

Experimental Study On Compressive Strength, Ultrasonic Pulse Velocity And Water Content Of Concrete At Early Ages After A 28 Day Curing Period

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Abstract

Concrete is most widely used as a building material. It is very important to know that the concrete compressive strength was influenced by many factors such as the aggregate type and size, cement type, humidity and water/cement ratio. Although the characteristic strength of the concrete has reached 99% in 28 days of curing time, still concrete continues to gain strength over long period since the hydration process is not confined up to this certain period which is long-lasting process. In this study an attempt was done to determine the variations of ultrasonic pulse velocity (UPV), uniaxial compressive strength (UCS) and water content (ω) of concrete cubes after a 28 day cure period. The concrete cubes for mix design CEM I 42, 5 R grade cement were tested. A clear relationship was found between (UCS) and (ω) with (UPV) over the 12 week period. (UCS), (UPV) and (ω) of concrete increase rapidly in the initial 6 weeks after curing period and then reach about a constant value.

Keywords: Concrete, ultrasonic pulse velocity, uniaxial compressive strength, water content

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Introduction

Compressive strength is a significant aspect in deciding its load carrying capacity used by the engineers in designing buildings and constructions. The compressive strength is affected by its age as well as aggregate type and size, cement type, humidity and water/cement ratio. Different methods have been offered to predict the concrete strength with age. Baykof and Sigalov (1984) compared the proportion of strength of concrete specimens stored in wet and dry conditions and determined that there was no increase in concrete strength of those stored in a wet condition (at 15°C). Washa and Wendt (1975) predicted the concrete strength of the concrete specimens with the age stored in particular conditions and determine a precious result. Washa and Wendt (1989) studied the concrete compressive strength of C2S content stored outdoors for 50 years. Gregor (1983) determined an equation between compressive strength and age using the same study of (Gregor (1983); Washa and Wendt (1989); Ramezaniyanpour and Malhotra (1995)) indicated that concrete cannot gain the required properties at desired level, if it is not well cured especially at the early age. Özer and Özkul (2004) indicated that the curing conditions affect the strength of Pollozona Portland cement concretes. Mamlouk and Zaniewski (2006) indicated that the concrete reaches about 60% of its strength after curing three days. It reaches 80% of the strength if it is cured seven days. Yi et al., (2003) observed the compressive stress-strain curve on which the effect of five different strength levels and various ages from 12h to 28 days experimentally and analytically. Gonnerman and Schman (1928) tested 1760 6-inch cylinders and 7x10x38-inch plain concrete beams with average compressive strength changing from 200 to 9200-psi. They determined the relationship between compressive strength and age if concrete stored in air, 7 and 28 days moist curing and moist cored entire time. Burg (1996) determined

relation between the compressive strength and age of concrete on different casting/curing temperatures. Many authors (Pessiki and Carino (1988); Arıoğlu et al., (1994); Kheder (1999); Uyanık et al., (2011)) have determined the concrete quality using ultrasonic pulse technique. Some authors (Elvery and İbrahim (1976); Chang and Lien (2008); BSI) measured the concrete strength at early ages using nondestructive technique. The water content of concrete is of significant importance on strength and durability of the concrete and effect on concrete ultrasonic pulse velocity (UPV). Koliaş and Georgiou (2005) reported that the effect of water content by volume on strength is stranger for lower water/cement ratios. A great deal of recent studies indicated that UPV in moisture-saturated concrete is higher than that in dry material. The effect of moisture saturation rates is defined within a wide range (Jones, (1953); Ohdaira and Masuzawa (2000); Hellier (2003); Malhotra and Carino (2004); Fadrakas and Gonzalez (2011)). Rollet et al., (2008) determined a linear correlation between UPV and moisture content. Some other authors reported exponential correlation (Dzenis and Lapsa (1972); Ohdaira and Masuzawa (2000); Alimov (2007); Fadrakas and Gonzalez (2011)). UPV testing of concrete is based on measuring of the travel time of ultrasonic pulse passing through the concrete being tested and is successfully used to provide information on the quality of concrete in terms of uniformity and integrity. Ultrasonic measurements and results on hardening concrete have been reported since 1994 Grosse and Reinhardt (1994). UPV testing on concrete has been reported by many authors (Jones (1962); Carino (1984); Popovics et al., (1990); Dennis et al., (1993); Hassan et al., (1995); Komlos et al., (1996); Reinfardt et al., (2000); Mirmiran and Wei (2001); Subramainam et al., (2002); Kolluru et al., (2002); Lin et al., (2003); Akkaya et al., (2003); Voigt et al., (2006); Lin et al., (2007)).

