ISSN 1061-8309, Russian Journal of Nondestructive Testing, 2017, Vol. 53, No. 11, pp. 805–815. © Pleiades Publishing, Ltd., 2017.

ACOUSTIC METHODS

Assessment of Thermally Deteriorated Concrete by Drilling Resistance Test and Sound Level[1]

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Received December 28, 2016

Abstract—Concrete being the most versatile and widely used construction material finds application in varied range of structures. Many of these like chimneys, furnaces and reactors have to sustain high temperatures and perhaps all structures have to perform at elevated temperatures in the event of fire accidents. Concrete at elevated temperatures undergoes changes in its physical structure and chemical composition and loses its strength characteristics. Need for quick assessment of fire damaged concrete for strength characteristics, has motivated this work, which explores the potential of drilling resistance test on concrete as a Non Destructive Testing (NDT) tool. Drilling times, penetration depths and sound level measurement while drilling have been recorded and analysed to provide monograms that are handy as reckoners in failure forensics.

Keywords: concrete, elevated temperatures, residual strength, drilling resistance tests

DOI: 10.1134/S1061830917110031

1. INTRODUCTION

When concrete is exposed to high temperatures during an accidental fire or sabotages changes in its physical, mechanical properties and durability occur. After the event of fire, structures need to be thoroughly examined in order to know the extent of damage. As concrete structures are composite in nature, evaluation of the residual strength properties of concrete exposed to elevated temperature is a very difficult task. Damage assessment is the first and the most important job for structural safety evaluation of a concrete building subjected to fire [1]. The knowledge of extent of damage helps the structural engineer to plan the repair work and also aids in future design of critical concrete structures.

The assessment of fire damaged concrete, starts with the collection of relevant information such as design of building, construction material, usage of building, cause of the fire and duration of fire spread, then followed by non-destructive testing [2]. Steps involved in assessment of concrete after it is exposed to elevated temperature include physical observation, and in-situ laboratory, non-destructive and partially destructive testing. Visual inspection and colorimetry tests are the ones dealt first, followed by other non-destructive testing methods. Primary objectives of NDT are to produce an immediate value of in-place concrete strength and to be used in structural capacity evaluation, or to locate internal defects in the concrete members which will assist in subsequent adequacy evaluation.

As concrete structures exposed to fire are heterogeneous in nature, the evaluation of the residual properties is quite a difficult task; no single technique can be treated as superior to others. Rebound hammer (Schmidt Hammer) and Ultrasonic Pulse Velocity (UPV) methods are the most commonly used NDT methods for assessment of concrete characteristics. The assessment of fire damaged structures with only non-destructive techniques, is not possible, because of some limitations in the NDT such as, spalling of concrete, extensive cracking, sufficient calibration, voids etc., nor can solely theoretical methods be relied upon, as their application implies knowing the effective temperature histories acting upon structural elements. The simplest way of estimating the loss of concrete strength is by sound level test. Some partially destructive test such as, penetration resistance test gives the indication of areas where the surface com-

[1] The article is published in the original.

Table 1. Physical properties of cement

Sl. no.	Properties	Results	IS Specification
1	Specific gravity (Le-Chatelier's flask)	3.1	Not specified
2	Standard consistency (Vicat's apparatus) (P), %	30	Not specified
3	Fineness (Blaine's Air permeability), m^2/kg	327	225 (Min)
4	Initial setting time (Vicat's apparatus), minutes	60	30 (Min)
5	Final setting time, (Vicat's apparatus) minutes	245	600 (Max)
6	Soundness (Le-Chatelier's), mm	2	10 (Max)
7	Average compressive strength, MPa		
	3 days	31	23 (Min)
	7 days	39	33 (Min)
	28 days	56	43 (Min)

Table 2. Chemical composition of cement

Chemical composition	Results, %
Calcium oxide, CaO	63.5
Silica, SiO_2	21.7
Alumina, Al_2O_3	6.6
Ferric oxide, Fe_2O_3	4.6
Magnesia, MgO	2.4
Alkali content, Na_2O	0.4
Sulfuric unhydrate, SO_3	1.1
Insoluble residue	0.5
Loss on ignition	1.5

pressive strength is relatively lower compared with undamaged areas [3]. The combination of several NDT methods would give a fair assessment.

