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Correlations between the Strength and Electrical Resistance of Concrete. Part 1. A Brief Overview

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Abstract

Introduction. The existing methods of non-destructive testing of concrete strength entail access to the concrete surface, which is not always possible to accomplish in concrete work technology. E.g., while continuously forming a structure in a sliding formwork, it is required that the strength of the concrete is identified during the molding process with no direct access to the layers of the hardening concrete mix being laid. The well-known method of identifying concrete strength by means of measuring its electrical resistance is neither commonly used nor standardized, and tends to yield contradictory results. The aim of the study of the first part of the article is to investigate the previously identified correlations between the concrete strength and its electrical resistance, to identify the advantages and disadvantages of measurement methods in order to find how feasible such an approach is for identifying a method for sinking concrete.

Materials and Methods. The classical method of literature review is employed with grouping of certain features into separate comparative tables followed by generalization assisting understanding an extent to which the research topic has been studied. Those were only the most important and informative, largely foreign, sources that were selected from the reviewed sources.

Research Results. The analysis of the review data enabled us to identify the methods of measuring electrical resistance (surface, volumetric, internal, direct ones), types of the investigated concrete, sample sizes, test dates, concrete strength ranges, types of dependencies and correlation coefficients. Among the factors affecting the measurement result were the following: water-cement ratio, type of binder and aggregates, type of additives, temperature of concrete, its porosity, etc. To explain the essence of the methods for identifying concrete electrical resistance, a brief overview is provided.

Discussion and Conclusion. The major difficulty of the indirect methods of identifying the strength lies in designing calibration dependencies with the results affected by a wide range of factors. There are also some difficulties with fastening of ohmic contacts to the formwork or concrete. All of these will be accounted for in follow-up studies to identify the relationship between the concrete strength and electrical resistance and to improve the measurement accuracy. The advantages of the method of strength control, such as maintaining the integrity of the structure, efficiency and low measurement complexity enable it to be employed in automated concrete technologies.

Keywords: non-destructive testing methods, concrete strength, concrete electrical resistance, concrete technology, correlation

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Оригинальное эмпирическое исследование

Корреляции между прочностью и электрическим сопротивлением бетона. Часть 1. Краткий обзор

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Аннотация

Введение. Существующие методы неразрушающего контроля прочности бетона предполагают доступ к поверхности бетона, что не всегда возможно в технологии бетонных работ. Например, при непрерывном формовании конструкции в скользящей опалубке требуется определять прочность бетона в процессе формования без непосредственного доступа к уложенным слоям твердеющей бетонной смеси. Известный метод определения прочности бетона посредством измерения его электросопротивления редко используется, не стандартизирован и часто приводит к противоречивым результатам. Целью исследования первой части статьи является изучение обнаруженных ранее корреляций между прочностью бетона и его электросопротивлением, выявление преимуществ и недостатков методов измерений, чтобы выяснить целесообразность такого подхода для способа опускающегося бетона.

Материалы и методы. Применен классический метод обзора литературы с группированием определенных признаков в отдельные сравнительные таблицы с последующим обобщением, что облегчает понимание разработанности темы статьи. Из рассмотренных источников были выбраны только самые важные и информативные, в основном, иностранные.

Результаты исследования. Анализ данных обзора позволил установить: способы измерения электросопротивления (поверхностный, объёмный, внутренний, прямой), типы исследованных бетонов, размеры выборок, сроки испытаний, диапазоны прочности бетона, типы зависимостей и коэффициенты корреляции. Среди факторов, влияющих на результат, измерений отмечены: водоцементное отношение, тип вяжущего и заполнителей, вид добавок, температура бетона, его пористость и др. Для пояснения сути методов определения электросопротивления бетона приведена краткая информация.

Обсуждение и заключение. Основной сложностью в косвенных методах определения прочности является построение градуировочных зависимостей, на результаты могут оказывать влияние различные факторы. Трудности связаны также с креплением омических контактов на опалубку или бетон. Все эти особенности будут учтены в дальнейших исследованиях для определения связи между прочностью и электросопротивлением бетона и повышения точности измерений. Преимущества рассмотренного способа контроля прочности, такие как сохранение целостности конструкции, оперативность и малая трудоёмкость измерений, обуславливают его применение в автоматизированных бетонных технологиях.