The main purpose of this study is to provide correlations among the ultrasonic pulse velocity, uniaxial compressive strength and water content of C35 type concrete later 28 days of its saturation period. For this aim UPV measurement, UCS and water content tests were conducted within the period of 12 weeks later its curing period to determine relationships between these properties.

MATERIALS AND METHODOLOGY

A. Materials

C35 concrete contains OPC grade, CEM I 42,5 R grade (ultratech cement) and fine sand passing through 4.75 mm sieve having specific gravity between 2.5 and 2.66. The size of the coarse aggregate used according to IS 383-1970 standard in concrete making is maximum 20 mm and its specific gravity is between 2.69 and 2.68 g/cm³. Sikament MB-1 was used as additive. Regular clean drinkable water free from suspended particles and chemicals was added for mixing of the concrete. C35 Concrete mixing ratios are given in Table 1.

Table 1. C35 class mix concrete weights

Mixtures	Weight (kg/m ³)
Cement	424
Water	161
Sand-1	658
Sand-2	90
Course aggregate-1	637
Course aggregate-2	424
Additive	6.355
Total	2390

B. Methodology

Experimental Procedure

12 concrete cube specimens size 150x150x150 mm in dimension as shown Fig.1 were used to figure out the effect of variation of age on compressive strength, ultrasonic pulse velocity and water content. The steel cube mold was used to cast the cubes during molding. The cubes were mechanically vibrated. The fresh cast specimens were stored in the molds for 24 hours before being de-molded and submerged in water tank for curing 28 days at 15-18°C. After 28 days concrete specimens were removed from water and wiped and clean. The cubic specimens were kept at room temperature in the laboratory. The testing procedure was started immediately after the end of the curing process. Each specimen was tested every week individually and its ultrasonic pulse velocity, uniaxial

compressive strength and water content values were determined in our Construction Geophysics Laboratory in room temperature.



Fig. 1. Cubic concrete specimens.

Nondestructive Testing

The main purpose of conducting ultrasonic Pulse Velocity (UPV) testing as a nondestructive technique, ASTM C 597 (2009), is the correlation of ultrasonic pulse velocity with the age of concrete under study. UPV measurements were conducted by using DT Quist-120t ultrasonic pulse generator instrument with piezoelectric transducers of natural resonance frequency of 54 kHz in accordance with the ASTM C 597 (2009). UPV was determined by direct transmission, where the transmitter and the receiver transducers are placed directly opposite each other on parallel surfaces. The parallel surfaces of the cubic concrete specimens were polished and covered with stiffer grease to accomplish a good coupling (Fig. 2). Ultrasonic pulse velocity as a function of age after curing is given in Fig. 3. In the figure, ultrasonic pulse velocity increases relatively rapidly for period up to 6 weeks and then exhibits a relatively stable region. The progress of the ultrasonic pulse velocity follows the same model as already presented (Van der Winden (1990); Grosse and Reinhardt (1994); Reinhardt and Grosse (1996)).



Fig. 2. Ultrasonic pulse velocity testing of cubic concrete specimens.

