CONCRETE CRACK POTENTIAL PREDICTIONS WITH THE AID OF A NOVEL PLASTIC RING, ELECTRICAL RESISTIVITY AND SETTING TIME

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Abstract:

Hydration and restrained shrinkage crack behaviours of different concrete grades were independently monitored using a non-contact electrical resistivity apparatus and a novel plastic ring mould respectively. The electrical resistivity curve trend is similar for all the concrete samples, in which the lowest concrete grade has the highest resistivity until reaching acceleration point which was then overtaken by the highest concrete grade. Four different hydration periods were identified upon which the hydration process can be based; these periods are classified into dissolution, induction, acceleration and deceleration periods. Also, initial and final setting times for the samples were examined, which confirmed that the decreasing rate of resistivity development for the lower concrete grade corresponds to its initial setting time range. Restrained shrinkage crack result shows that the highest concrete grade propagated cracks earlier than the lowest concrete grade and thereby the higher cracking potential of higher strength mixture was confirmed. Linear fitting was then developed to estimate concrete crack potential based on its electrical resistivity. Hence, both electrical resistivity measurement and novel plastic mould (which is very cheap, user-friendly and fast filled) are hereby proposed as a convenient alternative means of assessing concrete cracking potential.

1 Introduction

Once cementitious material has been mixed with water, cast and exposed to drying, there is always a decrease in the moisture from capillary and gel pore microstructure. These phenomena lead to the reduction in volume which is referred to as shrinkage. When such material is restrained from shrinking, a tensile stress is gradually being developed in it and once the stress has been generated in the material, it exceeds its attained tensile strength and eventually crack occurs. The crack susceptibility of any

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cementitious mixture depends on many factors such as type and quantity of the mixture constituents, temperature, relative humidity, the age (early-age or later-age shrinkage) when it is subjected to drying environment conditions, size/geometry of the structure and the degree of restraint [1].

It has been established by [2] that metal and concrete are strongly affected by adverse environmental effects and atmospheric weathering such as crack, which is why they are prone to failure during their service time. Therefore, measures need to be taken to avoid excessive failure, and this gives rise to the continuous search and use of the more modern concrete technology [3] which forms a part of an interesting objective of the present research. One method for eliminating or reducing the crack associated problems is to study the crack potential of any material before being used as a component/constituent of concrete so that optimum quantity of such material would be used. A standard procedure for determining crack potential of concrete has been provided by [4] so that any further proposed methods must comply with this. A steel ring was employed by [5] in order to ascertain the concrete restrained shrinkage crack behavior, but it took longer time before achieving the required result. Some of the previously tested apparatuses/devices for crack prediction of cementitious materials have not yielded any precise result [4]: Similarly, no research is conducted that correlates with the restrained shrinkage crack of concrete and its electrical resistivity. These are the points that make the present research new and different from the previously conducted research, which is the use of new apparatus that are convenient and fast in the prediction of crack propagation in concrete structures.

The present study is undertaken to make experiments with concrete samples of different strength and to explore their strength, durability, and behavioral differences which are due to different strength grade. The conducted experiments include electrical resistivity measurement, restrained shrinkage crack, and setting time.

Previous research papers showed that restrained shrinkage of cementitious materials was influenced by factors such as geometry of the specimen, properties of concrete constituents, humidity, shrinkage conditions, degree of restraint offered due to the stiffness of the restraining element, effect of micro cracking and creep parameters of concrete [6]. Therefore, this study is focused on monitoring the hydration process of concrete samples of strength grade 30 to 50 MPa using a non-contact electrical resistivity apparatus, restrained shrinkage cracking prediction of those samples using a novel restrained shrinkage plastic ring mould, determination of their respective setting times and then establishing a mathematical equation for concrete crack potential prediction based on experimental findings.

Therefore, utilizing the new plastic ring mould to assess the restrained shrinkage cracking potential of concrete proved to be convenient and fast, the adoption of such a tool and the mathematical equation based on electrical resistivity would become alternative tools of quality control in construction industry so that concrete durability problem would be addressed at the early age of concreting thereby improving construction productivity, structural safety, service performance and service life of structures obtained from such concreting.

