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Incorporating Non-Destructive Testing Methods in Concrete Production for Strength Gain Assessment

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Abstract: *Monitoring and predicting concrete strength during production is critical in assessing the effects of specific ingredients, proportioning, mix design optimization, curing effects and concrete homogeneity. Similarly, the estimation of concrete strength in the field is also critical for avoiding potential catastrophic failures during construction either due to early removal of the forms, applying additional "dead loads"(i.e., weight of concrete from additional floors and columns on the top of freshly poured slabs and foundation), and/or "live loads" from external in-service load related forces. Thus, quick and accurate methods of non-destructive testing, NDT, are particularly valuable in the Quality Assurance and Quality Control (QA/QC) process. NDTs are preferable in relation to standard destructive strength testing since they do not interfere with production and reduce testing time and cost. In this study, non-destructive testing methods, such as ultrasonic pulse velocity (UPV), resonance frequency, and infrared thermography, IRT, were used in order to identify their ability to be incorporated in the QA/QC process.The results from such NDT methods were coupled with maturity modeling providing good relationships in predicting strength. Thus, the adoption of such NDTs in QA/QC of concrete is feasible and the suggested approach is transferable elsewhere where similar materials and testing methods are used.*

Keywords:*Non-Destructive Testing, Quality Control, Quality Assurance, Concrete, Maturity.*

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I. INTRODUCTION

Monitoring of strength gain at early ages is one of the most critical aspects in concrete construction. Failure in determining the suitable time for removing formwork and applying loads on concrete structures lead often to catastrophic failures and in some cases loss of life. Collapse of the Skyline Plaza in Fairfax County, Virginia, in 1973 due to premature shoring removal, or the Willow Island cooling tower collapse in West Virginia in 1978 due to premature loading and inadequately cured concrete are only some examples of unsuccessful estimation of concrete strength gain (Carper, 1987). The hydration of the cement in the presence of water, and thus strength gain, has been modeled through maturity as a function of temperature and time. The interaction between cement and water, as well as other ingredients in concrete such as admixtures, is governed through chemistry kinetics and represents an exothermic reaction. Thus, during the early ages of concrete hydration can be monitored through concrete temperature. For typical concrete mixtures about 85% of the hydration process is complete within the first 28 days (ASTM C39). Measuring the temperature of concrete during the curing process is typically achieved through the use of embedded wired or wireless thermal sensors (Azenha et al., 2011; Upadhyaya et al., 2014). Hansen and Surlaker (2006) also used Radio Frequency Identification maturity tags (RFID) in monitoring concrete maturity while Ghods et al. (2017) developed an application for smartphones.

Although maturity has been successful in monitoring the concrete hydration process when coupled with compressive strength testing it does not always guarantee successful results. For example, in situations where concrete mixtures are not well mixed or properly placed, honeycombing, segregation, or excessive bleeding may occur. While the cement and water interaction may proceed, such effects may produce variable strength within the concrete structure that might not be detectable from the maturity monitoring. Therefore, for quality control and quality assurance purposes, monitoring the strength gain by another method is recommended (ASTM C1074). NDT methods provide the benefits of sampling a larger area of the concrete structure capturing such variability in in-place strength, and/or assessing the quality of a higher number of samples (i.e., testing frequency). This isparticularly important in the production of manufactured concrete such as precast and prestressed members (Goulias 2016). Following the recommendations of a recent Federal Highway Administration, FHWA, study and reinforcing the need to develop NDT based QA process for highway materials (Goulias 2017), it was the objective of this research to identify alternative NDT methods that can be used in monitoring and/or estimating strength gain in concrete, and thus to be adopted in an NDT based QA process. In order for these NDTs to be used in QA/QC and/or in acceptance testing specifications, they should be fast, accurate, reliable, and simple to run for both owners and concrete producers (Goulias, 2019). The alternative NDT methods explored in this study included: infrared thermography (IRT); ultrasonic pulse velocity (UPV); and fundamental resonance frequency. The use of infrared thermography for monitoring surface temperature of concrete has been explored for structures such as pavements, buildings, and concrete tunnels among other. Its use in monitoring the hydration process and strength gain has been limited (Azenha et al., 2011). For massive concrete structural elements, a significant temperature gradient is expected from the internal to the external sections, while for thin concrete sections such a difference is negligible (Upadhyaya et al., 2014). Some studies have also explored the use of ultrasonic pulse velocity (UPV) to assess the ability of maturity to properly predict in-place strength (Graveen et al., 2003; Kraußet al. 2006; Gebretsadik, 2013). In early concrete ages the wave propagation velocity is dependent on concrete density and thus strength, so UPV can be employed to validate the maturity strength predictions. In addition to wave propagation velocity, the fundamental resonance frequency of concrete can be used to calculate the dynamic modulus of elasticity and relate it to compressive strength. Such approach is more appropriate for lab and field samples casted and cured next to the concrete structures sites. Past studies have as well explored the ability of resonance frequency to measure the dynamic modulus of concrete during the early curing time (Jinet.al.,2001; Azenha et al., 2010).

