ECAS2002 International Symposium on Structural and Earthquake Engineering, October 14, 2002, Middle East Technical University, Ankara, Turkey

Indirect Determination of In-Situ Compressive Strength of Concrete as a Function of Ultrasonic Pulse Velocity

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ABSTRACT: Concrete cores of 10 cm dimensions are taken from randomly chosen columns and shear walls of various 3- to 30-years old reinforced concrete (RC) structures from nine different localities in Turkey in the period: 1999 to present. Cylindrical samples whose heights and diameters are 10 cm are cut out of those cores and both ends capped properly. The ultrasonic pulse travel time is measured at the center of core position before extraction. The core strength in kgf/cm^2 measured by crushing the sample in a certified compression machine is regressed against the in-situ ultrasonic pulse velocity in km/s, including a total of 55 data points, and a meaningful linear regression equation is obtained, which is believed to be applicable for 3-years old and older RC buildings in Turkey.

Keywords : Concrete core strength, utrasonic pulse velocity

ÖZET: 1999'dan günümüze kadar Türkiye'de dokuz farklı yöredeki 3 ile 30 yıl arası yaşlı betonarme binaların rast gele seçilen kolon ve perdelerinden 10 cm çapındaki karotlar alınmıştır. Bu karotlardan yükseklikleri çapına eşit olacak şekilde numuneler kesilmiş ve her iki uçları uygun biçimde başlıklanmıştır. Karot alınmazdan evvel belirlenen yerde ultrasonik ses dalgası seyahat zamanı ölçülmüştür. Hazırlanan karot numunelerin serifikalı bir beton presinde kırılarak kgf/cm^2 cinsinden ölçülen basınç mukavemetleri, yerinde alınan ultrasonik ses ölçümlerinden km/s cinsinden hesaplanan ultrasonik hızlara karşı, elde edilen toplam 55 adet çift değer ile regrese edilmiştir. Türkiye'deki 3 yıl ve daha yaşlı betonarme binalar için kullanılabilecek anlamlı bir lineer regresyon ifadesi elde edilmiştir.

Introduction

Non-destructive testing (NDT) of some salient concrete properties have always been attractive because of its being cost-effective, time-conserving, practical, and even necessary for some extraordinary cases like densely reinforced elements or fragile units. Indirect estimate of concrete strength by measuring surface hardness by a standard Schmidt hammer is the most popular NDT method. In the pertinent literature however, one can find precautionary and reserved comments about the reliability of a Schmidt hammer (e.g. Neville, 1995). It is a known fact that as concrete ages, the surface of any column attains a harder composition than its inner parts due to carbonation, which is formation of $CaCO_3$ by the reaction of $Ca(OH)_2$ with the CO_2 of the air, and this results in a falsely exaggerated strength estimate. Even the Schmidt hammer rebound readings may vary depending on its commercial brand. Another point is that the spring of the particular Schmidt hammer utilized may become slacker over time with usage and its readings may become erroneous. For concrete of a few weeks or a couple of months old, the Schmidt hammer may give more consistent results, which are still $\approx \pm 25\%$ off the true value according to the chart on the hammer itself. For rough and quick estimates of concrete of a couple of months age, the Schmidt hammer can be suitable within this range of prediction.

Relating concrete properties to the velocity of ultrasonic pulse (UP) transmitted through has been a standard practice since 1950's, and this NDT method has appeared in the standards of many countries. Komlos et al. (1996) and Qasrawi (2000) present a comprehensive review of the relevant literature together with the pertinent standards of so many countries. Although there seems to be a theoretically verifiable relationship between the modulus of elasticity of a homogeneous material as the dependent variable and the ultrasonic pulse velocity (UPV) as the independent variable, there is not a clear-cut theoretical proof indicating a similar relationship between the strength and the UPV (Qasrawi, 2000). Nevertheless, at least eight countries in the world, including the USA, UK, Russia, etc have standards which are for estimating concrete strength based on UPV measurement (Komlos et al., 1996).

As will be summarized in the ensuing sections, the practice of the authors of this article with new and old RC structures has suggested that there could be a meaningful relationship between the concrete strength and the UPV only for buildings 3-years old and older, and the plot between these two quantities for buildings of a few months old reveals noise and fails to exhibit a clustering tendency. The reason for this is probably due to 1) the presence of moisture and 2) incomplete hydration of cement paste of new concrete. The experience with assessing the strength of damaged or undamaged RC buildings in various towns in Turkey in the recent three years of the authors of this article led to development of a regression-based expression between the compressive strength of concrete and the in-situ UPV, and the objective of this study has been to reveal the developed relationship to anyone interested.