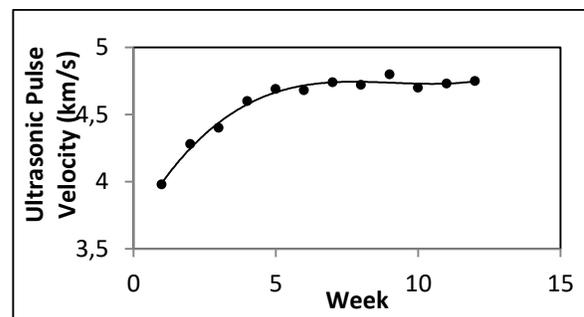


Fig. 3. Experimental data points for the variation of ultrasonic pulse velocity versus time for water and cement ratio $w/c=0.38$.

Uniaxial Compressive Strength Test (UCS)

Uniaxial compressive strength (UCS) test was performed separately for each cubic concrete specimen in consecutive weeks. For the compression test the cubic specimens were placed in the hydraulic testing machine of 150 kN capacity in such a manner that the load was applied on the forces perpendicular to the direction of the molding (Fig.4). The result is plotted as shown in Fig.5.



Fig. 4. The cubic concrete specimen in the testing machine.

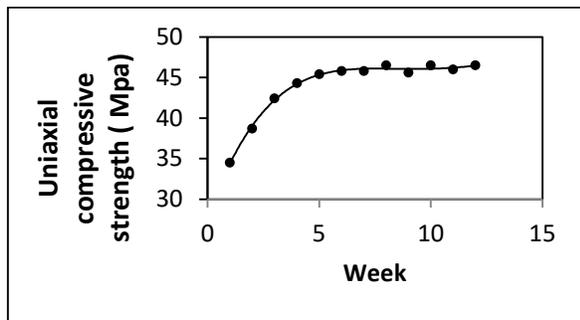


Fig. 5. Experimental data points for the variation of uniaxial compressive strength versus time for water and cement ratio $w/c=0.38$.

As seen in the figure, uniaxial compressive strength increases exponentially until the 6th week and then continues almost linearly.

Determination of Water Content (w)

In order to determine the water content of each concrete specimen, a constant amount of mass is taken from the specimen and is weighed (M_s) and then is dried at a temperature of 105°C . After that the mass allowed to cool 30 min in a dessicator. The oven-dry mass is measured (M_d). Water content (w) of the specimen is calculated using the following equation.

$$w = (M_s - M_d) / M_d \times 100$$

The sharpest decrease in the water content has been observed for 6 weeks (Fig. 6) after that it shows a very slight decrease. Fig.7 shows the linear correlation with the correlation coefficient of $R^2 = 0.96$ between ultrasonic pulse velocity and uniaxial compressive strength. The UCS increases directly as the UPV increases. Water content decreases linearly with increasing ultrasonic pulse velocity and uniaxial compressive strength (Figs. 8 and 9). Linear model was chosen with higher regression coefficient value for w and UPV ($R^2=0.94$) and for w and UCS with the simple formula. Table 2 summarizes the suggested models and the corresponding R^2 values. These proposed models can be used to estimate the approximate compressive strength and water content for the concrete over a 12 week period after cured 28 days using its measured ultrasonic pulse velocity value.

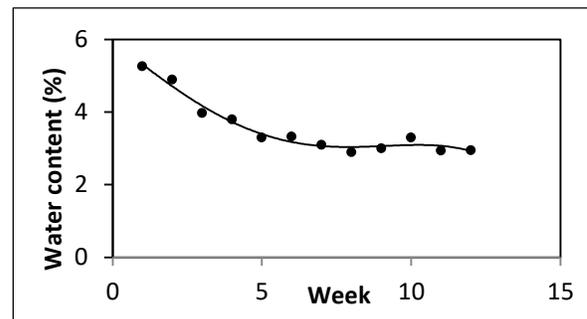


Fig. 6. Experimental data points for the variation of water content versus time for water and cement ratio $w/c=0.38$.

