Journal of International Scientific Publications:
Materials, Methods & Technologies, Volume 7, Part 1
ISSN 1313-2539, Published at: http://www.scientific-publications.net

USE OF COMBINED DESTRUCTIVE AND NON-DESTRUCTIVE TEST METHODS TO ASSESS THE STRENGTH OF CONCRETE

O. Arioz[1], K. Kilinc[2], K. Ramyar[3], M. Tuncan[4], A. Tuncan[4]

[1]Optimizing Consultancy, Izmir

[2]Kirklareli University, Department of Civil Engineering

[3]Ege University, Department of Civil Engineering

[4]Anadolu University, Department of Civil Engineering

Abstract

The compressive strength test applied on standard samples is one of the most important tests indicating the quality of concrete in structures. The results of the standard tests are compared with the values used in design calculations and the quality of concrete is controlled. Although the standard tests are well accepted by the construction industry, they may not represent the in-situ strength of concrete due to the differences between the degree of compaction and curing conditions of concrete and those of standard samples. In-situ strength is also important for the efficient planning of the construction works in huge projects. In the present study, the results obtained from standard tests, core tests, ultrasonic pulse velocity tests, and rebound hammer tests were extensively analysed for the assessment of concrete strength.

Key words: *Concrete strength, standard tests, core test, ultrasonic pulse velocity, rebound number.*

1. INTRODUCTION

Concrete is one of the most widely used structural material produced by mixing together aggregate, cement, water, and if necessary different types of admixtures (Neville 1981; Mindess&Young 1981; Troxell, Davis&Kelly 1968; Erdogan 2003; Taylor 1977; Arioglu E&Arioglu N 1998). One of the main characteristics of concrete is its compressive strength that is directly used in structural design calculations and also gives an idea about other important properties of concrete (Neville 1981; Erdogan 2003). Therefore, the quality of concrete is usually indexed by its compressive strength (Arioz, Yildiz, Nalcaci, Karaesmen and Erkay 2004). Different methods and techniques are utilised for the inspection and evaluation of concrete quality. Generally, standard cube and cylinder specimens are taken and tested at specified ages for the quality control of concrete cast in structures (Arioglu E&Arioglu N 1998). However, the standard specimens may not represent efficiently in-situ strength of concrete due to different curing and compaction. Moreover, the dimensions of the test specimen and those of the structural member are also different from each other (Chmielewski&Konopka 1999; Bartlett&MacGregor 1996; Bungey&Soutsos 2001). Therefore, actual strength of concrete may show some differences from design strength and the uniformity may not be obtained. In such cases, the quality of concrete can be assessed by means of destructive and non-destructive methods (Bartlett&MacGregor 1996; Bungey&Soutsos 2001; Haque&Al-Khaiat 1997; Abdel-Halim, Al-Omari&Iskender 1999; Miao, Aitcin, Cook&Mitchell 1993; Franco, Noli, Degiralomo&Ercolani 2000; Kenai&Bahar 2003; Price&Hynes 1996; Beek, Breugel&Hilhorst 1997; Ohtsu&Watanabe 2001; Zhu, Gibbs&Bartos 2001; Elverly&Ibrahim 1976). Core test is one of the most reliable methods for the determination of in-situ strength of concrete but the coring is difficult and time consuming.

Furthermore, core test is a destructive test and therefore the applicability of the test is very limited. Ultrasonic pulse velocity (UPV) and rebound hammer tests are popular non-destructive techniques used in the assessment of properties of concrete in the structures. Both UPV and rebound hammer tests do not give any damage to the structural member, and therefore, they can be applied whenever required.

The destructive and non-destructive tests performed for the estimation of in-situ strength of concrete can be compared according to some features such as cost, time, damage, representing, and correlation confidence. The comparison of some of these tests stated by Bungey and cited by Arioglu was given in Table 1 (Arioglu E&Arioglu N 1998). As it can be seen from this table, the core test is disadvantageous from cost, experiment velocity and damage points of view. However, it is able to give the strength of concrete with high correlation confidence. UPV and rebound hammer tests are very simple and easy to perform but their correlation confidences are weak.