2 Materials, sample preparation and experiments

2.1 Materials

Ordinary Portland cement PO 52.5, Natural River sand, crushed stones of average size5-10mm and portable water at varying proportions were used to form the concrete samples.

2.2 Sample preparation

Three different mix proportions were prepared and cast as concrete samples to achieve different compressive strength grades as C30, C40 and C50 presented in Table 1.

2.3 Experiments

2.3.1 Electrical resistivity

Three different samples corresponding to each particular strength grade were consecutively subjected to electrical resistivity measurement in which the average value of the resistivity measurement was considered as the resistivity trend of such concrete grade. Each concrete sample was cast in the non-contact electrical resistivity mould for resistivity measurement of 24 hours; this detailed operational procedure of the apparatus is as previously mentioned presented by [7]. Temperature and humidity conditions were maintained at 20 ± 2^0C and 98±2 respectively throughout the experiment.

The obtained result is plotted and presented under the results section.

Table 1. Mix proportion of the concrete samples

Sample	Water kg/m^3	Cement kg/m^3	Sand kg/m^3	Coarse Agg. kg/m^3
C30	250	455	523	1112
C40	250	521	486	1083
C50	250	610	447	1036

2.3.2 Restrained shrinkage crack

A new plastic ring mould shown in Figure 1 was adopted to provide restraint to a shrinking concrete. Under conditions of this experiment, similar concrete samples were prepared and cast in the mould, a glass plate of 1mm thick was fixed at half depth of the mould to induce the anticipated pre-crack. Having attained its setting time strength before hardening, the outer cover of the mould and the plate were removed in order to permit drying from top and side surfaces until crack occurred as shown in the figure. The cracking time and location for all the samples were monitored and presented in the results section.

Figure 1. Novel restrained shrinkage ring mould and cracked sample.

2.3.3 Setting time

Similar concrete samples were prepared and subjected to setting time test based on ASTM C403-08 penetration resistance method. Three different samples for each concrete strength grade were cast and subjected to setting time test., The average value of the three tested samples is considered to be the setting time of such strength grade. A graph of penetration resistance (in MPa) against the elapsed time, the initial and final setting time for each of the samples were those corresponding to 3.5 MPa and 27.6 MPa respectively. The temperature and relative humidity were also maintained at 20^{0}C$\pm$2^{0}C and 50%$\pm$2% respectively throughout the experiment.

3 Results and discussion

3.1 Electrical resistivity

The first 24 hours of electrical resistivity development $(\rho(t)-t)$ curve for the tested concrete grades is shown in Figure 2. It can be observed that all the curves followed the same trend and that they are similar to the heat evolution curve of cement, with C30 having the highest resistivity until when C50 reached its setting time, then they out-passed the others. This is due to low aggregate and higher cement content of C50, which is similar to the previous research findings of the research conducted by [8,9] on concrete containing some admixture of different strength grades.

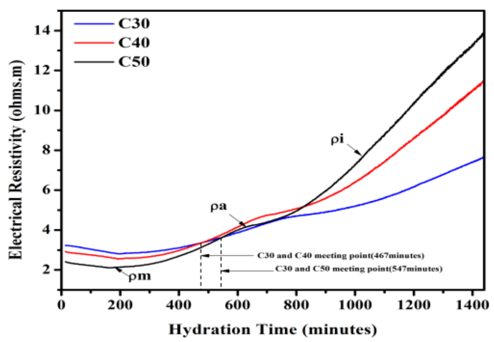

Figure 2. Electrical resistivity development of concrete for a period of 1440 minutes.

Figure 3 shows resistivity derivative curves $d\rho(t)/dt-t$ for all the tested samples, in which four periods were identified based on the critical points pm, pa and pi upon which the hydration process was classified. The four classified periods are dissolution period (I), an induction period (II), an acceleration period (III) and a deceleration/ diffusion controlled period (IV) which are similar to those reported previously on different strength grades and their definitions were described in the work carried out by [10,11,12], and hence re-presented in Table 2. Therefore, it is proved that electrical resistivity measurement is an effective indicator of the

hydration process of concrete as similarly obtained in the case of cement pastes [11].
It also shows that, as the concrete is hydrating, the pores are decreasing, thereby making the mixture less conductive to electricity and the phenomenon continues, as such making it a semiconductor. Secondly, inflection points (t_i's) for the various samples were also identified as shown in the Figure 3. It can be seen that the time when final inflection occurred is delayed as the concrete grade decreases, this is quite clear when considering the inflection time of C50 as 17.02 hours which is earlier than those of C40 and C30 which are 18.08 and 18.95 hours, respectively. Therefore, this confirms the higher resistivity of mixture containing higher cement and lower aggregate content after setting time.