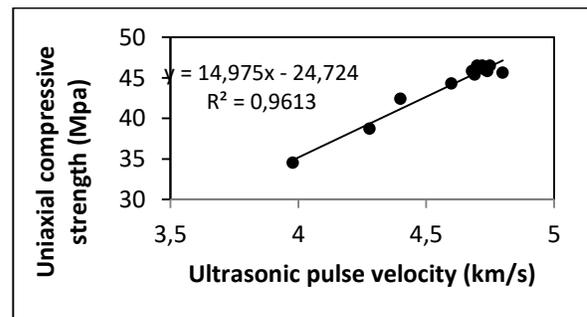


Fig. 7. Correlation between uniaxial compressive strength and ultrasonic pulse velocity

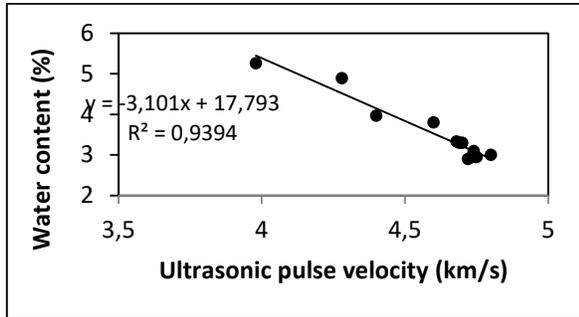


Fig. 8. Correlation between water content and ultrasonic pulse velocity

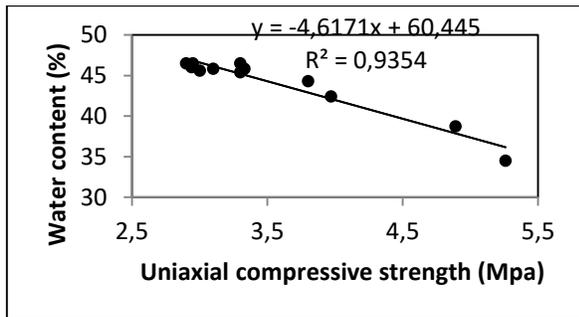


Fig.9. Correlation between water content and uniaxial compressive strength

Table 2. Suggested models for correlations between uniaxial compressive strength and ultrasonic pulse velocity, water content and ultrasonic pulse velocity and water content uniaxial compressive strength of the concrete over a 12 period range after cured 28 days

Relation	Correlation equation	R ²
UCS-UPV	UCS-14.975(UPV)-24.724	0.96
ω -UPV	ω =-3.101(UPV)+17.793	0.94
ω -UCS	ω =-4.6171(UCS)+60.445	0.94

Discussion

The experimental data determined in this study are intended to address the relationships among UPV, UCS and ω of concrete along with age are discussed. For 12 cubes were cast using C35 grade concrete and cured for 28 days. The ultrasonic pulse velocity as a function of age during the first 12 weeks is shown in Fig. 3. During the 6 weeks relatively rapid increase in the pulse velocity were observed. The time that the ultrasonic pulse velocity to reach about a constant value varies between 6th and 12th weeks. Similar studies were performed by various authors for curing

age or very early ages. Tavossi et al., (1999) conducted UPV measurements with time for 48 hours in white cement paste for water to cement ratios of 30%, 40%, 50%, and 60% and reported a rapid increase in UPC values within 16 hours and then gradual increase between 16 and 48 hours. This result is consistent with our 48-hour outcome as indicated in Fig.3. However, since the authors did not continue the tests for a longer period of time, the comparison was not possible.

Keating et al., (1989) indicated that the pulse velocity increased relatively rapidly for period up to about four hours and then at a progressively slower rate of increase for the time period until 24 hours. This result obtained in the 24 hour period is similar to the results we found in the same period (Fig. 3). Ye et al., (2001) reported that UPV increases rapidly for the concrete of the ω/c= 0.4, 0.45, 0.55 for period up to about 20 hours in curing age and then shown an increase gradually over a period between 20 hours and 180 hours which is consistent with our result determined for the ratio of w/c=0.38 (Fig.8). Albanoa et al., (2005) reported that UPV increases rapidly between the period about between 90 hours to 150 curing hours for the concrete-rubber mixes without coupling agent and shows a gradual increase up to 700 hours. These results obtained for concrete rubber are similar to those of our C-35 grade concrete. Mohammed et al., (2011) determined similar result with rubber concrete. Guang et al., (2001) found rapid increase in UPV over the curing period up to 15 hours and then at about constant rate until 180 hours for different curing temperature and w/c ratios. In our study, a very rapid increase in velocity was found in the first 5 weeks which complies with their work.