Method	Cost	Velocity	Damage	Representative	Correlation Confidence
Coring	High	Slow	Medium	Medium	Strong
Ultrasonic Pulse Velocity (UPV)	Low	Fast	No	Good	Weak
Rebound Hammer	Very low	Fast	No	Only surface	Weak

Table 1. The comparison of methods for estimation of concrete strength (Arioglu E&Arioglu N 1998)

In this experimental investigation, core test, rebound hammer test and ultrasonic pulse velocity test were conducted on different concrete mixtures. The results of these destructive and non-destructive tests were correlated and compared with those of compressive strength test of concrete performed on standard cube and cylinder samples.

2. CONCRETE TESTS

2.1. Standard tests

Compression tests on specimens prepared in a standard manner that means full compaction and moist curing for a specified period of time give potential strength of concrete. Two types of standard specimens are used; cylinder and cube. Cylinders are used in the United States, France, Canada, etc. and cubes are utilised in Great Britain and in many other countries in Europe (Neville 1981). In some countries such as Turkey, both cylinders and cubes are used to determine the compressive strength of concrete. The dimensions of the standard specimens may vary from country to country. Cube test is described in TS EN 12390 and BS 1881: Part 108: 1983 and cylinder test is described in TS EN 12390, ASTM C 192-90a, ASTM C 39, and BS 1881: Part 110: 1983 (TS EN 12390, 2002; ASTM C39, 1994; ASTM C 192-90a, 1994; BS 1881: Part 108: 1983, 1983; BS 1881: Part 110: 1983, 1983). It is stated that the shape and the dimensions of the specimens play an important role in the evaluation of the test results. It should also be noted that the relationships between the cube and cylinder strength

may be different for different concrete mixtures (Neville 1981). Fig.1. illustrates the preparation of the standard test samples in the experimental study.



Fig.1. Preparation of the standard test samples

2.2. Core test

The common method to measure the in situ strength of concrete is to drill cores from the structural member. Although it is the most reliable way to estimate the quality of concrete, the test results are influenced by a number of factors such as diameter, length-to-diameter (l/d) ratio and moisture condition of the specimen as well as the strength and the age of the concrete (Bartlett&Macgregor 1994a; Bartlett&Macgregor 1994b; Bartlett&Macgregor 1993; Bartlett 1979; Bungey 1979). Among these, diameter and l/d ratio of the specimen play very important role in the interpretation of the test results. Moreover, the comparison between the strengths of standard specimens and core specimens is not unique for all specifications. It is evident that the dimensions of the core specimens are also dependent on the standard sample for the proper comparison. Generally, the cores with l/d ratios of 2 and 1 are selected when their strengths are compared with those of cylinder and cube specimens, respectively. The core test is prescribed in TS 10465, TS EN 12504, ASTM C 42, and BS 1881: Part 120: 1983 (TS 10465, 1992; TS EN 12504-1, 2002; ASTM C 42-90, 1994; BS 1881: Part 120: 1983, 1983). The drilling of the core specimens from concrete sample is shown in Fig.2.