II. EXPERIMENTAL PLAN

For evaluating hydration and strength gain of concrete during early ages (i.e., first 28 days), an air-entrainedconcrete mixture was used, Table 1, representing a typical proportioning for various concrete applications in the northeast region of the United States. The experimental program included both destructive and non-destructive testing as outlined in Table 2. For monitoring the time- temperature effects iButton temperature sensors were incorporated into the concrete mix. Several replicates, typically from 3 to 5, were considered in each testing case of Table 2 to document potential repeatability of these methods in detecting concrete properties. At day one NDT measurements were not possible due to the high level of “free” moisture (ie, water not yet fully interacting with cementitiousparticiples) affecting NDT readings.

Table 1: Properties of the concrete mix

Cement Type	Water/Cement Ratio	Admixtures	Unit Weight (Kg/m^3)	Air Content (%)	Slump (mm)
Type II Portland Cement	0.44	air entertainer & water reducer	2350	6	25

Table 2: Testing plan

	Age (days)					
Tests	**1**	**2**	**3**	**7**	**14**	**28**
Compression	■	■	■	■	■	■
Infrared Thermography	■	■	■	■	■	■
Resonance Test Gauge		■	■	■	■	■
E-meter		■	■	■	■	■
Ultrasonic Pulse Velocity		■	■	■	■	■

III. EXPERIMENTAL RESULTS & ANALYSIS

The Maturity Index, MI,representing the time-temperature history of concrete during the hydration process is calculated based on Equation 1, as defined in ASTM C1074. The MI is also known as the Nurse-Saul maturity function or time-temperature factor and is the most common approach used in construction and incorporated in all commercially available maturity meters in the market.

$$M(t) = \sum (T_a - T_o)\Delta t \qquad (1)$$

where:

M(t) = the time- temperature factor at age t, degree-days or degree-hours

Δt = time interval, days or hours
T_a = average concrete temperature during time interval Δt, °C, and,
T_o = datum temperature, °C

Figure 1 shows the time-temperaturehistory as measured by the iButtons based on average values. As can be seen, the lab temperature during sample preparation was 15 ^{o}C. As soon as the hydration between cement particles and water started the concrete temperature increased for several hours until it reached a peak value at around 30^{o}C. This represents the heat generated due to the exothermic chemical reaction. After the initial hours of hydration, concrete temperature fluctuated to a lesser degree. Thus, during the first 24 hours the temperature sampling time interval (Δt) was set at every half an hour, while for the remaining period temperature was logged in every hour.

The strength-maturity relationship was developed between the average compressive strength of three cylinders and the time-temperature factor from the data collected with the iButtons,Figure 2. Compressive strength testing was conducted according to ASTM C39 on 100x200 mm cylinders based on the schedule shown in Table 2. As expected the compressive strength increased with curing age.

