic permeability of concrete materials. Taking formula (2) and formula (4) into formula (1), can get formula (5)

$$\tau_i = \frac{2\sqrt{\mu_i}}{\sqrt{\mu_i} + \sqrt{\varepsilon_i}} \quad (5)$$

In formula (5), amplitude transmittance is affected by relative dielectric constant and relative magnetic permeability. Ordinary concrete materials are non-magnetic materials. $\mu_i = 1$, can get formula (6)

$$\tau_i = \frac{2}{1 + \sqrt{\varepsilon_i}} \quad (6)$$

When use power to express transmission rate, denoted as $T_i$, can be express as

$$T_i = \tau_i^2 = \left(\frac{2}{1 + \sqrt{\varepsilon_i}}\right)^2 \quad (7)$$

From formula (7), transmission rate is only function of relative dielectric constant of materials. It has no relationship with frequency of incident wave. When relative dielectric constant increases, transmission rate decreases. When relative dielectric constant is in the range of $[1, 12]$, transmission rate decreases rapidly from 1 to 0.2. After that, transmission rate decreases slowly, when relative dielectric constant is over 30, transmission rate is very small, can be ignored. Only relative dielectric constant in the range of $[1, 30]$, transmitted wave can be appeared. When relative dielectric constant of materials is
over 30, the incident wave is mostly reflected and very small part of it can be transmitted into the inner space of materials. This also explains when material with big relative dielectric constant such as iron, electromagnetic wave is only reflected can not get into the inner space of such materials. Transmitted wave only appears in the concrete materials whose relative dielectric constant is in the range of [1, 30].

Cement, dry sand and dry aggregate are small relative dielectric constant materials, while water’s relative dielectric constant is much large. This makes concrete material’s relative dielectric constant changes in a range of [4, 20]. Transmission rate changes greatly in that range. According to the effective medium theory, concrete material’s relative dielectric constant is affected by composition and its dielectric properties, temperature and wave frequency, etc. Thus, transmission rate of electromagnetic wave in the concrete material’s surface is also affected by the factors. The experiment study is based on this analysis.

3. Experiment study

3.1. Principle and method

Through the above theoretical analyses, transmission rate in the concrete material’s surface will change in a range dramatically depend on factors, such as the material’s dielectric properties, temperature and wave frequency. In experiment study, temperature is choosed as room temperature in laboratory which changes very small. Also wave frequency is set to be a constant center frequency by setting the test apparatus. Test samples of concrete with different components were casted to study the influence of composition to the transmission rate. The relative dielectric constant is calculated based on the propagation velocity of electromagnetic waves in the concrete samples.

\[
v = \frac{c}{\sqrt{\varepsilon_r}}
\]  

(8)

In formula (8), \( v \) is the propagation velocity of electromagnetic waves in the concrete samples, \( \varepsilon_r \) is the propagation velocity of electromagnetic waves in vacuum.

Relative dielectric constant of concrete samples can be calculated by formula (8) based on the measured wave velocity. The wave velocity can be determined by electromagnetic pulse test. Delay time is measured as the time length between the two peaks, which is round-trip propagation time of electromagnetic waves in the specimen, denoted as \( \Delta t \). The wave velocity can be calculated by specimen thickness and delay time, that is

\[
v = \frac{D}{\Delta t/2} = 2\frac{D}{\Delta t}
\]  

(9)

The experimental study for testing the transmission rate is based on the formula (9), formula (8) and formula (7), by electromagnetic impulse test to a certain thickness concrete specimens with different components.