In-situ and Laboratory Tests Leading to the Relationship between the Strength and UPV

Estimation of compressive strength of concrete of structures which suffered earthquake damages, or those subjected to weathering, fire, or chemical attacks is a serious problem. After the devastating 1999 Marmara and Bolu earthquakes, in order to make a decision for demolishing those heavily damaged buildings, or for repairing and retrofitting moderately affected buildings, a realistic estimate of concrete compressive strength turned out to be a crucial step as most of the buildings were of reinforced concrete (RC) type. The most effective way of determining the compressive strength of concrete is by taking cores and directly crushing the core samples after end preparations in a compression machine (e.g. ASTM, 1978; BSI, 1983; TSI, 1992; and TSI, 2000).

Upon official appointments, the Department of Civil Engineering of Erciyes University was involved in 1) designing projects for retrofitting and repairing of a few earthquake-stricken RC buildings or 2) only determining the compressive strength of concrete of some buildings in various different parts of Turkey, in the recent few years. A thorough investigation of each building began taking a statistically sufficient, and yet the least possible number of cores from randomly chosen columns and shear walls. All of these buildings were of RC type, and some of them were just a few months old, as some others were between 3 to 30 years of age. The data of young buildings are not included in this study, because they deviated appreciably from those of the old ones.

Approximately 40 cm bands of outer plaster layers of both sides of any randomly picked column were initially stripped off and the concrete surface was exposed. Both the longitudinal and transverse steel reinforcement bars were carefully detected with the help of a standard cover-meter, and the core location so as to evade reinforcement bars was thus marked. Ultrasonic pulse travel time over the shortest length between the corresponding sides of the column exactly at the center of the core location were measured carefully twice by interchanging the transmitting and receiving probes of a Portable Ultrasonic Non-Destructive Digital Indicating Tester (Pundit) instrument in compliance with both ASTM C597-97 and BSI-1881-203. Next, that location was drilled throughout and the core whose length equaled the width of the column was extracted. After having been marked and transported to the laboratory, samples of lengths equaling the diameters were cut with the help of a rock-cutting saw. Both faces of each such sample were properly capped with sulfur+graphite compound, and the sample was crushed in a certified compression machine one day later in air-dry condition. Average of two compressive strengths was taken as the actual strength of that core, because two samples were obtained out of each core mostly. All the cores had 10 cm diameters, and the sample lengths after capping were also 10 cm. According to both BS-1881-120 and TS-10465, the direct compressive strength of a horizontally drilled core sample, whose length equals its diameter, is equivalent to that of a cubic sample, 15 cm cube in the former and 20 cm cube in the latter. In the recent TS-500, the 15 cm cubes instead of the 20 cm ones are specified (TSI, 2000). The possible slight scale effect difference of about 0.96 between the 15 cm and 20 cm cubes can be ignored and 15 cm and 20 cm cubes may be rated equally.

Calibration of the Pundit device were carefully repeated at each different floor of the building worked at, although there were not appreciable changes most of the time. Ordinary gear grease was applied amply on concrete surfaces against which the sensors were held. The length in mm divided by the UP travel time in micro-seconds yielded the direct ultrasonic pulse velocity in km/s through the column at the point where the core was extracted. Over the past three years, out of nine different sites having RC buildings of ages between 3 to 30 years, a total of 55 pairs of direct core strength versus UPV values have been obtained.

The names of the towns and sites enclosing the investigated RC buildings between ages of 3 to 30 years are: (1) Administrative and storage buildings of Maltepe complex of State Materials Office in Istanbul, (2) personnel lodging buildings of Maltepe complex of State Materials Office in Istanbul, (3) various buildings of State Materials Office in Balıkesir, (4) various buildings of General Directorate of Sugar Production Factories in Ankara, (5) various buildings of General Directorate of Sugar Production Factories in Afyon, (6) the building of a High School in Hacıbektaş, (7) an old water storage tower in Kayseri, (8) the cafeteria building of an Elementary School in Yahyalı, and (9) the exposition building of Kayseri Industrial Fair.