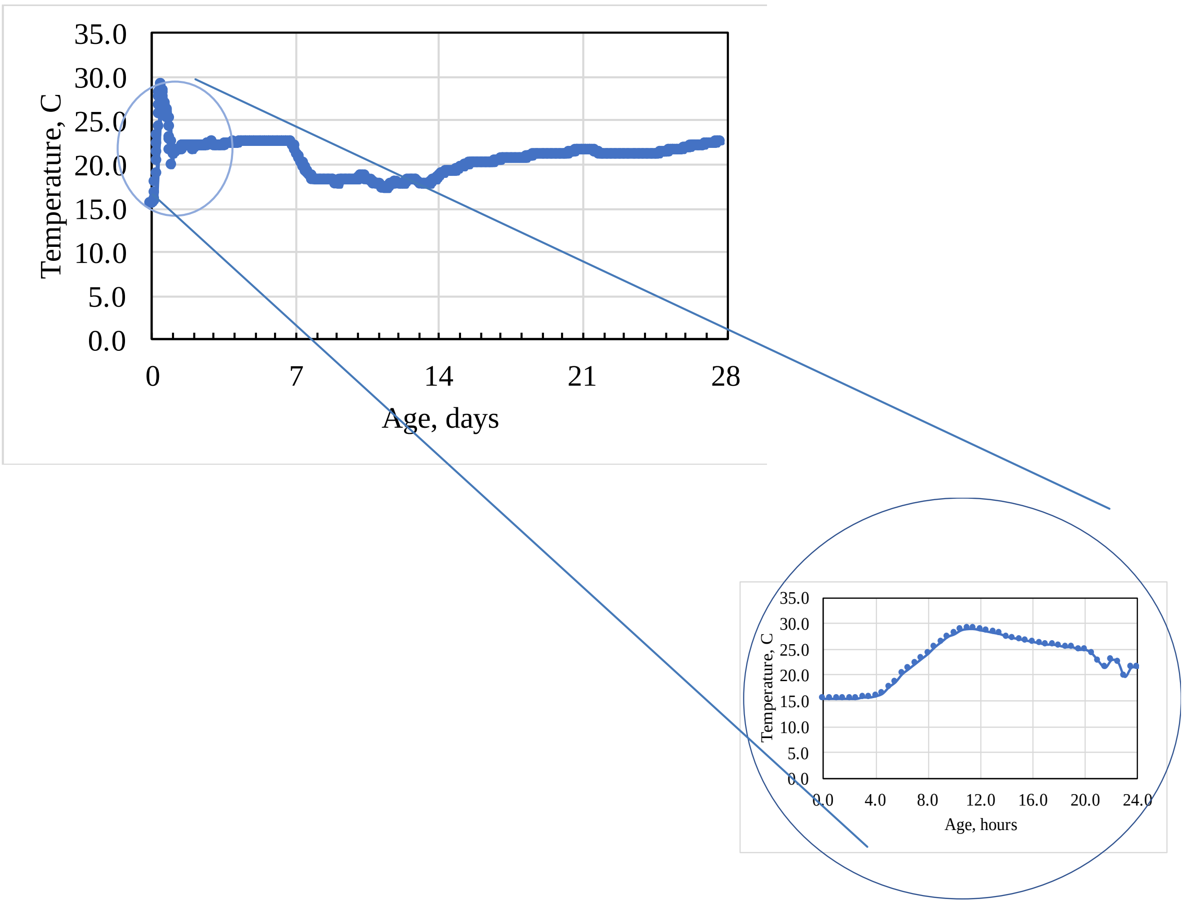

Fig. 1: Time-Temperaturehistory of concrete during hydration.

To assess whether infrared thermography can provide strength predictions thought the maturity approach, the relationship between compressive strength and time-temperature was examined by using infrared thermography data. To this aim, the time-temperature product was calculated from temperatures recorded with an infrared camera and using the Nurse-Saul function. Figure 3 shows the infrared image of a control cylinder (i.e., with the embedded sensors) after the mold removal. The temperature of the cylinder is relatively uniform through the cylinder surface, and equal to 20.5℃ in the infrared camera "target" circle location shown in Figure 3. In comparing the temperature data recorded from the embedded iButtons and the infrared thermography, it should be noticed that the iButtons measure the internal concrete temperature while the infrared camera measures the surface temperature. However, since these are small samples (cylinders) and at controlled curing conditions (room temperature and water bath) no significant changes in temperature gradient is expected from the surface to the inner portion of the samples (as opposed to large mass concrete samples exposed to field conditions). The maturity indices calculated from both temperature sensing methods are shown in Figure 3. As can be observed the two approaches provided identical results (i.e., no difference on MI calculated from the two sensing methods) at early ages, which is the primary reason of using maturity for predicting early strength. Therefore, even though internal temperature is more desirable for evaluating the hydration of concrete, especially in mass concrete structural elements (Maierhofer et al., 2006) for thin concrete structural members using an infrared camera to record the time-temperature history is possible and beneficial due the speed of data collection and its non-destructive characteristics. In regards to mass concrete structural members, Upadhyayaet. al., (2014) reported that time-temperature profiles at the edge versus the interior of mass concrete members follow similar trends.