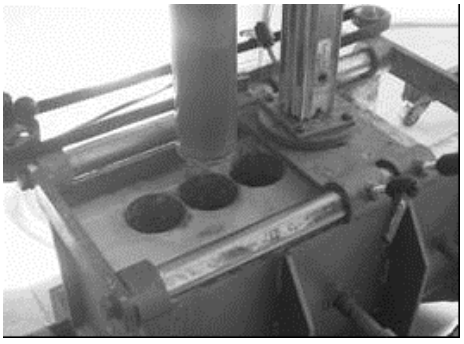


Fig.2. Drilling of the core specimens from concrete

ISSN 1313-2539, Published at: http://www.scientific-publications.net

2.3. Ultrasonic pulse velocity (UPV) test

The ultrasonic pulse velocity (UPV) test is a popular non-destructive test. It is fast and easy to perform. Thus, it can be considered as a successful method for quick checking of uniformity of concrete and for indicating the presence of voids or internal cracks in concrete (Yaman, Inci, Yesiller&Aktan 2001; Tomsett 1980; Ye, Van Bruegel&Fraaij 2003; Van Hauwaert, Thimus&Delannay 1998). UPV test is prescribed in ASTM C 597 and BS 1881: Part 203 (ASTM C 597-83, 1994; BS 1881: Part 203: 1986, 1986). The test is yet involved in Turkish Standards. Although there is no statistically difference between the results obtained from direct and indirect transmission (Yaman, Inci, Yesiller&Aktan 2001). Generally the direct one is preferred in the application of the test. A number of factors such as types and properties of aggregates, mix proportions of concrete and the presence of steel reinforcement, voids or cracks affect the results of the test (Ohdaira&Masuzawa 2000; Davis 1977; Qasrawi&Marie 2003; Hernandez, Anaya, Izquiredo&Ullate 2002). Although there are several proposals, it may not be possible to develop a unique relationship between the strength and the ultrasonic pulse velocity. Fig.3. shows the application of UPV test in this investigation.

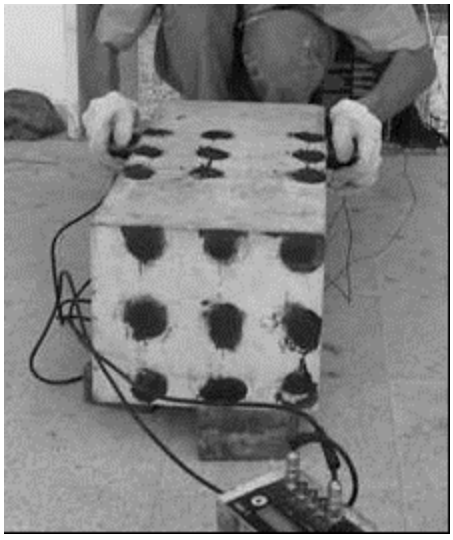


Fig.3. Application of UPV test

2.4. Rebound hammer test

Rebound hammer test is one of the oldest non-destructive methods and it is still used owing to its simplicity. It is based on the principle that the rebound of an elastic mass depends on the hardness of the surface against which the mass impinges (Neville 1981; Erdogan 2003). The result of the test is very sensitive to local variations in concrete. For instance, presence of large pieces of aggregate just under the plunger may result in abnormally higher values, conversely, presence of a crack or void under the plunger will cause lower rebound number (RN) values. Moreover, the rebound number depends also on the type and properties of the aggregate, mix proportions, surface texture as well as the wetness of the surface of the concrete. It is clear that the rebound number reflects only the surface properties of the concrete (Neville 1981). Rebound hammer test is prescribed in TS 3260, ASTM C 805-85, and BS 1881: Part 202: 1986. Fig.4. illustrates the application of rebound hammer test in this experimental study (TS 3260, 1978; ASTM C 805-85, 1994; BS 1881: Part 202: 1986, 1986).

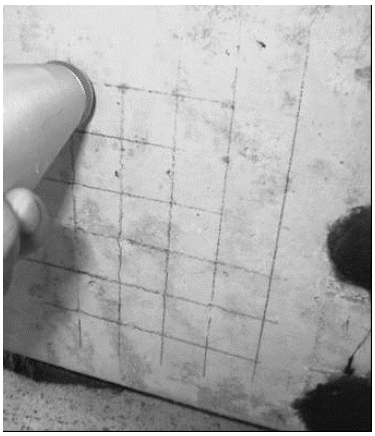


Fig.4. Application of rebound hammer test

3. EXPERIMENTAL STUDY

In this investigation, twelve different concrete mixtures were produced using two different types of aggregates with four different maximum sizes. An ordinary Portland cement and a crushed limestone and a natural aggregate were used in concrete production. The maximum aggregate sizes were 10, 15, 22 and 30 mm for both aggregate types. To maintain a constant slump of 150±20 mm in all of the mixtures, a plasticizer was also used in some of the mixtures. Proportions and some properties of concrete mixtures are given in Table 2 and Table 3, respectively.