Ключевые слова: неразрушающие методы испытаний, прочность бетона, электрическое сопротивление бетона, технология бетона, корреляция

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Introduction. In the patented technology of sinking concrete developed at South Ural State University [1] and in other automated concrete technologies, there is a task of controlling concrete strength directly in the mold (formwork), which allows no access to a concrete surface for traditional methods of non-destructive testing. The possibility of assessing the strength of concrete by its electrical resistance was accepted as a hypothesis with monitoring sensors easily placed on the formwork and requiring no stopping of production and access to the structure.

Concrete strength tests must be conducted in compliance with the requirements of GOST 28570 "Concretes. Methods for Identifying Strength Based on Samples Taken from Structures", GOST 22690 "Concretes. Identifying Strength with Mechanical Methods of Non-Destructive Testing", GOST 17624 "Concrete. Method for Identifying Ultrasonic Strength", GOST 18105 "Concrete. Rules for Strength Control and Evaluation", GOST 10180 "Concretes. Methods for Identifying

Strength Using Control Samples". There are three groups of concrete strength control methods: destructive, non-destructive direct and non-destructive indirect ones. The first group of methods enables one to obtain the most reliable data on concrete strength, as the deep layers of the structure are tested, but they are labour-intensive during testing and call for local damage in structures to be fixed. At the same time, non-destructive methods retain the structure integrity, are relatively not costly, but call for calibration dependencies to be designed for each concrete type and composition. At the same time, a broad range of factors has a major effect on the measurement accuracy, such as defects and fittings in the measuring area, concrete surface condition, temperature, humidity, etc. [2].

Materials and Methods. Non-destructive testing is an essential part of the technology of production and application of ready-mixed concrete and precast reinforced concrete. Modern standards establish the mandatory use of non-destructive methods in order to identify concrete strength based on pre-established calibration dependencies [3]. The complexity of non-destructive testing lies directly of measuring a parameter with a device (striker rebound, impact pulse, ultrasound velocity, fingerprint diameter, etc.) after an appropriate number of measurements has been performed.

However, the above standards fail to standardize the method of electrical resistance strength control. According to the literature on the topic [3–13], electrical resistance is largely closely related to concrete strength, but calls for proper calibration and accounting for the parameters of the mix, and for certain types of concrete there might be no or a negative correlation.

The literature review explored the following research aspects: concrete type, sample size, method of measuring electrical resistance, concrete strength range, correlation coefficient type, influencing factor type and influence outcome.

Research Results. Measurements of electrical resistance have different correlations with concrete compressive strength. The studies [4] identified a logarithmic dependence, and at the same time, the authors of [8] using the Venner probe confirm a strong nonlinear logarithmic dependence (R^2 > 0,99). In [10] it is concluded that the methods of internal electrical resistance reliably predict the strength of mixes with different properties of binder and filler. This study also serves as evidence of a strong positive correlation (R^2 values from 0,823 to 0,999). On the contrary, the authors of [12] failed to identify a considerable correlation in electrically conductive concretes, and [7] notes a negative correlation while replacing a large aggregate with steel slag (which appears to make sense).

Some studies also show that the parameters of the concrete mix, such as the ratio of water and cement or water and binder, the cement type and the use of additives (zeolite or pozzolan) impact both electrical resistivity and strength [9]. Different methods of measuring resistance also have an effect on the correlation strength [10]. These results show that provided proper calibration is performed and the influencing factors are accounted for, measurements of electrical resistivity can serve as a practical non-destructive method for evaluating concrete strength of building materials [8]. The key characteristics of the studies are shown in Table 1.