In conclusion, a statistically significant linear regression model is formed using the data obtained as summarized above, relating the actual concrete compressive strength to the UPV based on in-situ measurement of travel time of ultrasonic pulse with the help of a standard Pundit device.

Figure 1 shows the relationship between the compressive strength of concrete cores of 10 cm diameter and 10 cm length dimensions, obtained by direct crushing in air-dry conditions versus ultrasonic pulse velocity measured at the site as summarized above, separately for all the nine different sites, and Figure 2 reveals the same relationship as a whole without differentiating among different sites together with the 95% confidence band on regression. Equation (1) below is the regression model representing these data.

$$(\text{Compressive Strength, kgf/cm}^2) = -199 + 123 \cdot (\text{Ultrasonic Pulse Velocity, km/s}) \qquad (1)$$

Here, the determination coefficient after adjustment for degree of freedom is: $R^2 = 0.82$, and the ratio of (magnitude/standard deviation) for the +123 coefficient is: +15.9, which means this regression equation is 99.99 % meaningful according to the t test. The dependent variable of Equation (1) is the compressive strength of concrete core samples of 10 cm dimensions both in diameter and in length, measured directly in a compression machine while in air-dry condition, for 3- to 30-year old RC buildings. The aggregates in some of those cores had a maximum grain size of about 40 mm, and some were natural as some others were crushed stones. The cements used in these buildings were mostly ordinary portland cement, close to Type I cement of ASTM C 150 (ASTM, 2000), and some were pozzolan-blended cement whose strength is the same as the former.

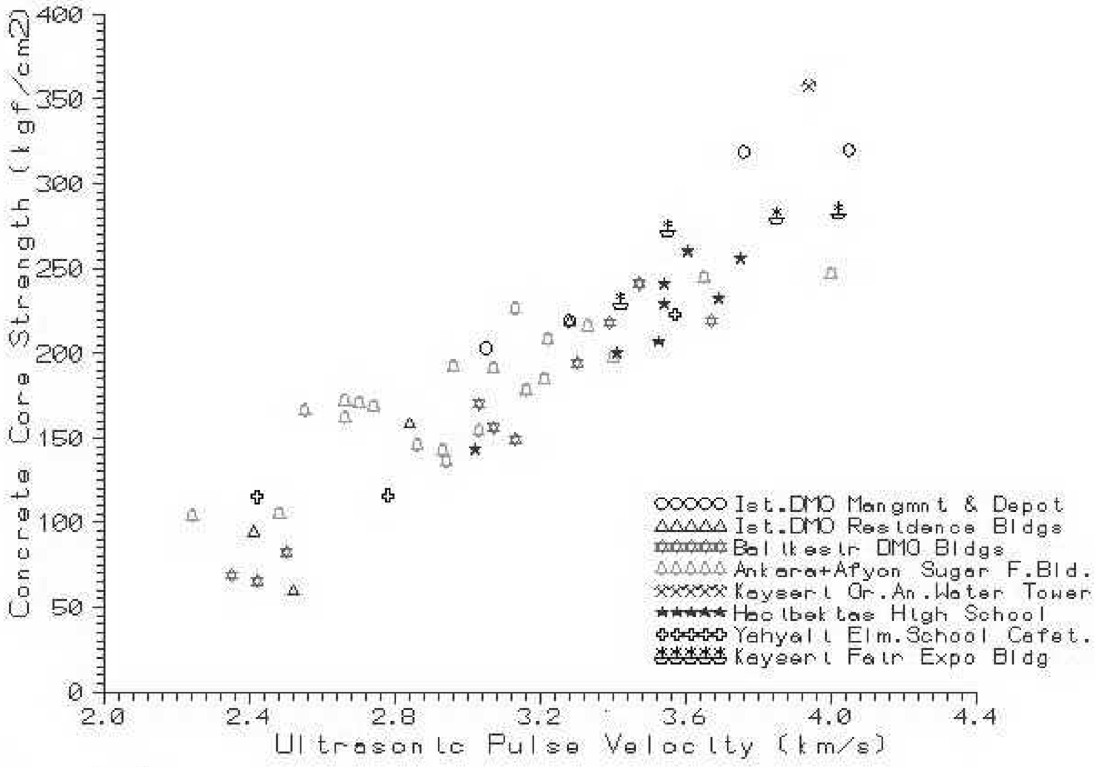

Figure 1. Concrete core strength versus ultrasonic pulse velocity with cores taken from Istanbul, Balikesir, Ankara, Afyon, and Kayseri