Mixture	Coarse Aggregate	Fine Aggregate	Cement	Water	Admixture
MIX-A	696	1043	356	215	-
MIX-B	729	1094	331	200	-
MIX-C	1034	846	315	190	-
MIX-D	1128	752	315	190	-
MIX-E	507	1259	356	195	-
MIX-F	833	994	331	181	-
MIX-G	1158	706	315	173	-
MIX-H	1300	565	315	173	-
MIX-I	1036	877	320	174	3.2
MIX-J	1043	850	360	170	3.6
MIX-K	1048	817	390	172	3.9
MIX-L	1083	640	500	200	6.0

Table 2. Proportions of concrete mixtures (kg/m^3)

Mixture	w/c ratio	Aggregate Type	Maximum Aggregate Size (mm)	28-day 150 mm Cube Compressive Strength (MPa)
MIX-A	0.60	Crushed Limestone	10	28.4
MIX-B			15	28.1
MIX-C			22	27.4
MIX-D			30	27.8
MIX-E	0.55	Natural Aggregate	10	26.6
MIX-F			15	26.2
MIX-G			22	25.6
MIX-H			30	25.2
MIX-I	0.54	Crushed Limestone	22	34.2
MIX-J	0.47			38.0
MIX-K	0.44			39.9
MIX-L	0.40			43.3

Table 3. Some properties of concrete mixtures

By using concrete mixtures, 150 mm cube, 150x300 mm cylinder and 250x300x650 mm beam specimens were cast and moist cured in the laboratory until testing. The cube and cylinder specimens were prepared for standard tests. Compressive strength tests were performed on cube and cylinders at specified ages. The cores of 144, 94, 69, and 46 mm diameter were removed from the beams by drilling in the direction perpendicular to the direction of concrete placement. Then, the cores were trimmed to proper lengths so that to have the l/d ratios of 1.0 after capping. Core specimens were capped with high early strength cement paste. The compressive strengths of cores were determined at the ages of 7, 28, and 90 days. The compressive strength test results obtained from the core tests are the average of at least six specimens. A type N rebound hammer with impact energy of 0.225 kgm was used in rebound hammer tests which were performed on beam specimens. In each rebound hammer test, 12 readings were taken and the average was noted as rebound number of the corresponding concrete. The hammer was applied horizontally in all readings. Three beams were tested for each concrete mixture and averaged. In UPV tests, a testing apparatus consisting of a pulse generator, a pair of transducer, an amplifier, a time measuring circuit, and connecting cables was used. Ultrasonic measurements were performed on beams through nine paths by direct transmission perpendicular to the direction of concrete casting. The average of nine values was reported as UPV value for the corresponding beam. Three beams were tested for each concrete mixture and averaged. Totally, 648 cubes, 288 cylinders, 5243 cores, and 560 beams were tested in scope of this experimental investigation on assessing concrete strength by standard, destructive and non-destructive methods.

ISSN 1313-2539, Published at: http://www.scientific-publications.net

4. RESULTS AND DISCUSSIONS

4.1. Standard tests results

The compressive strength developments of standard cube specimens are indicated in Figs.5-7. Although the w/c ratios of natural aggregate bearing concretes were lower than those of crushed limestone bearing concretes, cube compressive strengths of concretes produced from crushed limestone were higher than those of concretes produced from natural aggregate (Fig.5 and 6). This is most probably caused partly by the porous structure of the natural aggregate and partly by the weaker bonding between the aggregate and cement paste.

