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Study on the electrical properties of young concrete*

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Abstract: The process of hydration and solidification of young concrete has significant effect on the long term strength and durability of concrete. The electrical property of concrete provides a direct and practical method for monitoring and investigating the hydration process of young concrete. This study developed an advanced system for measurement of electrical parameters, used to study the electrical properties of young concrete. The test results provided the electric parameters for concretes with different water binder ratios and different mineral admixture incorporations. The variations and characteristics of the measured electrical parameters were closely related to the physical and chemical properties of young concrete. These parameters were used to analyze and study the hydration process of young concrete.

Key words: Early age, Electrical property of concrete, System of measurement

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INTRODUCTION

The electrical properties of concrete had long been used to study its characteristics. The earliest research started in 1929 (Khalafan et al., 1999), when a DC voltage of 4-8 volts was applied across the two ends of the concrete sample to get its resistance by Ohms Law. But it was found that the value of the current decreased continuously after the voltage was applied for tens of seconds. It was impossible to accurately measure the resistance of the concrete under such condition. Some researchers connected a switch in the measuring circuit and the controlled direction of the voltage by using a controlling signal with frequency of 2 Hz. A more reasonable method was later proposed, to measure the resistance of the cement or the concrete by using an AC probing signal.

There are three problems in resistance measurement of concrete by DC signal.

1. The polarization effect produced electrolytic gas on the electrode (Hughs et al., 1985).

2. The respective movement of positive and negative ions to the negative and positive electrodes caused concentration of the ions at the electrodes and fewer and fewer ions were left in the central area. The current decreases so it is impossible to get accurate measurement. This phenomenon is observed at any time. So a multimeter using a DC detecting voltage cannot be used to measure the resistance of concrete.

3. The directional movement of the positive and negative ions changes the spatial distribution of the chemical composites in the concrete. Obviously, this method affects the original property of the concrete.

During the years of booming development and progress in studies on the resistance mechanism of cement (Hhalafand et al., 1999; Tumidajski et al., 1996a; 1996b),

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researchers bypassed the 3 problems by using the method of measuring the resistance of the concrete sample by AC probing signal instead of DC probing signal.

However, when the AC measurement is adopted, the value of the frequency should be taken into consideration. When the frequency is too low, the period will be longer. During the time of the positive or negative half-cycle, the AC is like a transient DC with some not easily determinable DC effect. This does not mean higher probe signal frequency yields better result. Higher frequency not only leads to radiation and disturbance but more important, brings along the Maxwell-Wager effect, viscous conduction effect and combined effect. These effects influence the measurement of the parameters so that their analysis is complicated (Wilsonetal et al., 1990). That is why the measuring frequency should not be too high. Then which frequency is optimal? According to related research, the maximum frequency should not exceed 10 MHz. For technical reasons, we hope to find a frequency within an appropriate range. The frequency is from 7 to 7.5 kHz in (Banthea et al., 1992) and 31 kHz in (Lakshminarayanan et al., 1992) (AboEI-Eneinetal et al., 1995). Generally, frequency of 1 kHz to 50 kHz is appropriate.

The electric conduction effect of the young concrete is due to the existence of ions in the cement paste. Provided that there is water; the ions can be driven by an electrical field. The ionization of the chemical composites will not occur without water, the ions cannot move without water. So the existence of the water is essential for the electric conduction of the cement paste. Furthermore, it should be the free water but crystallized water that cannot ionize the chemical composite has no effect on the electric conduction. The content of the free water is reflected by the resistivity of the concrete.

This study on the electrical properties of young concrete deals mainly with two parameters: resistance and capacitance. The geometric parameters of various samples are different, so the comparison cannot be made based on these parameters. That is why the measurement of the resistance and capacitance would be transformed to resistivity and dielectric constant before carrying out the analyses and comparisons.

EXPERIMENTAL PROGRAM

1. Materials

Concrete with two different water cement ratios and four different admixtures were used. The details are shown in Table 1.