3.2. Specimens and testing

The experiments consider three factors’ influence to the transmission rate of concrete materials, which are concrete unit water consumption, maximum size of aggregates and concrete strength. Three different types are unit water consumption series, maximum size of aggregates series and concrete strength series. The unit water consumption series have three different unit water consumption number, they are 175 kg/m\(^3\), 190 kg/m\(^3\) and 205 kg/m\(^3\), denoted as type I, type II and type III. Each unit water consumption series made A and B two test samples to compare the test result and take average value. In this series, maximum size of aggregates is 25mm, design concrete strength is 40MPa. The specimens’ number of this series are I A, I B, II A, II B, IIIA, IIIB. The maximum size of aggregates series takes the same mix proportion and sand ratio with unit water consumption series. Design concrete strength is 40MPa. It has three maximum sizes of aggregates, they are 20mm, 30mm and 40mm. Each group produced the same two test specimens. The specimens’ numbers of this series are 20A, 20B, 30A, 30B, 40A, 40B. Six different design concrete strength specimens of 10MPa, 15MPa, 20MPa, 30MPa, 45MPa,
60MPa poured in concrete strength series, the first four groups’ specimens take 32.5 grade portland cement, the left take 42.5 grade portland cement. Each group produced the same two test specimens. Unit water consumption is 175kg/m3. Maximum size of aggregates is 25mm. The specimens’ numbers and mix proportion of concrete is shown in Table 1.

Specimens size is 200mm × 200mm × 200mm. The concrete specimens take ordinary portland cement, coarse river sand, gravel stone, mechanical stirring, shaking table vibration and outdoor sprinkling conservation. The Handy Scan radar equipment produced by US, GSSI Company is used in test as electromagnetic pulse transmitter; the center frequency of electromagnetic waves emitted by the equipment antenna is 1GHz. The center frequency is used for all specimens’ test. The test temperature is room temperature in summer day changing nearly in the range of 10℃ to 30℃.

### Table 1: The specimens’ numbers and mix proportion of concrete (kg/m³)

| Sample type                  | Specimens’ number | Cement | Water | Sand | Aggregates |
|------------------------------|-------------------|--------|-------|------|------------|
| Unit water consumption series | I A. I B          | 460    | 175   | 545  | 1271       |
|                              | II A. II B        | 500    | 190   | 529  | 1232       |
|                              | IIIA. IIIB        | 540    | 205   | 512  | 1193       |
| Maximum size of aggregates series | 20A. 20B. 30A. 30B. 40A. 40B | 460 | 175 | 545 | 1271 |
| Concrete strength series     | C10               | 188    | 175   | 835  | 1253       |
|                              | C15               | 305    | 175   | 749  | 1221       |
|                              | C20               | 363    | 175   | 669  | 1243       |
|                              | C30               | 422    | 175   | 593  | 1260       |
|                              | C45               | 489    | 175   | 536  | 1250       |
|                              | C60               | 583    | 175   | 474  | 1218       |

By laying a steel plate in the bottom of all specimens, achieve getting the echo waves and transport it to a notebook computer by the cable connecting the Handy Scan radar equipment and the computer. The transported information is saved in the computer for further analysis using the radar signal analyzing software RADAN that comes with the equipment.

### 3.3. Experimental results and analysis

Since there are three different sample types, the testing result is also divided into three groups, each group reflect an influence factor to the transmission rate.

1. Group one: the influence of unit water consumption.
   After 7 days conservation, electromagnetic pulse test is carried out to the unit water consumption series. From the 7 day to 90 day, 14 different times of test is done to the one test sample. By the delay time, for the two specimens of one same unit water consumption, average value of delay time is taken to calculate the transmission rate. The transmission rate result is shown in Table 2.

### Table 2. Transmission rates of unit water consumption series

| Day | 7   | 8   | 9   | 10  | 12  | 14  | 16  | 18  | 20  | 24  | 28  | 56  | 90  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Type I | 0.176 | 0.181 | 0.189 | 0.192 | 0.202 | 0.202 | 0.203 | 0.205 | 0.241 | 0.245 | 0.247 | 0.248 | 0.244 |
| Type II | 0.168 | 0.171 | 0.176 | 0.180 | 0.187 | 0.190 | 0.191 | 0.192 | 0.232 | 0.232 | 0.236 | 0.237 | 0.237 |
| Type III | 0.164 | 0.167 | 0.174 | 0.176 | 0.183 | 0.186 | 0.187 | 0.188 | 0.228 | 0.230 | 0.231 | 0.233 | 0.234 |