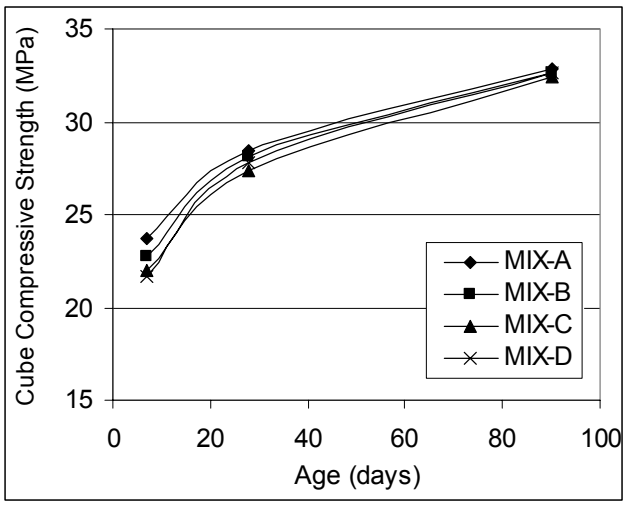


Fig.5. Compressive strength developments of concrete produced from crushed limestone

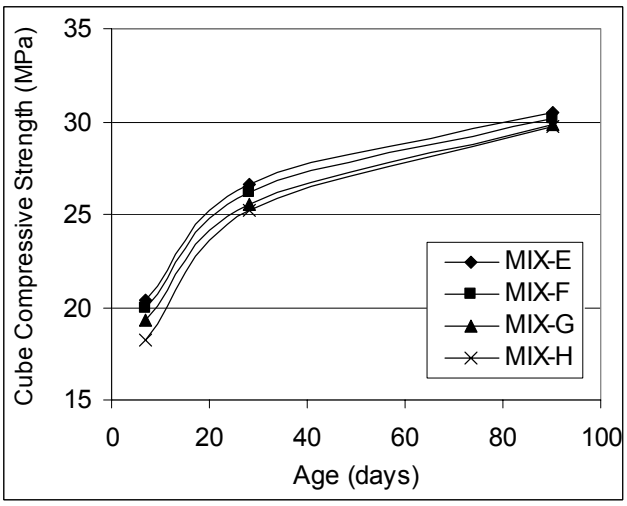


Fig.6. Compressive strength developments of concrete produced from natural aggregate

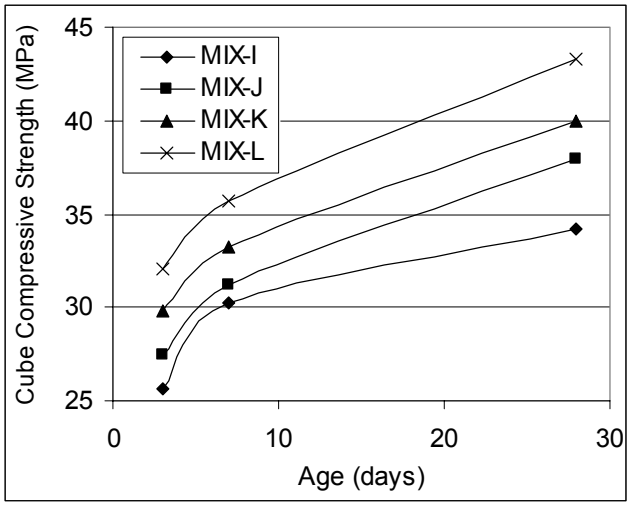
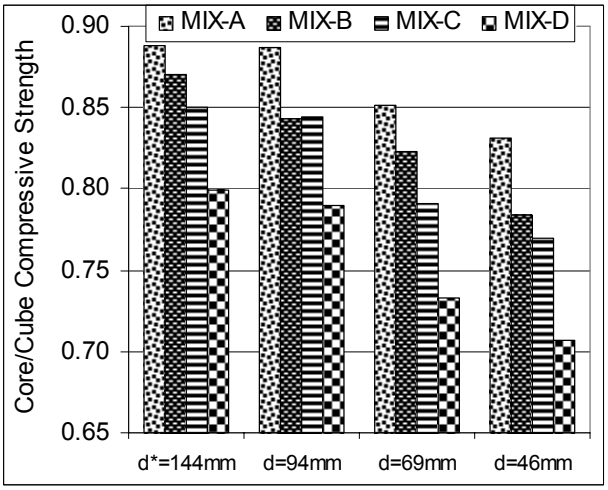