Table 1 Concrete of different water cement ratios and different admixtures as well as mix proportions

Group	W/B	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)	Mineral admixture
PL - 1	0.6	436	261	654	1047	Plain concrete
PL	0.5	444	222	666	1067	Plain concrete
SF	0.5	400	222	666	1067	Silica fume (44 kg/m^3)
SL	0.5	222	222	666	1067	Slag (222 kg/m^3)
FA	0.5	333	222	666	1067	Fly ash (111 kg/m^3)
MK	0.5	400	222	666	1067	Metakaolin (44 kg/m^3)

2. Compressive test of the concrete

The compressive strength is a key factor determining the mechanical property of concrete. In the early stage, the variation in the strength is quite complicated. In order to compare the compressive strength with two electric parameters, the compressive strength of the concrete in the early stage was measured. The specimens were cylinder with dimension of the 100 × 200 mm. The test time was set at 0.5 day, 1 day, 2 days, 3 days and 7 days. The test was carried out on an MTS machine with maximum loading capacity of 3300 kN.

3. Resistivity measurement

There have been many methods for measuring resistivity. Generally, a small amptitude AC signal was used as probing signal. On one hand, there are strong chemical reactions in the young concrete. If the amplitude is large, it will induce electrochemical reactions, so the amptitude should be as small as possible. On the other hand, there should be a critical value. If the signal is too small, it will make the measurement difficult due to the poor signal to noise ratio. So a bridge is sometimes introduced to enhance the sensitivity (McCarter et al., 1984). To facilitate the collection of computer data, researchers used pulse sampling and holding circuit and applied the pulse amplitude as a DC voltage to be stored on computer after A/D conversion. The two methods above apply the probing signal on the test specimen during the process of measurement, inducing some undesirable electrochemical reactions.

The test setup for measuring the resistance and capacitance of concrete is shown in Fig. 1a. The specimen used to measure the resistivity was a 100 × 180 × 250 mm cuboid. A copper sheet was put at each of the two ends as electrode and the test was carried out in a mold made of organic glass (Fig. 1b). The probing signal applied was a sine in waveform, 5V in amplitude and 2 kHz in frequency. To reduce the disturbance of the signals on the electrochemical reactions of the specimen, the signal was applied for only very short duration on the specimen totally computerized during sampling process (flow chart, Fig. 2).

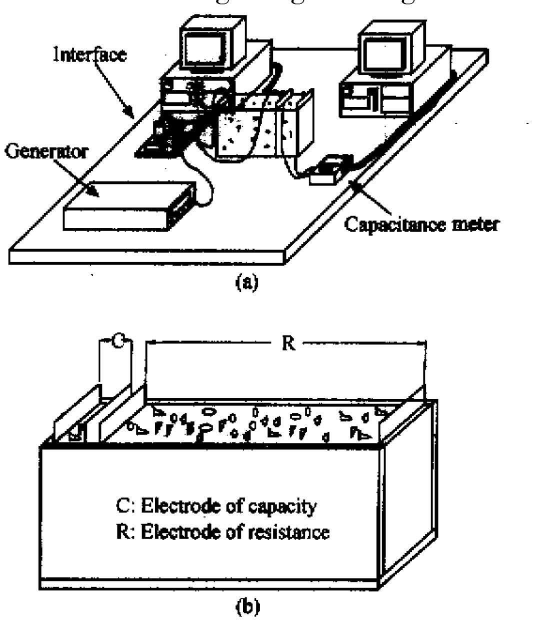

Fig.1 (**a**) **Test setup for resistance and capacitance measurement;** (**b**) **Concrete specimen**

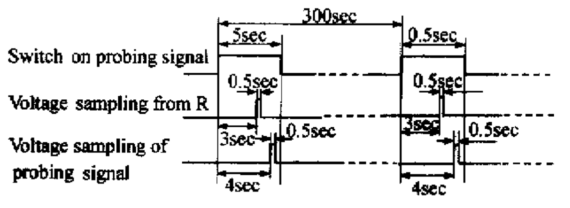

Fig.2 Sampling flow chart

The probing time was 5 seconds and the period was 300 seconds. The ratio of the probing signal on the specimen to the probing period was 5s/300s = 1/60 so that the influence of the probing was reduced to a very low level. To make the sampling easier, two rectifiers were used to detect the measured AC signal to a DC signal with contain peak amplitude. The rectifiers were special ones with good rectification linearity from 0 – 5 volts. The schematic of the measuring system is shown in Fig. 3.