The data in Table 2 are plotted in Figure 1; it shows the significant effect of the unit water consumption of concrete to the transmission rate of electromagnetic wave in the concrete materials surface.
The unit water consumption series have three different unit water consumption numbers, they are 175 kg/m³, 190 kg/m³ and 205 kg/m³, denoted as type I, type II and type III. 14 different times of tests show the same result that the greater unit water consumption is, the smaller transmission rate is. This is because when water consumption grows in unit concrete volume, according to the effective medium theory, as water's relative dielectric constant is 81, which is much more than concrete materials, the increase of water content in concrete body will inevitably increase the concrete materials' relative dielectric constant, which makes a lower transmission rate of electromagnetic wave in the concrete materials surface, also makes a bigger ratio of reflected wave. Concrete with bigger ratio of reflected wave have good shielding performance against electromagnetic radiation. The concrete shielding performance can be improved by increasing the unit water consumption. The quantitative theoretical analysis is verified by the experimental results.

Figure 1 also shows that in concrete age of 18 day to 20 day, transmission rate will increase greatly and then keep relatively stable with very little rising, just like the formation of concrete strength. Although the three type series have different unit water consumption, in age of 90 day, transmission rate is nearly the same value. The influence of unit water consumption to transmission rate is relatively obvious before age of 90 day.

(2)Group two: the influence of maximum size of aggregates series.

With the same average processing of two samples A and B as the unit water consumption series, transmission rate of maximum size of aggregates series can be got listed in Table 3, which shows that all samples of maximum size of aggregates series have nearly the same value of transmission rate which is 0.23. It means that when unit water consumption and design concrete strength is fixed, the change of maximum size of aggregates has little influence on transmission rate of electromagnetic waves in the concrete materials surface; the difference of transmission rate between maximum size of aggregates series is very small.

| Day | Maximum size of aggregates | 21 | 28 | 42 | 56 | 90 |
|-----|----------------------------|----|----|----|----|----|
| 20  |                            | 0.231 | 0.227 | 0.230 | 0.231 | 0.236 |
| 30  |                            | 0.231 | 0.229 | 0.230 | 0.232 | 0.239 |
| 40  |                            | 0.231 | 0.230 | 0.232 | 0.236 | 0.241 |

(3)Group three: concrete strength series

Testing results and transmission rates of concrete strength series is listed in Table 4.
Table 4  testing results and transmission rates of concrete strength series

| specimens’ number | 7 day strength (MPa) | transmission rate | ratio | 14 day strength (MPa) | transmission rate | ratio | 28 day strength (MPa) | transmission rate | ratio |
|-------------------|----------------------|-------------------|-------|-----------------------|-------------------|-------|-----------------------|-------------------|-------|
| C10               | 6                    | 0.245             | 0.041 | 8                     | 0.262             | 0.033 | 9                     | 0.255             | 0.028 |
| C15               | 12                   | 0.241             | 0.02  | 15                    | 0.25              | 0.017 | 16                    | 0.247             | 0.015 |
| C20               | 15                   | 0.24              | 0.016 | 19                    | 0.231             | 0.012 | 21                    | 0.244             | 0.012 |
| C30               | 22                   | 0.235             | 0.011 | 27                    | 0.237             | 0.008 | 32                    | 0.239             | 0.007 |
| C45               | 36                   | 0.245             | 0.007 | 42                    | 0.244             | 0.006 | 49                    | 0.251             | 0.005 |
| C60               | 48                   | 0.248             | 0.005 | 61                    |                   |       |                       |                   |       |

In Tab 4, there are 6 different specimens designed with different concrete strength, test carried out in 3 concrete ages, they are 7 day, 14 day and 28 day. Test results consist of measured concrete strength, transmission rate and the ratio of the two values. Measured concrete strength means the testing concrete compressive strength. Take the design concrete strength as x-axis; take transmission rate as y-axis, can get Figure 2, in three concrete ages, transmission rate of C20, C30 specimens is less than other design concrete strength specimens, C20, C30 specimens with 20MPa and 30MPa design concrete strength have better shielding performance than other design concrete strength specimens. Take the measured strength as x-axis; take the ratio value as y-axis, can get Figure 3. Figure 3 shows that even in different test time before 28 day, the ratio curves of transmission rate and measured strength are nearly coincident. The ratio of transmission rate and measured strength has little relationship with test time before 28 day, and it is decreasing with the increasing of measured strength.