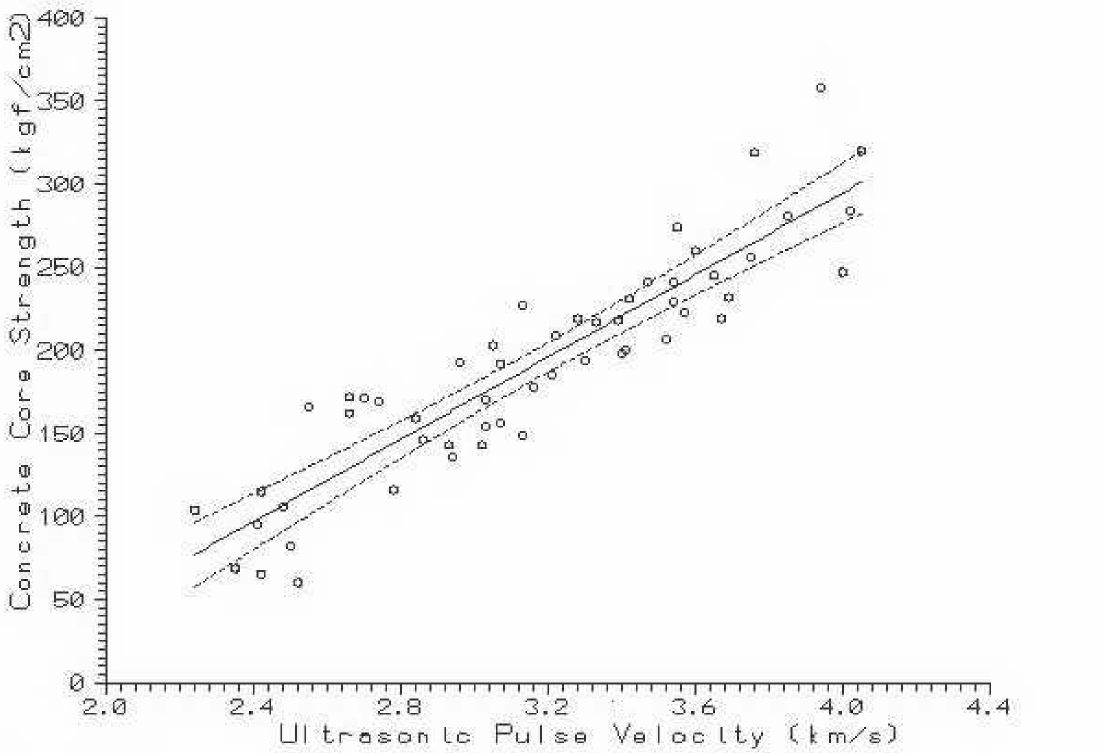

Figure 2. Regression of concrete core strength versus ultrasonic pulse velocity and %95 confidence interval for the regression

Discussions and Conclusions

It is believed herein that the actual compressive strength of concrete for RC buildings older than 3 years can be indirectly predicted by Equation (1) with an acceptable accuracy. Usage of the suggested equation would free the technical personnel from the time-consuming and laborious burdens of core drilling, sample cutting, capping, and crushing, and would enable a practical and fast determination of concrete strength using only a standard Pundit device.

Qasrawi (2000) developed a regression-based equation similar to equation (1) above. He squeezed cubic samples of 15 cm dimensions between the compressing heads of a compression machine with a small force and measured the UP travel time through these cubes. Next, he crushed the cubic sample, and he regressed the strength to the UPV obtained for these 15 cm cubic samples. This procedure is not realistic and does not reflect the actual in-situ conditions. His model can substitute the crushing operation of cubic samples which necessarily must be taken from fresh concrete during placement of concrete into the forms of a new construction. Once the cubic samples are taken, the crushing part of these tests is straightforward because compression machines are amply available everywhere. Propagation of the UP through a RC column of a structural frame will most probably be not the same as that through a standard cube of 15 cm dimensions because of the appreciable differences in the tested mediums. Therefore, equation (1) of this study is more realistic than such other equations developed by methods similar to that by Qasrawi (2000).

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