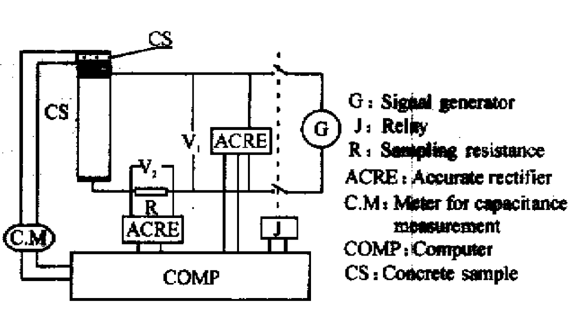

Fig.3 Schematic circuits for resistance and capacitance of concrete

As can be seen from the signal, the resistance of the specimen can be represented by:

$$R_c(t) = R\,\frac{V_1(t)}{V_2(t)} - R \qquad (1)$$

Where, $V_1(t)$ is the output voltage of the signal generator;

$V_2(t)$ is the voltage across the resistance R;
$R_c(t)$ is the resistance of the specimen;
t is the time (the casting time is taken as zero point).

Once the resistance is obtained, the resistivity can be calculated. The capacitance effect of the two electrodes was negligible for frequency below 50 kHz, because the difference of resistances measured by 2 kHz and 50 kHz probing signals was smaller than 1%.

4. Measurement of dielectric constant

The measurement of the capacitance was often not introduced in previous studies. In some references, an equivalent circuit formed by parallel connection of a resistance (the real part) and a capacitance (the imaginary part) was used for impedance measurement. But the inaccuracy in the capacitance measurement was a problem, because the plate capacitance formula below was used:

$$C = \varepsilon\varepsilon_0 S/d \qquad (2)$$

Where, C: capacitance
ε_0: the dielectric constant in vacuum
ε: the relative dielectric constant of the medium
S: the area of the plate
d: the distance between the two electrodes

To use Eq. (2) to calculate the capacitance, the distance between the two plates should be kept small so that the electric field is mainly confined in the medium; that is, $S >> d$. The accuracy will be poor if this condition is not satisfied. The geometry of the specimen cannot meet this requirement. Before capacitance measurement, it is necessary to know the resistivity range of the cement products (including fresh and hardened concrete). The resistivity of the cement product is within the range of 100 – 1000($\Omega\cdot$cm). Generally, the resistivity is $1.5 \times 10^{-6} - 10 \times 10^{-6}$ ($\Omega \cdot$ cm) for metals; $10^{13} - 10^{18}$ ($\Omega\cdot$cm) for insulators; $10^{-4} - 10^{4}$($\Omega\cdot$cm) for semi-conductors. So the resistivity of the cement product is close to that of the semi-conductor. The conductivity of the cement product is close to that of some electrolytical solutions, so cement products can be treated as a weakly conducting dielectrics. Under this supposition, the specimen was a square, $30 \times 100 \times 180$ mm^3 (with $S >> d_2$), copper sheet used as electrode. The measurement be done with a capacitance meter if the copper sheets directly touch the specimen. That is why we regard it as a dielectric to carry out the measurement similar to that for electrical leakage capacitance. The method utilized two polyethylene membranes to separate the electrodes and the specimen (Fig.4).

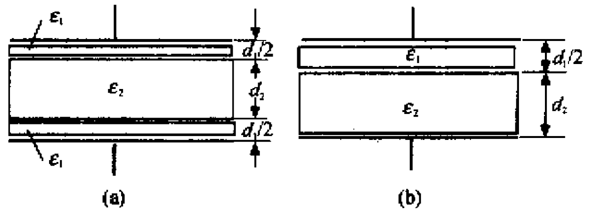

Fig.4 Schematic of dielectric constant measurement
(a) polyethylene membranes inserted between speciment and electrodes; (b) equivalent circuit of (a)

As the thickness of the membrane and its dielectric constant are known, so the dielectric constant of the concrete can be calculated from the formula below by applying the measured capacitance.

$$\varepsilon_2 = C\varepsilon_1 d_2/(\varepsilon_1\varepsilon_0 S - Cd_1) \qquad (3)$$

Where, ε_1: the relative dielectric constant of the polyethylene membrane (= 2.3);
ε_0: the dielectric constant in vacuum;
d_1: the thickness of the polyethylene membrane;
d_2: the thickness of the concrete specimen;
ε_2: the relative dielectric constant of the concrete specimen;
S: the area of the concrete specimen (electrode plate);
C: measured capacitance;
$d = d_1 + d_2$ the distance between the two electrodes.

For comparison of the resistivity and the dielectric constant with time, the specimens used to measure the resistivity and the dielectric constant were put in the same mold to keep the same curing environment (Fig.1).