The first application of the drilling resistance test was based on the measurement of thrust to be exerted on the drill to drive bit at a constant rate in the tested material (bit diameter 4–8 mm, maximum hole depth of 15–20 mm for concrete and mortar) [4]. The drilling resistance test is used to identify the rock types or class and its mechanical properties. The process of drilling produces sound as a by-product. One of possible ways to determine the actually drilled rock type (class) is to analyse the noise produced by drilling process. The acoustic identification of rocks during drilling process was studied by Zborovjan et al. [5], Miklusova et al. [6] and Vardhan et al. [7] have investigated the usefulness of sound level in determining rock and rock mass properties, using the jackhammer drill on a laboratory scale, by fabricating a jackhammer drill setup, wherein, the thrust applied can be varied while drilling the vertical holes. Rajesh Kumar et al. [8] carried out a study on estimation of rock properties such as uniaxial compressive strength, Schmidt rebound hammer, Young's modulus using sound levels measurements produced during rotary drilling.

This research demonstrates the potential of using drilling resistance tests for evaluating strength retention characteristics of fire damaged concretes. A weighted equivalent sound is also measured while drilling and correlated with strength of thermally deteriorated concrete.

2. MATERIALS AND METHODS

2.1. Materials Used

2.1.1. Cement. In this investigation commercially available 43 grade Ordinary Portland Cement (OPC) conforming to IS: 8112-1989 [9] has been used. The physical properties of cement are presented in Table 1. The cement was tested for the chemical composition according to IS: 4032:1985 [10]. The mean of three test results are presented in Table 2.

Table 3. Properties of aggregates

Property	FA	CA	
		12.5 mm	20 mm
Compacted bulk density, kg/m^3	1600	1459	1413
Water absorption, %	1.50	0.50	0.50
Specific gravity	2.65	2.67	2.67
Fineness modulus	2.33	7.2	7.2

Table 4. Mix proportion per cubic meter of concrete

OPC, kg	FA, kg	CA, kg		Free water, kg	Super-plasticizer, % by weight of binder
		12.5 mm	20 mm		
500	630	589	589	140	2

2.1.2. Aggregate. Fine Aggregate (FA) was sourced from local river bed. The grading of fine aggregates conforms to Zone—III of IS 2386-1975 [11]. The siliceous Coarse Aggregates (CA) of 20 mm and 12.5 mm size were obtained from local quarries and were taken in 1 : 1 proportion to make graded aggregate conforming to IS 383-1970 [12]. Table 3 gives properties of fine aggregates and coarse aggregates.

2.1.3. Super-palsticizer. Sulphonated naphthalene polymer based High Range Water Reducing Admixture (HRWRA) was used. The specific gravity of HRWRA was 1.18. This HRWRA was a brown liquid and containing 41.34% solids.

2.1.4. Water. In this investigation, potable water has been used for producing concrete and for the purpose of curing.

2.2. Specimen Preparation and Exposure to Elevated Temperature

High strength concrete has been designed for 28 days compressive strength of 70 MPa and having slump greater than 170 mm. The mix proportions adopted are detailed in Table 4. The mix design involves the right selection of water/cement ratio. Then, quantity of water and cement were determined. The volume of entrapped air was assumed to be 2%.

A horizontal shaft mixer was used for preparing the various concrete mixes. The concrete mixing was done as per the ASTM C 192-90a (1994) [13]. Compaction of concrete was done by using table vibrator. Then concrete cube of size 100 mm × 100 mm × 100 mm were cast and cured in water for 28 days. After 28 days of curing, 100 mm size cube specimens were taken out and air dried.