The uniaxial compressive strength of the same concrete cubes was tested individually as a function of age during the first 12 weeks after their UPV tests. Experimental results indicated that the UCS values start to increase rapidly during 6 weeks from 34.5 MPa to 44.68 MPa and then at a steady rate of increase in strength for the rest of the period up to 12th week. Kaszanyi (1989) determined an almost linear relationship between cube strength and age of light weight concrete over the period up to 90 days. However, we determined linear relationship with the correlation coefficient of R²=0.96. Shah and Patil (2015) conducted compressive strength test on concrete cubes over the curing period up to 28 days and found a linear relationship that supports our results.

Metwally (2014) determined a linear relationship between the compressive strength and age of the concrete mix as we found.

A linear relationship was determined between UCS and UPV of the concrete cubes over a 12 week period with the correlation coefficient of $R^2=0.96$. Similar relationships were found by Naik et al., (2004), and Kurtuluş and Bozkurt (2011). Chang and Lien (2008); Trtnik et al., (2009); Panzera et al., (2011) and Yılmaz and Erçikdi (2015) determined exponential relationships between UCS and UPV.

The water content decreases gradually over the period for 6 weeks and then shows very slight decreases up to 12th week. The effect of water content on UPV was examined and found a linear relationship between water content and UPV which shows how the variations of water content affect the UPV. Water content decreases with increasing UPV. Philippidis and Aggeleis (2003) found a similar relationship between the velocity and w/c ratio for the mortar. A linear relationship between water content and UCS was found with the correlation coefficient of ($R^2=0.93$) which indicates that UPV tests are sensitive tools to analyze the variations in UCS. Gilkey (1961) and Neville (1996) conducted compressive tests on specimens of different ω/c ratios and found exponential relationships between these parameters.

Conclusion

The aim of this study is to examine the variations of ultrasonic pulse velocity, uniaxial compressive strength and water content of concrete by age. Measurements were performed on 12 C35 degree concrete cube specimens. Each of the 12 concrete cube specimens saturated in the standard conditions for 28 days and afterwards subjected to ultrasonic pulse measurement by using direct transmission as well as uniaxial compressive strength and moisture tests individually each successive week.

A linear relationship was determined between UCS and UPV, ω and UPV and ω and UCS of the concrete cubes whereas UCS increases as UPV increases and ω decreases as UPV and UPV increase over a 12 week period later on curing period of 28 days.

Table 2 summarizes the proposed correlation equations. These equations can be used to estimate the approximate concrete compressive strength and water content using their ultrasonic pulse velocity.

From the above findings we can conclude that the UPS and UCS values of concrete cubes cured 28 days reach their almost constant values after 6 weeks whereas water content of the concrete decreases gradually over the period for 6 weeks and then shows very slight decreases up to 12th week. The proposed correlation equations given in this study can be used to estimate the approximate concrete compressive strength and water content from ultrasonic pulse velocity.

Since this study is conducted in longer period (12 weeks) than other studies, it has completed the missing parts of the other studies in order to show how the concrete has become stationary in a long period of time considering the velocity, compressive strength and water content.