Table 1

Key characteristics of the studies included

Researchers, source	Concrete type	Sample size	Research duration
Araújo and Meira, 2022 [4]	Six different mixes	No mention found	No mention found
Deda, 2020 [10]	24 mixes with a different content of fillers, water-binder ratio, additives	24 mixes	Up to 28 days
Dehghanpour and Yılmaz, 2019 [12]	Electrically conductive concrete with carbon fiber and black carbon	8 mixes and control series	28 days
Hnin et al., 2016 [13]	Different water-binder ratio, ash-cement paste content	No mention found	No mention found
Medeiros-Junior et al., 2014 [9]	12 mixes with four types of Brazilian cement	12 mixes	The same
Medeiros-Junior et al., 2019 [6]	Mixes with two cement types and different pozzolan content	No mention found	The same
Nzar et al., 2022 [7]	Normal strength concrete with steel slag waste as a coarse aggregate	338 data points	1–180 days
Scasserra et al., 2023 [8]	Precast reinforced concrete	No mention found	Up to 28 days
Silva et al., 2016 [5]	No mention found	The same	Up to 28 days
Yurt et al., 2023 [11]	Alkali-activated concrete composites	4 mixes	28 days
Stackelberg et al., 2010 [3]	Cement-concrete composites	8 mixes	No mention found

An analysis of the studies included revealed the following.

Concrete types: in 6 studies a few mixes with different compositions were used; in 4 studies, specialized concretes (e.g., electrically conductive, precast, alkali-resistant) were used; in one study, no information on the concrete type was found.

Sample size: mentioned in 6 studies and is not indicated in 5 studies. The reported sample size ranged from 4 to 24 mixes, and one study included 338 data points.

Study duration: there are mentions of study duration in 6 studies; there are no mentions in 5 studies. Of these, 3 studies took up to 28 days to complete, two studies took exactly 28 days to complete, and one study lasted from 1 to 180 days.

The analyzed studies to identify the correlation type between the electrical resistance and concrete strength, the research results are summarized in Table 2.

Table 2

Correlations between the electrical resistance and strength

Researchers, source	Method of electrical resistance studies	Strength range	Correlation coefficient	Results
Araújo and Meira, 2022 [4]	Surface electrical resistance	No mention found	No mention found	The logarithmic ratio
Deda, 2020 [10]	Volumetric, surface and internal	The same	The same	Electrical resistance is reliable for strength prediction
Dehghanpour and Yılmaz, 2019 [12]	Dual Probe Sensor, Venner Method and ASTM C1760-12	The same	Not relevant	No correlations to mention
Hnin et al., 2016 [13]	Four Venner probes	The same	No mention found	A good correlation
Medeiros-Junior et al., 2014 [9]	Surface electrical resistance	The same	R^2 = 0.823–0.999	A strong positive correlation
Medeiros-Junior et al., 2019 [6]	No mention found	The same	No mention found	The inverse proportionality of the water-cement ratio (w/c)
Nzar et al., 2022 [7]	The same	10–55 MPa	The same	Negative correlation with steel slag
Scasserra et al., 2023 [8]	Venner's method (four-probe)	No mention found	$R^2 > 0.99$	Strong nonlinear logarithmic correlation
Silva et al., 2016 [5]	No mention found	The same	No mention found	A close bond
Yurt et al., 2023 [11]	Direct measurement (megaohmmeter)	The same	The same	Strong bond, decrease in the strength as the proportion of zeolite in the composition rises
Stackelberg et al., 2010 [3]	No mention found	2–72 MPa (according to the graphs)	The same	A linear or close to linear correlation

Let us provide a brief explanation of the essence of the major methods employed. The two-probe method (a sensor) is used to measure the resistivity of samples with a regular geometric shape and a constant cross-section. In this case, ohmic contacts are made on the end faces of a sample, e.g., in the form of a rectangular plate, i.e., contacts between a metal and a semiconductor or two dissimilar semiconductors with linear and symmetrical volt-ampere characteristics. An electric current is passed through these contacts along the sample. Two contacts in the form of metal probe needles are installed on a sample surface along the current lines, which have a small contact area with the surface and allow the potential difference to be measured. If the sample is homogeneous, its resistivity is measured in Ohm · cm.