Then, 2 sets (6 cubes) of specimens for each exposure were exposed from 100 to 800°C, at an interval of 100°C and retained for 2 hours of exposure duration. Figure 1 shows the muffle furnace and arrange-

Fig. 1. Muffle furnace and arrangement of specimen for exposure.

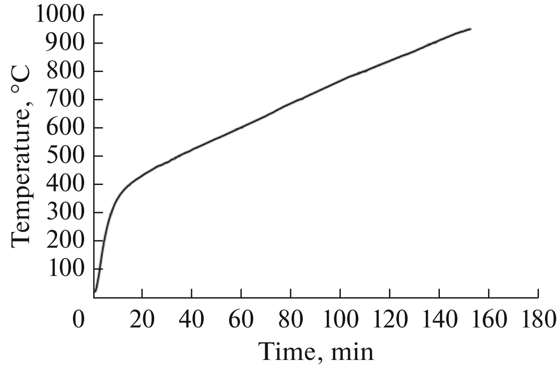

Fig. 2. Time temperatures build up curve.

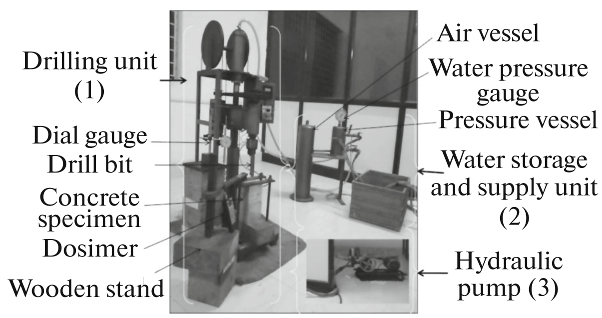

Fig. 3. Rotary drilling machine (Source: Mining Engineering, NITK, Surathkal).

ment of specimen for exposure. Necessary precautionary measures were taken during placing of specimen and handling the specimen, such that there is uniform temperature exposure on all sides of the specimen, for ensuring this, small pieces of ceramic tiles were placed below the specimen to allow heat from bottom also. Figure 2 shows the time temperatures build up curve.

After exposure to designated temperature the specimen were allowed to cool in the furnace to the room temperature. After cooling to room temperature, one set of specimen were taken to assess the residual compressive strength by destructive method as per IS 516-1959 [14]. The compressive strength ratio is expressed as ratio fcT/fc27, where fcT is the compressive strength after heating at T°C and f27 is the compressive strength of concrete at 27°C. Another set of specimen was tested for drilling resistance test.

2.3. Assessment of Residual Strength of Concrete by Drilling Resistance Test

2.3.1. Equipment/instrumentation. Rotary drilling machine. Rotary Drill Machine was used for drilling the specimen using continuous thrust mechanism and rotation control. Figure 3 shows the rotary drilling machine. It consists of three major units namely (i) The drilling unit (ii) The water storage and supply unit and (iii) The hydraulic pump.

The drilling unit consists of, a RPM controller and drilling mechanism. The hydraulic pump delivers water and feeds back to the supply unit, which is used by the drilling mechanism unit for applying thrust. The specific drilling work is more or less influenced by number of operational parameters such as bit type and size and shape, rotational speed and exerted thrust and it cannot be strictly regarded as a material constitutive property [15].

Since the drilling method affects drilling time and sound produced, an attempt was made to standardize the testing procedure. Throughout the drilling operation, relatively constant rotational speed and applied thrust was maintained, in order to obtain homogeneous data. Titanium Carbide drill bit of 8 mm diameter and 200 mm shank length was used for drilling operations.

Sound level meter. A Dosimeter, (Model: Spark 706 from Larson Davis, Inc., USA) was used for sound measurements. Instrument is equipped with a detachable 10.6 mm microphone and 7.6 cm cylindrical mast type preamplifier. A Larson Davis CAL 200 precision acoustic calibrator was used for calibrating the

Fig. 4. Dosimeter.