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References

- AKKAYA Y, VOIGT T, SUBRAMANIAM KV and SHAH SP (2003) Nondestructive measurement of concrete by ultrasonic wave reflection methods, *Materials and structures*, 36(8):507-514
- ALBANOVA C, CAMACHO N, REYES J, FELIU JL, HERNANDEZ M (2005) Influence of scrap rubber addition to Portland I concrete composites: Destructive and non-destructive testing, *Composite Structures* 71, 439–446
- ALIMOV AG (2007) Improvement of the theoretical foundations of the ultrasonic diagnosis of concrete and reinforced concrete hydrotechnical structures, *Hydrotechnical Construction*, vol. 2. [In Russian]
- ARIOĞLU E, ODBAY O, ALPER H, APIOĞLU B (1994) Birleşik yıkıntısız yöntemle beton dayanımının kestirilmesi için yeni formül ve uygulama sonuçları. *Beton Prefabrikasyon*, 29, 5-11
- ASTM C 597 (2009) Standard Test Method for Pulse Velocity Through Concrete. American Society for Testing and Materials.

- BAYKOF F, and SIGALOF Y (1984) Reinforced concrete structure, Moskow: Mier
BSI. Testing concrete. London BS 1881. Parts 5-209, 1970-1998.
- BURG, RONALD G (1996) The influence of casting and curing temperature on the properties of fresh and hardened concrete, research and development Bulletin RD113, Portland Cement Association, [Influencia de la temperatura durante el colado y el curado en las propiedades de concreto fresco y endurecido, Boletín de Investigación y Desarrollo RD113, Asociación de Cemento Portland], Skokie, Illinois, USA
- CARINO NJ (1984) Laboratory study of flaw detection in concrete by impact-echo method, In-Situ/Nondestructive Testing of Concrete, Malhotra, V. M., Ed., ACI SP-82, A.C.I., 557
- CHANG CHE-WAY and LIEN HUNG-SHENG (2008) Nondestructive measurement of concrete strength at early ages, department of civil engineering and engineering informatics chung-hua university, Email: ccw@chu.edu.tw
- DENNIS A, SACK DA and OLSON LD (1993) Advanced NDT Methods for Concrete Structures, Proceedings of the International Conference on Nondestructive Testing of Concrete in the Infrastructure, sponsored by the Society for Experimental Mechanics, Inc., Dearborn, Michigan
- DZENIS VV and LAPSA VH (1972) Ultrasonic testing of hardening concrete. Leningrad: Strojizda (Publishing House for the construction), 1972. [In Russian]
- ELVERY RH and IBRAHIM LAM (1976) Ultrasonic assessment of concrete strength at early ages, Magazine of Concrete Research, December, 181-190
- FADRAGAS CR and GONZALEZ MR (2011) Dependence of ultrasonic pulse propagation velocity on free water content in concrete structure under tropical climate conditions, presented at 5th Pan American Conference for NDT, Cancun, Mexico
- GILKEY H J (1961) Water/Cement Ratio versus Strength – Another Look. J. Amer. Concr. Inst., Part 2, 58, 1851-1878
- GONNERMAN HF and SCHMAN HS (1928) Test of plain concrete, Proceedings, Am. Soc. Testing Mats. V.28, Part II, 527
- GROSSE CU and REINHARDT HW (1994) Continuous ultrasound measurements during setting and hardening of Concrete. Otto Graf Journal 5, 76-98
- GUANG YE, K.VAN BREUGEL, ALA. FRAAJI (2001) Experimental study on ultrasonic pulse velocity evaluation of microstructure at cementitious material at early age, Heron, V.46, No.3
- HASSAN M, BURDET O, FAVRE R (1995) Ultrasonic measurements and static load tests in bridge evaluation, NDT&E International, 28 (6), 331-337
- HELLIER C (2003) Handbook of Nondestructive Evaluation: Blacklick, OH: McGraw-Hill Professional Publishing, USA
- JONES R (1953) Testing concrete by ultrasonic pulse technique, Proc. Highway Research Board. Vol.32, 258
- JONES R (1962) Non-destructive Testing of Concrete. London: Cambridge University Press, 1962
- KASZANYI G (1989) The strength deformation and thermomechanic properties of crushed brick aggregate light-weight concrete, Technical University H-1521 Budapest <http://www.pp.bme.hu/ci/article/download/3917/3022>
- KEATING J, HANNANT DJ, HIBBERT AP (1989) Correlation between cube strength, ultrasonic, V.19, Issue 5, 715-726
- KHEDER GF (1999) A two stage procedure for assessment of in situ concrete strength using combined non-destructive testing. Mater Struct, 32(6), 410-417
- KOLIAS S and GEORGIU C (2005) The effect of paste volume and of water content on the strength and water absorption of concrete, Cement and Concrete composites, V.27, Issue 2, 211-216
- KOLLURU G R, ZUK M AND CHAPPELL MA (2002) Reduced reproductive effort in male field crickets infested with parasitoid fly larvae. Behavioral Ecology 13: 607-614
- KOMLOS K, POPOVICS S, NIERNBERGEROH T, BABD B and POPOVICS J S (1996)