TEST RESULTS AND DISCUSSION

Concrete conducts electricity due to the movement of the ions in the electric field. The conductance is related to both the concentrations of the ions and the movement route of the ions. Firstly, the concentration of the ions is related to the content of the free water in the concrete. Generally, the more the free water, the greater is the conductance. But when the water is too much, after the molecules have been ionized to anions and cations, the extra water will reduce the ions concentration of ions and thus the conductance, but this will not be so, as the water content in the concrete is far from the condition mentioned above. It is only taken into account if the concentration increases with the increase of the free water.

1. Compressive strength of the concrete

The test results for concrete with water to cement ratio of C/W = 0.5 are shown in Fig. 5 obviously showing that:

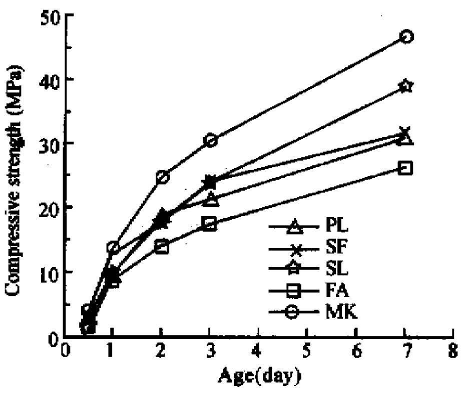

Fig.5 Compressive strength of concrete vs age
SL: slag; SF: silica fume; PL: plain concrete; MK: metakaolin; FA: fly ash

1) The compressive strength of the concrete increases with time. The water to cement ratio plays an important role, especially at the early stage.

2) For the same water to cement ratio, the compressive strength of concrete with different admixtures is different. The compressive strength of concrete with metakaolin is always higher than that of other kinds of concrete. Concrete with slag is lower in compressive strength before two days, while its incremental rate is obviously higher than that of other kinds of concrete after that time. The compressive strength of the concrete with incorporation of fly ash is always lower than that of other kinds of concrete.

2. Resistivity

The resistivity vs time curves of concrete with different admixtures at a water to cement ratio of 0.5 are shown in Fig.6; those of normal concrete with different water cement ratio are shown in the Fig.7.

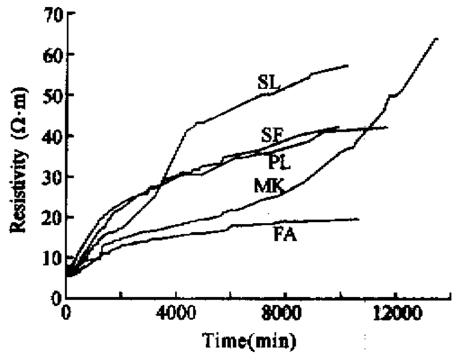

Fig.6 Resistivity vs time (water to cement ratio of 0.5)

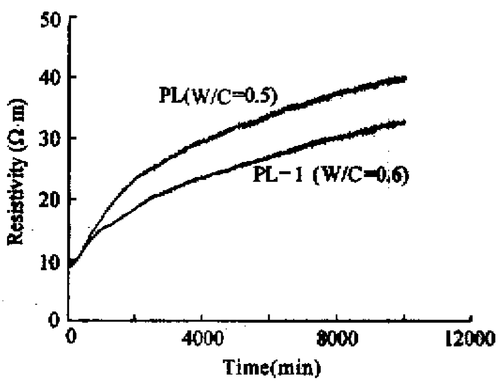

Fig.7 Resistivity of ordinary concrete with different water to cement ratio vs time

Fig. 6 shows that the resistivity of concrete with slag is quite low before 2 days but increases fast, and finally exceeds that of other kinds of concrete after two days. The resistivity of the concrete with fly ash is always lower than that of other kinds of concrete. This trend agrees well with compressive test results.

Fig.7 comparing the receptivity of concrete with different cement to water ratio shows that: (1) The resistivity of concrete with higher water to cement ratio is small and increases slower with time. With passage of time, the water changes to either combined water in some of the composites, or crystallized water, so that the free water becomes less and less; (2) as the time passes by, the free water reduces while the resistivity of the concrete increases. Ions are ionized by the free water in the cement paste (the coarse and fine aggregate, as the rock and sand cannot be ionized). On the other hand, the ions mainly go through the cement paste, only legibly few ions go through the aggregates; (3) Based on the two reasons above, the higher the cement to aggregate ratio, the lower is the resistivity. The resistivity is also related to the porosity of the concrete. The more the pores, the higher the water content, the shorter the route of the movement; (4) the more the pores in the young concrete, the lower is its resistivity.