Fig. 5. Test setup for determination of drilling time.

sound level meter. Before taking sound measurement, the acoustical sensitivity of sound level meter was checked using calibrator.

2.3.2. Determination of drilling time. For the determination of drilling time, concrete specimen was kept on drilling platform and clamped in order to avoid displacement while drilling. Figure 5 shows the test setup for the determination of drilling time. Drilling time measurements were carried out on specimen at a rotation speed of 300 RPM, and an applied thrust of 14 kg/cm^2 for building materials and 18 kg/cm^2 for concrete specimen.

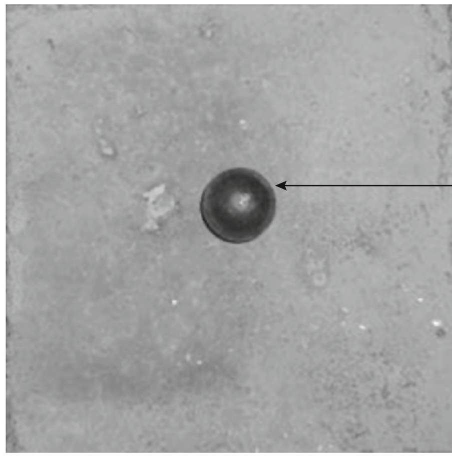

Fig. 6. Steel ball and concrete specimen.

The drilling time in seconds was noted at every 5 mm penetration depth of interval and penetration depth was monitored with the help of a dial gauge. The drilling time were measured on three faces of a cube which are mutually perpendicular to each other. The Drilling time ratio (DTr) is expressed as ratio DTT/DT_{27}, where DTT is the drilling time after exposure to T°C temperature and DT_{27} is the drilling time of concrete at 27°C.

2.3.3. Measurement of A-weighted equivalent sound level (L_{eq}) and impact sound level. A-weighted equivalent sound level and impact sound test recording data during drilling resistance test were also carried out to enhance NDT capabilities. The instrument used (Model: Spark 706 from Larson Davis, Inc., USA) measures relative loudness of sound levels better than that perceived by human ear with the inbuilt data acquisition system that assigns weightage to background noise levels.

Prior to drilling resistance test, impact sound test was carried out by dropping a steel ball of diameter 16 mm and weight 16.31 gram from a height of 1 m on the top of cube to be tested. Figure 6 shows steel ball and concrete specimen. With the help of dosimeter, impact sound was measured. The microphone of dosimeter was placed at the edge of the specimen. The background noise was measured to be 56 dB.

The A-weighted equivalent sound level, while drilling was recorded by a dosimeter continuously from beginning to 50 mm penetration depth. For this, microphone of dosimeter was placed 15 mm away from the periphery of the drill bit. A-weighted equivalent sound is the equivalent steady sound level of a noise energy averaged over a period. The sound level of 75 dB was recorded without any process of drilling, due to noise of the hydraulic pump and drilling unit.

3. RESULTS AND DISCUSSION

3.1. Drilling Resistance Test on Conventional Building Materials

To study the potential of drilling resistance test in strength assessment, it was envisaged to conduct tests on a few building materials like wax, brick, wood, granite samples and cement mortar cubes. These materials have different density and strength characteristics. Penetration depth with drilling time for these materials has been presented in Fig. 7. For soft materials like wax, less drilling time is required to penetrate a designated depth. Whereas for granite which is harder, penetration time for the same depth is more than that for wax. Drilling time curve for cement mortar, that has intermediate hardness is in between the curves for hard and soft materials. It is recognized that denser the material, harder and stronger it is, and this fact has found place in concrete technology too. As can be seen from the curves, harder materials have more linear relationship between penetration depth Vs time, which makes usage potential of drilling resistance quite appealing and accurate.