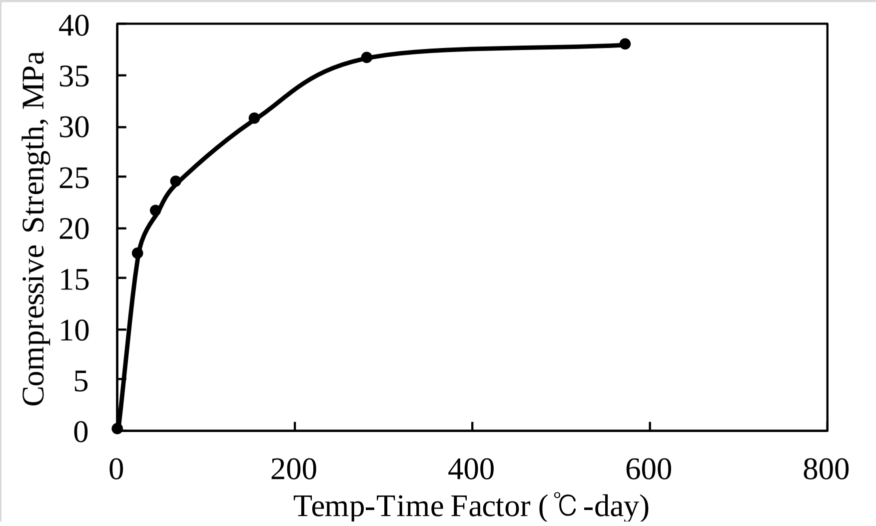

Fig.2: Compressive strength versus time-temperaturefactor during 28 days of curing

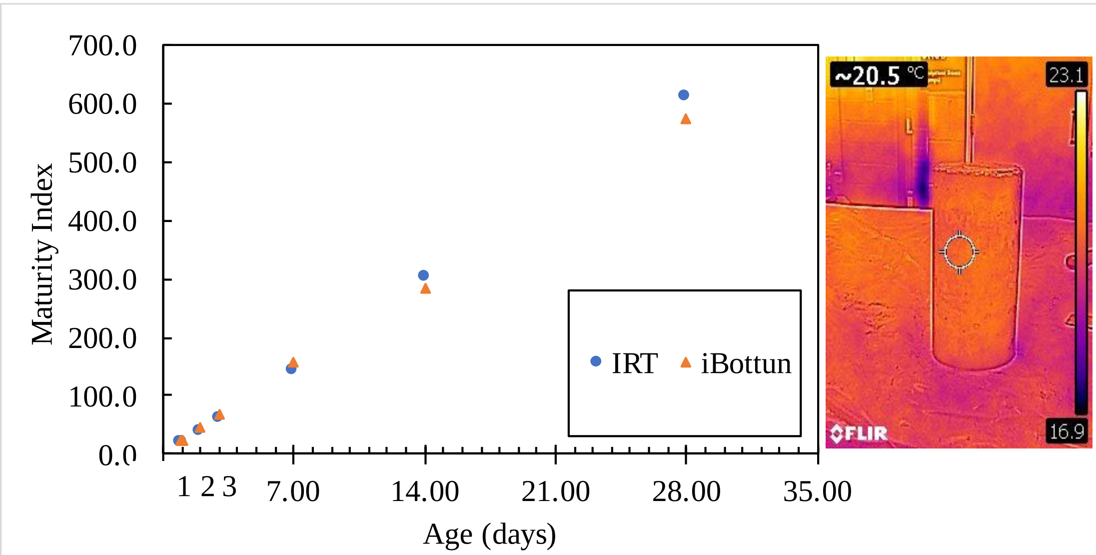

Fig. 3: Comparison of maturity index calculated from iButton and infrared thermography, IRT.