Figure 2  Transmission rates of concrete strength series

Figure 3  the ratio and measured strength

4. Discussions
For determine influence factors to the concrete materials’ transmission rate, experimental study is done in laboratory. The experiments consider three factors’ influence to the transmission rate of concrete materials, which are concrete unit water consumption, maximum size of aggregates and concrete strength. Among the three factors, unit water consumption and concrete strength has influence to the transmission rate, while maximum size of aggregates has little influence to it. There come some questions about the experimental testing result.

(1) Question 1: why the ratio of transmission rate and measured strength has little relationship with test time?
When consider influence of concrete strength to the transmission rate, there’s no need to consider the influence of concrete age, this situation may be explained as a significant correlation between concrete strength and concrete age. In certain other conditions, the concrete hydration is much more fully with increase of concrete age, concrete strength is increasing with concrete age. Thus, when consider influence of concrete strength to the transmission rate, concrete age can be ignored.
(2) Question 2: between the unit water consumption and concrete strength, which one has more important impact to the transmission rate?

In Figure 1, when concrete strength formed in 20 day, after then, concrete strength can be seemed as a constant with little change, different unit water consumption samples has different transmission rate. In Figure 3, different measured concrete strength has different ratio of transmission rate and measured strength. By applying the least square method to the test result of relative dielectric constant, get the relationship between relative dielectric constant and concrete age, unit water consumption and concrete strength, as shown in formula (10).

\[ \varepsilon_r = 4.7565 - 0.0057T + 0.0262X + 0.0016f_c \]  

(10)

In formula (10), \( T \) is concrete age (day), \( X \) is unit water consumption (kg/m³), \( f_c \) is concrete strength (MPa). Residual sum of squares of formula (10) and test result is 2.847, which means formula (10) is in good agreement with the test result and can be used in predicting the relative dielectric constant of concrete materials within the test range. From formula (10), coefficient of unit water consumption is much more than coefficient of concrete strength, which means that the unit water consumption has more influence to the transmission rate than concrete strength. Taking formula (10) into formula (7) can determine the transmission rate of electromagnetic waves by concrete material compositions.

5. Conclusions

In this paper, transmission of electromagnetic waves passing through concrete materials surface is studied by theoretical analyses and experimental research. Theoretical analyses show that in normal incidence of electromagnetic wave case, relative dielectric constant of concrete materials is the only factor to influence transmission of electromagnetic waves, the relationship of the relative dielectric constant and transmission rate is shown in formula (7). When relative dielectric constant increases, transmission rate decreases. When relative dielectric constant is in the range of [1, 12], transmission rate decreases rapidly from 1 to 0.2. After that, transmission rate decreases slowly, when relative dielectric constant is over 30, transmission rate is very small, which can be ignored. Relative dielectric constant of ordinary concrete materials is in range of [4, 20], in this range, transmission rate is decreasing dramatically. The purpose of experimental research is to determine the important factor of concrete components and its influence to the transmission rate. Test results show that under room temperature, unit water consumption is the most important factor to influence the transmission rate. The greater unit water consumption is, the smaller transmission rate is. The increase of water content in concrete body will inevitably increase the concrete materials’ relative dielectric constant, which makes a lower transmission rate. Factor of maximum size of aggregates has little influence to transmission rate. Before 28 day, as a significant correlation between concrete strength and concrete age, when consider influence of concrete strength to the transmission rate, concrete age can be ignored. Unit water consumption has more influence to the transmission rate than concrete strength. Taking formula (10) into formula (7) can determine the transmission rate of electromagnetic waves by concrete material compositions.

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