3.2. Drilling Resistance Test on Concrete

Penetration depth with drilling time for concretes with varying strengths, are presented in Fig. 8. It was contemplated to perform the drilling test on a few samples of concrete with variations in mix proportions and water cement ratio, to generate as random a sample as possible and to check the veracity of linearity

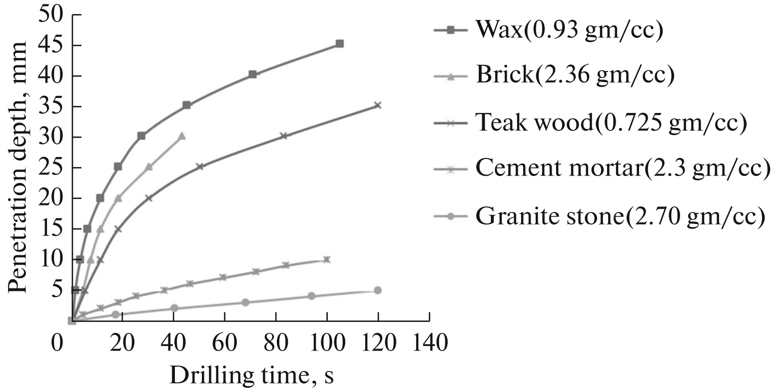

Fig. 7. Penetration depth Vs drilling time for building materials.

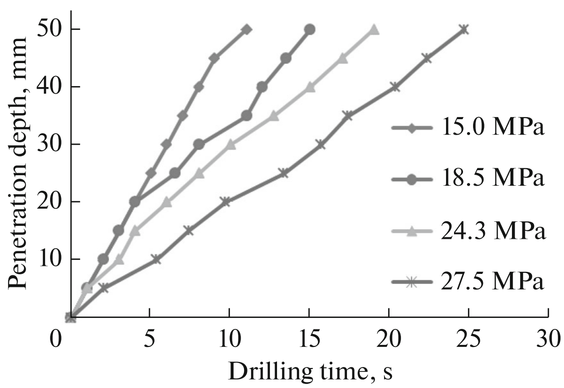

Fig. 8. Penetration depth Vs drilling time for concretes with varying strengths.

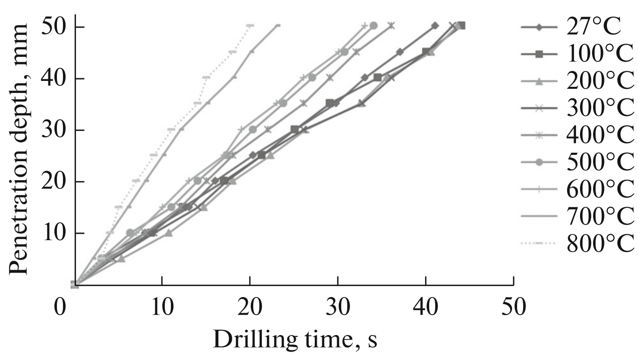

Fig. 9. Penetration depth with drilling time for concrete exposed to temperature.

of drilling time with penetration depth. Figure shows that drilling time increases with strength. Within error bounds the curves are almost linear and indicate that drilling time for a designated depth or drilling depth for a specified time can be pointers to strength.

3.3. Drilling Time Test on Concrete Exposed to Elevated Temperature

In drilling test for concrete exposed to elevated temperature, drilling time has been measured for 50 mm depth of penetration at an interval of 5 mm. Figure 9 shows variation in drilling time for concrete specimen exposed to different temperatures. Drilling time for designated depth increases with decrease in

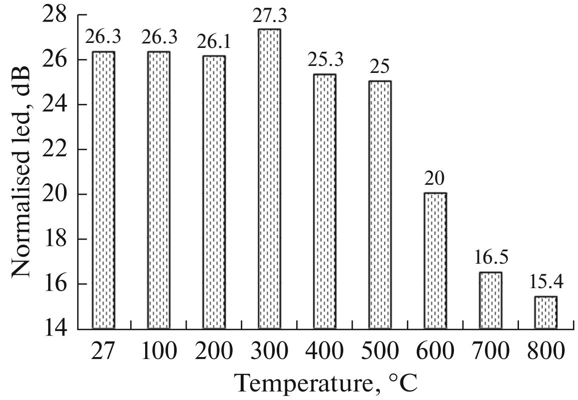

Fig. 10. Normalised A-weighted equivalent sound level with temperature.