As indicated above, past studieshighly recommend that in the QA/QC process to couple and verify concrete strength predictions from the maturity approach with non-destructive testing (Goulias, 2019). Similarly, ASTM 1074 indicates that the temperature monitoring and maturity index modelling should be accompanied with at least one other test for estimating the in-place strength of concrete. Therefore, the ultrasonic pulse velocity, UPV, and the resonance frequency methods were employed to monitor the strength gain of concrete in this study. UPV measures the wave propagation velocity through materials. The wave propagation velocity depends on the dynamic modulus, Poisson's ratio, and density of the materialwith a range of 3700 to 4200 m/s (Malhortaet. al., 2003). As identified in Table 2, UPV was performed on day 2, 3, 7, 14, and 28.Figure 4 presents the relationship of UPV with the time-temperature product. UPV testing was conducted using the direct method (i.e., along the longitudinal direction generating compression waves). As expected, the results of Figure 4 indicate that velocity of wave propagation increases with increase in time-temperaturefactor. Once the Maturity Index (i.e., relationship of time-temperature product and concrete strength) has been established from laboratory samples for a specific concrete mixture, UPV can be used for assessing and correlate the results to compressive strength without: (i) having to install and monitor temperature sensors in concrete; and, (ii) test companion samples for compressive strength representing the field conditions for verification purposes. The use of UPV also provides: (i) the ability to test a larger portion of in-place concrete without significant increase in QA/QC cost and testing time; and, (ii) real time monitoring of construction quality (in this case strength) without having to wait for strength testing results. This is particularly beneficial during construction since it provides the possibility for immediate forensic and/or corrective action when lower strength values are observed.

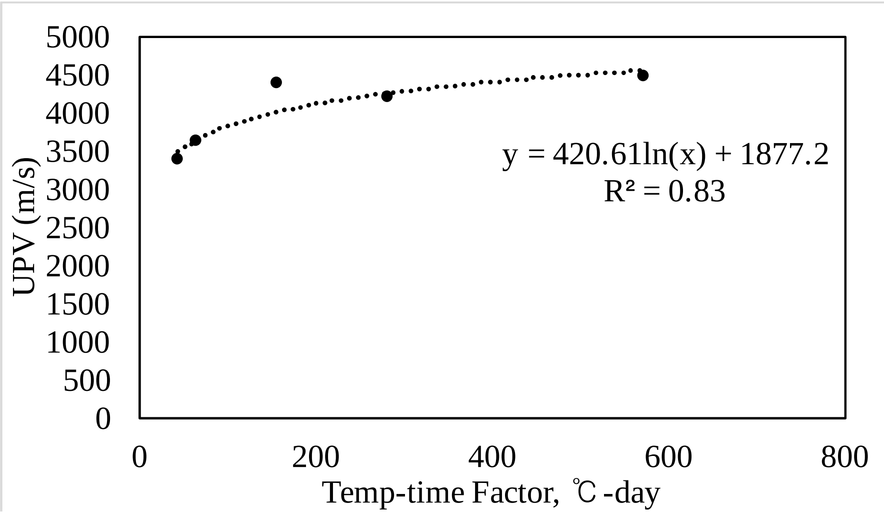

Fig.4: Relationship between UPV and time-temperature factor.

The hardening process of concrete is also reflected in the dynamic modulus determined from NDT testing. Similar to compressive strength, dynamic modulus is also expected to increase during the hardening and strength gain process. In this study two devices were used to measure the resonance frequency of concrete, the resonance test gauge (RTG) and the Emodumeter (E-Meter).Testing was performed according to ASTM C215 using the direct method (i.e., along the longitudinal direction). The dynamic modulus is then calculated using equation 2:

$$E = DM(n')^2 (2)$$

where E is the dynamic modulus, in Pascals, n' is the fundamental longitudinal frequency, in Hz, M is the mass of the specimen in kg, and D is 5.093 $(\frac{L}{d^2})$, in m^{-1}, for a cylinder, or 4 $(\frac{L}{bt})$, in m^{-1}, for a prism. L represents the length of the specimen, d is the diameter of a cylinder, in meters, while t and b are the cross section dimensions of a prism, all parameters in meters.The dynamic modulus of elasticity varies from 14 GPa, for early ages to 48 GPa for fully cured concrete atlater ages (Malhotran and Carino, 2003).The average dynamic moduli from each device was related to the time-temperature, shown in Figure 5. As expected an increase in dynamic modulus with hardening of concrete is observed. Even though the dynamic moduli from the two devices are very close at early ages (i.e., day 2 and 3), after 7 days of curing, RTG provides systematically higher values.As in the case of UPV, once the Maturity Index (i.e., relationship of time-temperature factor and concrete strength) has been established from laboratory samples, dynamic modulus testing can be used for assessing in-place field conditions and correlate to strength gain through the maturity index. Similar to UPV or any other NDT result, the use of dynamic modulus also provides: (i) the ability to test a larger portion of in-place concrete without significant increase in QA/QC cost and testing time; and, (ii) real time monitoring of in-place field construction quality without having to wait for strength testing results, and thus possibility for immediate forensic and/or corrective action when lower strength results are observed. Finally the testing reliability of the NDT methods was compared to the repeatability of the destructive compressive strength testing. As it can be seen from Table 3, the NDT methods have a lower variability than compressive strength testing, providing thushigher testing repeatability and more consistent results.

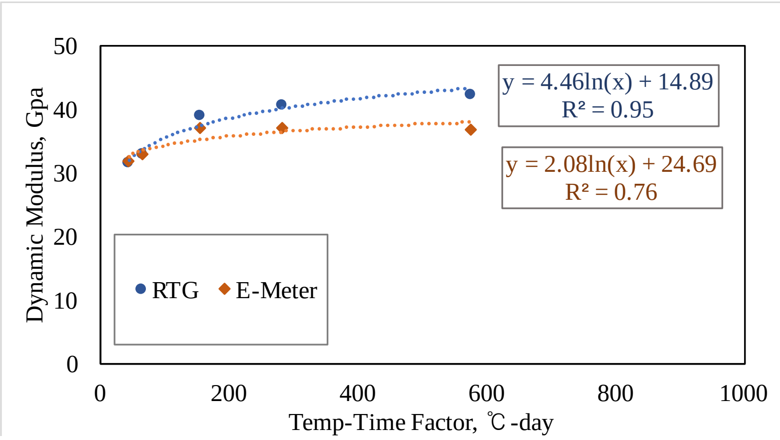

Fig.5: Relationship between dynamic modulus and maturity.

Table 3: Coefficient of variation for compressive strength and NDT testing methods.

Testing Method	Coefficient of Variation (%)
Compressive Strength	0.6 - 9.6
UPV	0.7 – 3.5
E-Meter	0.5 – 1.4
RTG	0.4 – 1.5

IV. CONCLUSIONS

This study examined alternative NDT methods that can be used in monitoring and/or estimating strength gain in concrete, and thus to be adopted in an NDT based QA process. These NDTs included: infrared thermography (IRT); ultrasonic pulse velocity (UPV); and fundamental resonance frequency (E-meter and RTG). Infrared thermography provided satisfactory result in maturity modeling of concrete for predicting strength without the need of incorporating temperature sensors. The UPV, RTG and E-meter wave propagation velocity and/or fundamental frequency of concrete were also successfully related to the time-temperature history of concrete during hydration, and thus related to strength gain. The NDT methods also provided higher repeatability than the destructive compressive strength testing of concrete. Thus, the results of the study provided promising relationships that could be used for estimating in-place strength without (i) having to install and monitor temperature sensors in concrete, and, (ii) without the need to test companion field samples for compressive strength for verification purposes (a time consuming and costly QA/QC process).The methodology presented herein is transferable elsewhere and to comparable concrete mixtures. The use of these NDT methods in the QA/QC process provide: (i) the ability to test a larger portion of cast-in-place concrete without significant increase in QA/QC cost and testing time; and, (ii) real time monitoring of construction quality (in this case strength) without having to wait for strength testing results, and thus possibility for immediate forensic and/or corrective action when lower strength results are observed.

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