- Ultrasonic Pulse Velocity Test of Concrete Properties as Specified in Various Standards. *Cement and Concrete Composites*, Vol. 18, 357-364
- KURTULUS C and BOZKURT A (2011) Determination of concrete compressive strength of the structures in Istanbul and Izmit Cities (Turkey) by combination of destructive and non-destructive methods, *International Journal of the Physical Sciences* Vol. 6(16), 4044-4047
- LIN Y, LAI CP and YEN T (2003) Prediction of Ultrasonic Pulse Velocity (UPV) in Concrete. *ACI Materials Journal* 100 (1), 21–28
- LIN, YICHING, KUO, SHIN-FANG, HSIAO, CHIAMEN and LAI, CHAO-PENG (2007) Investigation of pulse velocity-strength relationship of hardened concrete, *ACI Materials Journal*, Vol.104. No. 4, pp. 344-350
- MAC GREGOR JG (1983) Load and resistance factors for concrete design, *ACI Journal* 84(4): 279-287
- MALHOTRA VM and CARINO NJ (2004) *Handbook on Nondestructive Testing of Concrete*. Second edition: ASTM International, CRC Press LLC, USA
- MAMLOUK MS and ZANIEWSKI JP (2006) *Materials for Civil and Construction Engineers*, 2nd ed., New Jersey: Pearson Prentice Hall
- METWALLY ABD ALLAH ABD ELATY (2014). Compressive strength prediction of Portland cement concrete with age using a new model, *HBRC Journal*, Volume 10, Issue 2, 145–155
- MIRMIRAN A, WEI Y (2001). Damage assessment of FRP-encased concrete using ultrasonic pulse velocity. *J. Eng. Mech.*, 127: 126-135
- MOHAMMED BS, AZMI NJ and ABDULLAHI M (2011) Evaluation of rubbercrete based on ultrasonic pulse velocity and rebound hammer tests. *Construction and Building Materials*, Vol. 25, pp. 1388–1397
- NAIK TR, MALHOTRA VM and POPOVICS JS (2004) The Ultrasonic Pulse Velocity Method, In: V.M. MALHOTRA and N.J. CARINO, Edited 2004, *Handbook on Nondestructive Testing of Concrete*, Crc Press
- NEVILLE AM (1996) *Properties of Concrete* (4th ed.). New York: J. Wiley
- OHDRAIRA E and MASUZAWA N (2000) Water content and its effect on ultrasound propagation in concrete – the possibility of NDE, *Ultrasonics*, vol.38, 546–552, issues 1–8
- OZER B, OZKUL MH (2004). The influence of initial water curing on the strength development of ordinary Portland and pozzolanic cement concretes. *Cem. Concrete Res.* 34(1):13-18.
- PANZERA TH, CHRISTOFORO AL, COTA FP, BORGES PHR and BOWEN CR (2011) Ultrasonic Pulse Velocity Evaluation of Cementitious Materials, *Advances in Composite Materials - Analysis of Natural and Man-Made Materials*, Dr. Pavla Tesinova (Ed.), ISBN: 978-953-307-449-8, InTech
- PESSIKI P S AND CARINO NJ (1988) Setting Time and Strength of Concrete Using the Impact-Echo Method, *ACI Materials Journal*, V. 85, No. 5, 389-399
- PHILIPPIDISA TP, AGGELEIS DG (2003) An acousto-ultrasonic approach for the determination of water-to-cement ratio in concrete, *Cement and Concrete Research* 33, 525 – 538
- POPOVICS S, ROSE LJ and POPOVICS J S (1990) The Behavior of Ultrasonic Pulses in Concrete, *Cement and Concrete Research*, V. 20, No. 2, 259-270
- RAMEZANIANPOUR AA and VM MALHOTRA (1995) Effect of Curing on the Compressive Strength, Resistance to Chloride-Ion Penetration and Porosity of Concretes Incorporating Slag, Fly Ash or Silica Fume”, *Cement and Concrete Composites*, 17(2)
- REINHARDT HW and GROSSE CU (1996) Setting and hardening of concrete continuously monitored by elastic waves. In Bartos, JPM, Marrs, DL, Cleland, DJ (eds.) *Production methods and workability of concrete*. Chapman & Hall, London, 415-425
- REINHARDT HW, GROBE CU, HERB AT (2000) Ultrasonic monitoring of setting and hardening of cement mortar – a new device. *Materials and Structures*, Vol. 33, pp. 580-583