temperature exposure levels. The linearity between depth Vs time, again is apparent. From the penetration rate it is clearly observed that, concrete exposed up to 300°C lies in one group, second group is for the temperature range of 300 to 600°C and third group is for the temperature range of 600 to 800°C. Penetration resistance time gives an idea of temperature attained, which provides indirect information of residual strength of concrete. The drilling resistance test is a rapid performing test and results were immediately available for the assessment of the condition of thermally deteriorated structure.

3.4. Recordings of Sound Levels Associated with Drilling Test

Sound levels were recorded during the drilling resistance test, for analysis and interpretation and possible exploitation as an assessment tool. The A-weighted equivalent sound level while drilling resistance test was measured by dosimeter continuously from beginning of drilling to the 50 mm depth of penetration. Figure 10 shows the variation between normalised A-weighted equivalent sound level and exposure temperatures. Normalised A-weighted equivalent sound level is that sound measured during drilling, free from the sound of drilling machine and hydraulic pump. Back ground noise was 75 dB. Suitable adjustments to recordings for back ground noise have been incorporated.

From Fig. 10 it is observed that, concrete exposed up to 300, 400 and 600°C produces 26, 24 and 20 dB of normalised A-weighted equivalent sound respectively. For 700 and 800°C, sound levels were 15 dB. It can be concluded that drilling sound levels vary with temperature exposure and hence can be employed in assessment of strength characteristics.

The process of drilling, in general, always produces sound as a by-product. This sound is generated from the rock-bit interface, regardless of the material the bit is drilling in. As exposure temperature increases, concrete gets deteriorated and becomes softer. The compositions of the surfaces influence the overall sound level by reflecting or absorbing the incident sound energy. The compressive strength of the media being drilled affects the acoustic absorption properties. Harder media reflect more acoustic energy than softer media.

3.5. Impact Sound Test

Impact sound test is used to detect hollowness of concrete. Figure 11 shows the variation of normalised impact sound level with temperature.

Figure 11 indicates that impact sound levels increase as temperature increases. This trend can be of help in preliminary assessment of concrete exposed to elevated temperatures, wherein impact sound levels can give an idea of exposure temperature levels.

3.6. Compressive Strength of Concrete Subjected to Elevated Temperature

Variation of compressive strength ratio of concrete subjected to exposure temperatures is shown in Fig. 12. From Fig. 12 it is observed that, at 100°C small reduction in strength is observed and then a little increase in compressive strength observed at 200 and 300°C. This may be due to the high pressure stem curing (Autoclaving) effect [16]. Then compressive strength of concrete is decreases continuously

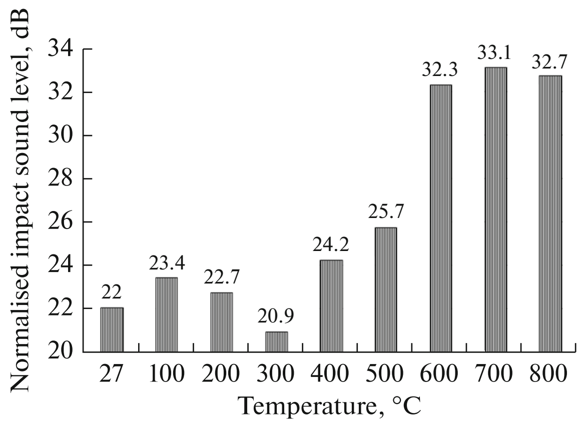

Fig. 11. Impact sound level with temperature.