The four-probe method for measuring the resistivity of semiconductors (the Wenner method) is the most common one. In addition to high metrological parameters, the advantage of the method is that its application does not call for designing ohmic contacts to the sample, it is possible to measure the resistivity of bulk samples of a wide range of shapes and sizes, as well as the resistivity of layers of semiconductor structures. As far as the sample shape is concerned, it can be used provided that there is a flat surface with the linear dimensions beyond those of the probe system. Four probes placed at an equal distance are applied to the sample in a line. Two external probes supply current to the sample, and two internal probes measure the resulting potential drop. All the probes are mounted on the same sample surface making the method suitable for on-site measurements of bulk concrete resistivity.

The method according to the ASTM C1760-12 standard is designed to identify the volumetric electrical conductivity of saturated samples of hardened concrete. The aim of the method is provide a quick evaluation of concrete resistance to chloride ion penetration by means of diffusion. The measurement procedure is as follows:

1) a cylindrical sample with a diameter of 10 cm and a length of 20 cm is placed between two cells filled with a sodium chloride solution;

2) A potential of 60 volts is applied between the cells;

3) the total amount of current in a minute between two cells is measured;

4) based on the measured current, applied voltage, and sample size, the volumetric concrete electrical conductivity is calculated.

The measurement results were influenced by a number of factors, including the water-cement materials ratio, the type and quantity of additional cement materials, polymer additives, etc.[1]

The analysis of the correlations of electrical resistance and strength revealed the following. References to methods of identifying electrical resistance were found in all of the studies:

– surface methods were mentioned in 3 studies;

– Venner's methods were mentioned in 3 studies;

– the other methods (internal, volumetric according to ASTM C1760-12, direct) were mentioned in individual studies;

– no mention of a specific method was found for 4 studies.

Correlation coefficients: correlation coefficients were mentioned in 3 studies:

– a strong correlation was reported in two studies ($R^2 > 0.99$ or $R^2 = 0.823–0.999$);

– in one study, it was concluded that there was no considerable correlation (corresponding to $r < 0.6–0.7$ in technical sciences).

The importance of the mutual bonds: all of the studies provided some information on the significance of a relationship between electrical resistance and concrete strength:

– logarithmic dependencies were reported in 2 studies;

– strong ratios with no type specification were reported in 2 studies;

– a negative correlation with concrete additives was found in 2 studies (steel slag, zeolite);

– individual studies reported: a linear or close to linear correlation, inconsiderable correlation, good correlation, inverse dependence on the water-dry matter ratio, as well as a correlation from the internal electrical resistance reliable for predicting the strength.

Concrete strength range: the concrete strength range was mentioned in only 2 studies (10–55 and 2–72 MPa).

The influencing factors were directly indicated in most of the studies included (Table 3).

The analysis of the influencing factors showed the following.

Types of the factors: The types of factors are indicated in all of the studies included. The most common factors were the water-binder ratio and temperature mentioned in 2 studies. Each of the other 14 factors was mentioned in only one study.

The effect on electrical resistance was indicated in 8 studies: various factors were report to influence electrical resistance in 4 studies; in each of the 11 studies, a significant effect was reported: increased conductivity, decreased electrical resistance, or that it depends on time and water-cement ratio (w/c).

The effect on the strength was mentioned in 7 studies: the experiments revealed a considerable or enhanced strength; each study reported that strength depends on the cement type, water-cement ratio, porosity, additives, and decreases when zeolite is added. No mention of the effect on the resistance in 2 studies and the effect on the strength in 4 studies was found.

[1] Note:the ASTM C1760-12 method was abolished in January 2021

Different methods of measuring the electrical resistivity were used in the studies, including surface, volumetric and internal ones. Although a direct comparison of accuracy and reliability in all of the studies is limited due to a wide range of approaches being employed, a few key conclusions can be made.