- ROLLET F, MANSELL M, COCHRAN S (2008) Determining moisture content in concrete under simulated precipitation using ultrasonic propagation time measurements, *Nondestructive Testing and evaluation*, vol. 23, No. 4, 241–255
- SEONG-TAE YI, JIN-KEUN KIMB, TAE-KEUN OHC (2003) Effect of strength and age on the stress–strain curves of concrete specimens, *Cement and Concrete Research*, V. 33, Issue 8, 1235–1244
- SHAH S, and PATIL A (2015) An experimental investigation of effect of variation of curing time on compressive strength of concrete, *International Journal of Emerging Technology and Advanced Engineering*, Volume 5, Issue 3, 151-154
- SUBRAMANIAM KV, MOHSEN JP, SHAW CK and SHAH SP (2002) Ultrasonic technique for monitoring concrete strength gain at early age, *ACI Materials Journal*, Vol.99. No. 5, 458-462
- TAVOSSO HM, TITTMANN BR and COHEN-TENOUDJI F (1999) Ultrasonic characterization of cement and concrete, *Review of progress in Quantitative Nondestructive Evolution*, V./8 Kluwer Academic/ Plenum Publishers, 1943-1948
- TRTNIK G, KAVCIC F, TURK G (2009) Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks *Ultrasonics* Vol. 49, 53–60
- UYANIK O, KAPTAN K, GÜLAY FG, TEZCAN S (2011) Beton dayanımının tahribatsız ultrasonik yöntemle tayini, *Yapı Dünyası* 184, 55-58
- VAN DER WINDEN NGB (1990) Ultrasonic measurement for setting control of concrete. In Reinhardt, H.W. (ed.) *Testing during concrete construction*, Chapman & Hall, London, 122-137
- VOIGT T, SUN, ZHIHUI AND SHAH, SURENDRA P (2006) Comparison of ultrasonic wave reflection method and maturity method in evaluating early-age compressive strength of mortar, *Cement and Concrete Composites*, Vol.28. No.4, 307-316
- WASHA GW and WENDT KF (1975) Fifty-year properties of concrete, *ACI Journal* proceedings, 72(1). 20-28
- WASHA GW and WENDT KF (1989) Concrete compressive strength variation with time. *Concrete technology*, <http://theconstructor.org/concrete-compressive-strength-variation-with-time/5933/>
- YE G, BRUGEL KV and FRAAIJ ALA (2001) Experimental study on ultrasonic pulse velocity evaluation of the microstructure of cementitious material at early age. *Heron*, V. 46, No.3, ISSN 0046-7316
- YILMAZ T and ERÇIKDI B (2015) Prediction of the uniaxial compressive strength of paste backfill by ultrasonic pulse velocity test, *Türkiye 24. Uluslararası Madencilik Kongresi ve Sergisi*, Antalya-Turkey