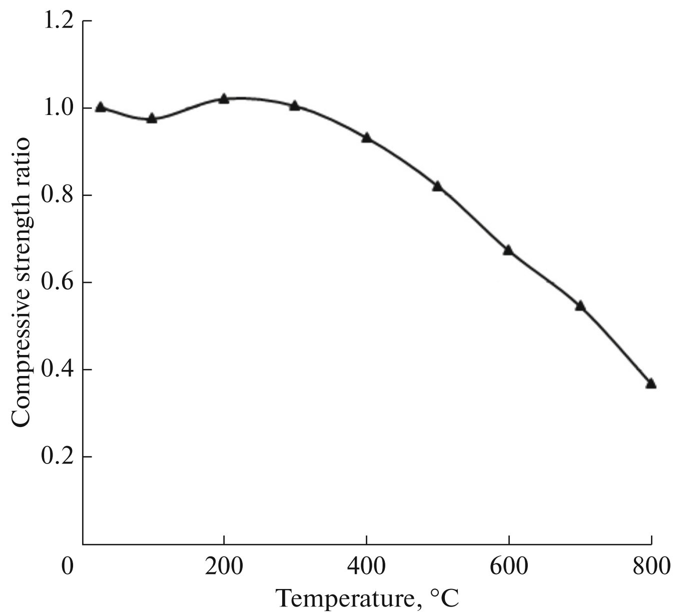

Fig. 12. Compressive strength V/s Temperature.

with increase in temperature. At 400 and 500°C, temperature exposures, loss in compressive strength of 7%, and 12% are observed. Concrete subjected to 600, 700 and 800°C has shown 33, 45 and 63% decrease in compressive strength. The decrease in strength is due to the decomposition of calcium hydroxide and Calcium Silicates Hydrate (C–S–H) in the cement paste [17].

3.7. Nomograph for Compressive Strength Ratio from Drilling Time Ratio and Temperature

Figure 13 shows the variation of relative drilling resistance time and residual compressive strength of concrete subjected to elevated temperatures. From Fig. 13 it is observed that both the curve follows similar trend pattern. Hence an attempt has been made to propose the nomograph for the damage diagnosis of thermally deteriorated concrete. From the experimental results, and analysis, a parallel scale nomograph has been prepared and is presented in Fig. 14. Knowing two parameters from among the three related the third can be obtained.

3.7.1. Illustration of nomograph. If the concrete is exposed to 400°C and drilling time ratio 0.8 then, a straight edge held connecting 400°C temperature scale and 0.8 on drilling time ratio scale shall read 0.75 as the residual compressive ratio on strength scale.

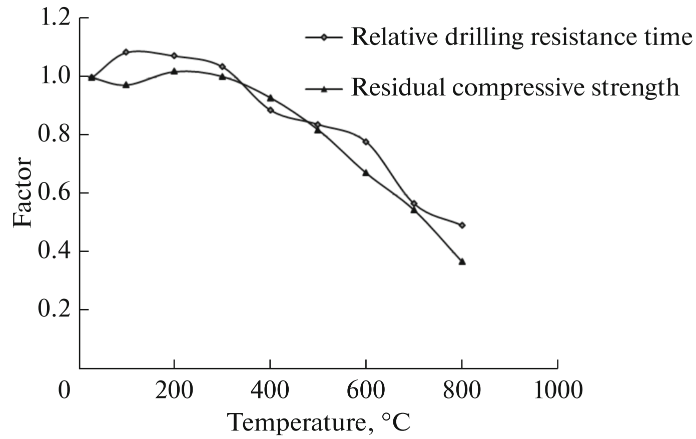

Fig. 13. Relative drilling resistance time and residual compressive strength V/s Temperature.