3. The relationship of resistivity with compressive strength

The relationship between the compressive strength of normal concrete with water to cement ratio of 0.5 and the resistivity is shown in Fig.8 (solid line is the calculated roughly linear curve) showing that. 1) there is high correlation between the resistivity and compressive strength; 2) the resistivity of young concrete (before 7 days) can be represented by the compressive strength at 28 days.

$$\rho_c = (3.362e^{0.0405t}) f_{c28} \tag{4}$$

ρ_c: resistivity of the concrete (Ωm)
f_{c28}: compressive strength at 28 days (Mpa)
t: age of the concrete (day) [$0.5\text{day} \leqslant t \leqslant 7.0\text{ day}$]

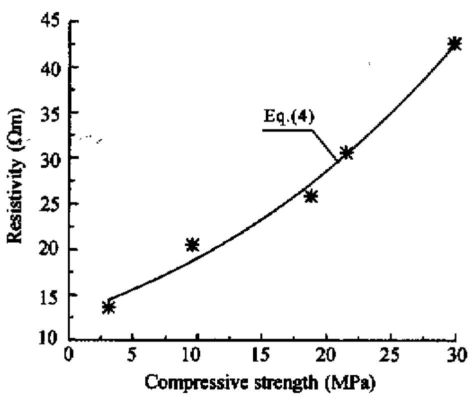

Fig.8 Relationship of the resistivity to compressive strength

4. Dielectric constant

During the concrete formation process from adding water-initial set-final set-hardening, the viscosity gradually increases until the concrete finally hardens to stop the movement of the polarized molecules, which will reduce the dielectric constant to a finally basically fixed value. Meanwhile, the hardering of the concrete impedes the movement of the movement of the ions and makes the route more complicated. The dielectric constant vs time curves are shown in Fig.9 showing that: (1) The change of the dielectric constant occurs before the final set of the concrete, and are very much slower after the final set, when conditions are rather stable. This is different from the change of the resistivity. (2) There is an obvious peak during the initial set of concrete with metakaolin, while no change can be found in other kinds of concretes. It can be seen that there is obvious drop in the final set of all the concretes, in particular, the reduction amplitude is very large in the final set of the concrete with metakaolin and the concrete with silica fume. There are few re-

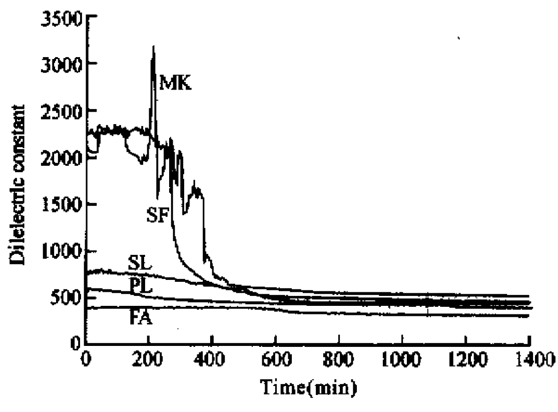

Fig.9 Dielectric constant vs time

ports on the concrete micro-structure's influence on the dielectric constant. McCarter et al.(1984)'s report of a descending peak in the resistivity during the hydration process (around 500 - 1000 minutes after casting); and an ascending peak in the dielectric constant, indicated that the chemical activity was re-generated at the time when the cement paste started to harden. When the water to cement ratio is high, the hardening of the cement is slower, so that the chemical activity occurs late. The curve's peak value drifts later with the increment of the water. Similar phenomena were observed in some concrete specimens of our experiments.

CONCLUSIONS

1. To study the characteristics of young concrete, measurements of the resistivity and the dielectric constant were carried out on specimens with different admixtures and mixture proportions. The measuring technique developed in this study has very little influence on the electrochemical reactions and can yield accurate long duration data automatic for autocratic collection.

2. The resistivity vs time curve of young concrete is similar to the compressive strength vs. time curve, so the hydration level can be monitored by measuring the resistivity.

3. There was obvious change in the resistivity during the final set of the concrete sample.

4. Increasing the water to cement ratio reduces the resistivity, whose change is then slower with time, so that the hardening of the concrete is delayed.

5. There is sudden change in the dielectric constant around the time of the initial set and the final set. The change of the dielectric constant occurs before the final set. It stays almost stable after that, which is different from the change of the resistivity.

6. The relationship of the normal concrete strength and the resistivity before the age of 7 days can be represented by Eq. (4).

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