Table 3

Description of the influencing factors

Researchers, source	Factor type	Impact on the electrical resistance	Impact on the strength
Araújo and Meira, 2022 [4]	No mention found	No mention found	No mention found
Deda, 2020 [10]	A binder type, a filler nature	Considerable impact	Considerable impact
Dehghanpour and Yılmaz, 2019 [12]	Carbon fiber, black nanocarbon	Increased conductivity	Enhanced strength
Hnin et al., 2016 [13]	Water/binder ratio, fly ash content	Influenced by the factors	Influenced by the factors
Medeiros-Junior et al., 2014 [9]	Cement type, water/binder ratio	Increases with time, decreases as the w/c ratio rises	Depends on the cement type
Medeiros-Junior et al., 2019 [6]	Pozzolan content in the water/cement ratio (w/c)	Higher with a larger amount of pozzolan, lower with a higher w/c ratio	Lower with a higher w/c
Nzar et al., 2022 [7]	Steel slag content	Reduced	Increased
Scasserra et al., 2023 [8]	Temperature, shape, sample size	Influenced by the factors	No mention found
Silva et al., 2016 [5]	Temperature	Influenced by the temperature	The same
Yurt et al., 2023 [11]	Zeolite replacement, activation temperature	Influenced by the factors	Decreases as the zeolite content rises
Stackelberg et al., 2010 [3]	Porosity of the cement stone and cement-concrete compositions	Proportional to the increase in the gel porosity	Proportional to the increase in the strength

Surface and internal measurements: in [10] the methods of internal electrical resistance proved to be especially reliable for predicting compressive strength. This is indicative of likely differences in accuracy between surface and internal measurement methods.

Comparison of a few methods: in [12], three different methods were compared (two-probe, Venner method and ASTM C1760-12). Although none of them was able to identify a significant relationship with the strength of conductive concretes, the linear relationships between the resistivity values measured by means of these methods proved to be appropriate indicating the consistency of the results obtained using a range of measurement methods.

Using Venner probes: in [8, 12, 13] the Venner probe method was used indicating its wide application range in this kind of studies. The authors of [8] reported a very strong correlation ($R^2 > 0.99$) while using this method indicating its potential reliability.

Special equipment: The researchers [11] made use of a megaohmmeter to directly measure resistance, which might be an advantage for some concrete types (e.g., for alkali-activated composites).

Discussion and Conclusion. The studies identified a few potential practical applications of measuring electrical resistivity to evaluate concrete strength.

Non-destructive testing: In [8] the importance of using electrical resistance as a non-destructive method for evaluating concrete strength in producing precast reinforced concrete structures is emphasized.

Concrete strength evaluation at an early age: the researchers [5] demonstrated the possibility of predicting strength at the age of 28 days by measuring resistivity at an early age.

Quality control: The strong correlations identified in most of the studies suggest that resistivity measurement can be employed as a fast and efficient method of continuous quality control in concrete production [3, 4, 8–10].

Specialized concretes: Studies of conductive concretes [12] and alkali-activated composites [11] show that resistivity measurements can have unique applications in specialized types of concrete, although the dependencies might differ from those for conventional concretes.

The authors of [8] noted the need for calibration and use of correction factors emphasizing the importance of developing standardized procedures for diverse types of concrete and applications to ensure reliable strength evaluation.

As indicated in an article looking back on lots of years of research [3], the correlations between the strength of cement-concrete compositions and their electrical conductivity are either linear or close to linear ones. In the ongoing study we have attempted to reveal the physical essence of the linear correlations of "strength-electrical resistance". At the same time, it is shown that linear correlations depend on the type and amount of a hardening retarder additive, cement brand and concrete class. The increase in electrical resistance is due to that in the gel component of the porosity formed during hardening, as well as a change in its own electrical conductive properties [3].

Therefore, having considered the advantages and disadvantages of the existing concrete strength control methods, what was clear was that a non-destructive strength control method by means of electrical resistance (indirect method) is applicable for the sinking concrete method. In order to identify further research directions and a method of measuring electrical resistance, the results of the recent research were analyzed with comparative tables designed according to a number of criteria where research methods, sample features, sample sizes, type and degree of correlation, and influencing factors were identified. The analysis was a foundation for further research on a relationship between electrical resistance and concrete strength that the authors are going to report in the second part.

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