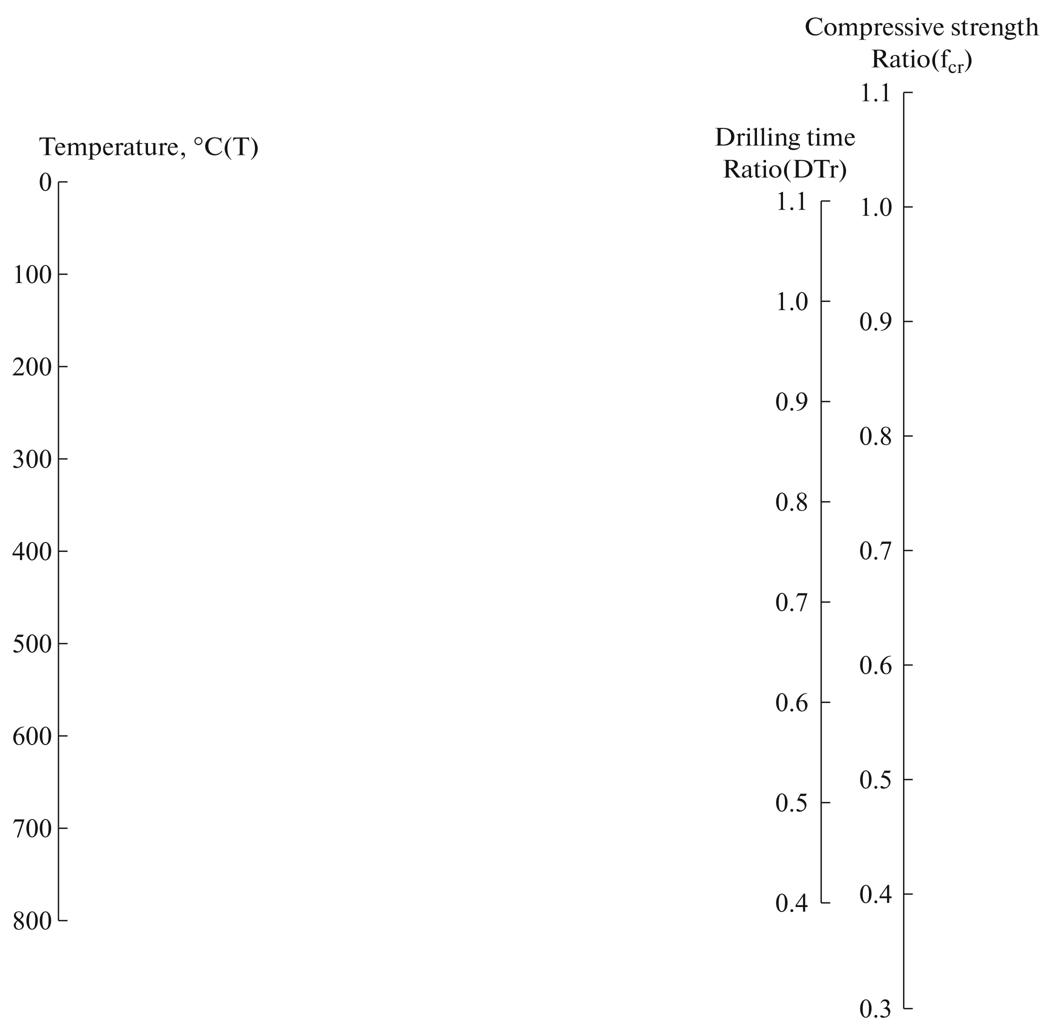

Fig. 14. Parallel scale nomograph for compressive strength ratio.

CONCLUSIONS

Possible application of drilling time, sound levels, and impact sound tests in assessment of concrete quality has been elaborated. The linearity of drilling depth with time is appealing accurate, and is amenable for exploitation as a potential NDT tool, has been demonstrated. Drilling resistance indirectly measured as penetration time and sound level recordings, during drilling can be a pointer of the extent of deterioration and a measure of residual strength as demonstrated by the present investigation. Nomograph of the kind presented as a result of the investigation is a valid decision making tool in failure forensics.

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