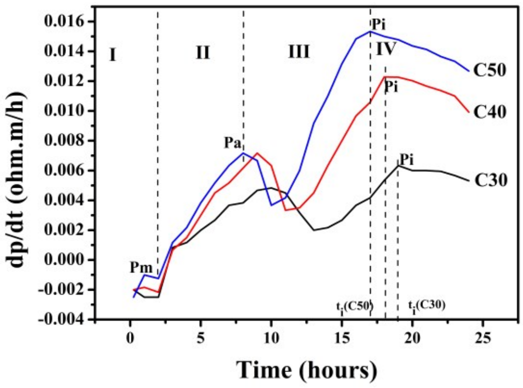

Figure 3. Electrical resistivity derivative curves for the concrete samples.

Table 2. Hydration stages and their characteristics

Period name	Range	Characteristics	$\rho_0(t)$ and φ (t)
Dissolution period (I)	$t \le tm$	$d\rho / dt \le 0$, dissolution of cemented-based materials, chemical control	φ (t) changes slightly $\rho_0(t)$ changes significantly
Induction period(II)	$tm < t \le ta$	$d\rho / dt \le 0$ coating formation and retarding dissolution, nucleation or diffusion control	φ (t) changes slightly $\rho_0(t)$ changes slightly
Acceleration period (III)	$ta < t \le ti$	$0 < d\rho / dt \le d\rho(i) / dt$ accelerating growth of hydrates, chemical control	$\varphi(t)$ changes significantly $\rho_0(t)$ changes slightly
Deceleration and diffusion controlled period (IV)	$t > ti$	$0 < d\rho / dt \le d\rho(i) / dt$ slow and steady formation of hydrates, chemical and diffusion control	φ (t) changes slowly $\rho_0(t)$ changes slightly

3.2 Crack susceptibility

Based on the result obtained from restrained shrinkage crack test shown in Table 3, it indicates that C50 cracked 50.22 hours after casting, which is earlier than that of C40 that cracked 64.32 hours later and C30 that cracked at a later time of 70.03 hours and all the cracks occurred beneath the artificially introduced pre-crack, which signifies that the higher the concrete grade, the earlier the crack time, which therefore confirmed its higher susceptibility to crack and which is consistent to the previous findings obtained from different apparatuses. This shows that the new plastic ring mould can predict the crack time of concrete mixture within a short experimental period. Therefore, it is introduced as an alternative method; it would be useful in quality control of concrete mixture.

Table 3. Experimental results

Sample	Inflection Time t_i / h	Crack Time t_c / h	Setting Time / h	
			Initial	Final
C30	18.95	70.03	7.58	10.38
C40	18.08	64.32	7.18	10.33
C50	17.02	50.22	6.32	8.83

3.3 Relationship between electrical resistivity and restrained crack results

The sequence of the inflection point occurrence time among tested concrete samples is similar to the time sequence of their respective cracking occurrence. Therefore, this shows that a positive relationship between the two parameters which lead to the formulation of a mathematical equation relating to the two. A mathematical model for predicting propagation crack time in concrete structures based on electrical resistivity has been developed. This has been achieved from the linear fitting between the inflection points for various concrete samples identified on the $d\rho(t)/dt - t$ curves and their respective time-dependent crack propagation as shown in Figure 4 and the mathematical expression is presented in Equation 1 below:

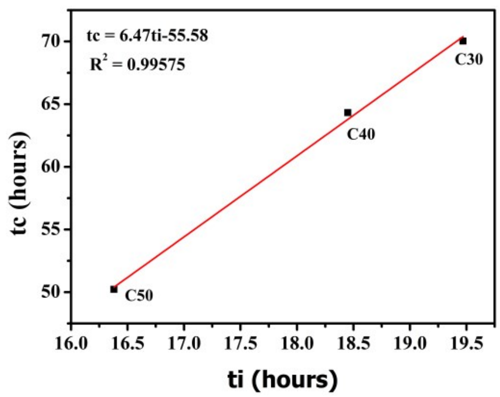

Figure 4. Relationship between the cracking time t_c and inflection time t_i of concrete.

$$t_c = 6.47t_i - 55.58, \quad R^2 = 0,9985 \qquad (1)$$

where t_c and t_i are the crack and inflection time expressed respectively in hours. It, therefore, proved that concrete electrical resistivity can be effectively utilized to predict its crack propagation tendencies with a limitation to the range of the grades considered (C30-C50). Equation 1 shows that highest concrete grade (C50) has higher potential for crack propagation and vice-versa; this equation is useful at design stage to enable the adoption of optimum quantity of the concrete constituents in order to avoid the risk associated with restrained shrinkage cracking.

3.4 Setting time and crack susceptibility

A study has already been undertaken by [13] on the relationship between the electrical resistivity and setting time of cement paste, whereas in the present work, a relationship has been developed between the crack growth rate and the final setting time of concrete. Table 2 shows the final setting time for the various types of concrete grades which follows a similar sequence of occurrence to the sequence of cracking occurrence among the concrete sample. Figure 5 shows the t_c's plotted against t_f's for the samples and Equation 2 shows the linear fitting obtained from the correlations of the two parameters.

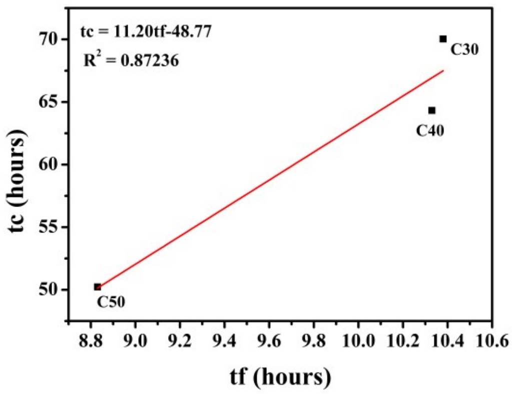

Figure 5. Relationship between the cracking time t_c and final setting time t_f of concrete.

$$t_c = 11.20t_i - 48.77, \quad R^2 = 0,87 \qquad (2)$$

where t_c and t_f refer to cracking time and final setting time respectively expressed in hours. Equation 2 shows that the shorter the setting time, the earlier the crack time which is consistent with the various experimental results shown in Table 3, namely, the lower the water cement ratio, the higher concrete grade, and consequently, the earlier setting and crack growth time. It is limited to the range of the concrete grade considered as C30 to C50. This indicates that setting time is an alternative method for predicting the cracking potential of concrete mixtures.

4 Conclusions

Based on the above findings, the following conclusions were drawn:

1. That electrical resistivity as an indicator of the hydration process of cementitious mixture can also

be effectively utilized to predict potential crack propagation in concrete.

2. The novel restrained shrinkage cracking plastic ring mould has been tested and proved convenient tool for assessing the potential cracking of different concrete mixture within a short experimental period so that measures would be taken to control the dosage of constituents and exposure condition in concrete structures. The experiment revealed that high- early-strength concrete may cause premature cracking under the same given degree of restraint. Generally, higher concrete grade achieved from lower water-cement ratio has higher electrical resistivity, longer setting time, and earliest cracking time, therefore proved its higher potential for cracking.

3. A linear fit equation has also been developed on the relationship between electrical resistivity and restrained shrinkage crack which can also be used to predict the cracking tendency of concrete mixture, another model has been developed based on restrained shrinkage crack and setting time of concrete. These equations have some limitations to their application with regard to the range of concrete grades which lies between C30 and C50 grades and no influence of admixture is considered in the equations. It indicates that, potential for concrete cracking can be predicted easily from its electrical resistivity measurements and or its setting time result. Therefore, these items are proposed as alternative methods for predicting potential cracking propagation in concrete structures.

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