Fig.7. Compressive strength developments of higher strength concrete



*d=core diameter

Fig.8. Core/cube strength for crushed limestone bearing concretes

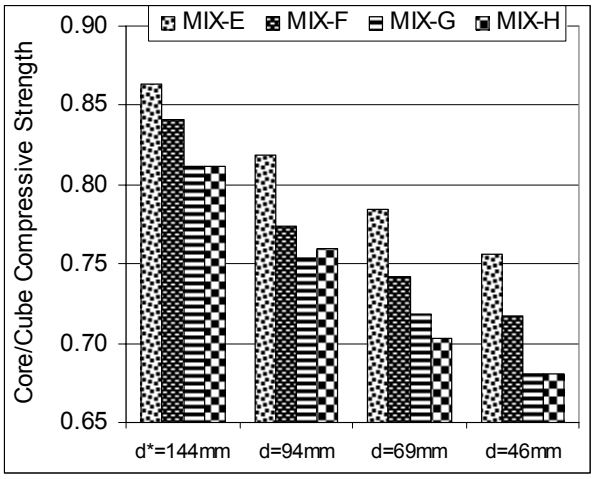
Test results in Figs.5 and 6 indicated that the effect of maximum aggregate size on 150 mm cube strength was not significant. However, it should be noted that the cube strength slightly decreased as the maximum aggregate size increased. This can be attributed to the wall effect which is more pronounced for concrete produced by larger aggregate sizes. Compressive strength values measured on standard cube specimens varied between 18 and 33 MPa for MIX-A, B, C, D, E, F, G, and H.

It is clearly seen from Fig.7 that the compressive strength of concrete increased gradually with decrease in w/c ratio and with the increase of age, as it was expected. The compressive strengths of the cube specimens ranged between 26 and 43 MPa for MIX-I, J, K, and L.

4.2. Core tests results

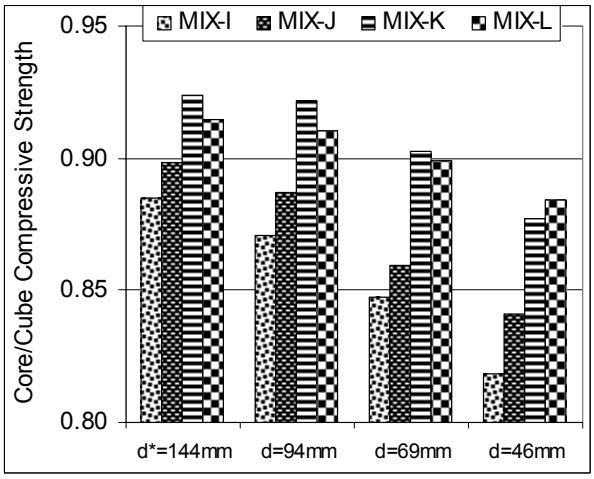
ISSN 1313-2539, Published at: http://www.scientific-publications.net

The core/cube compressive strength values are illustrated in Figs.8-10. It is clearly seen from Figs.8 and 9 that the core to cube strength ratio is significantly affected by maximum size of the aggregate used in the concrete production. The core/cube strength values gradually decreased with the increase in aggregate size. The effect is more pronounced for 46 mm diameter cores bearing natural aggregates. The relative strengths of 46 mm diameter cores with respect to standard cube specimens were 0.71 and 0.68 for cores drilled from crushed limestone and natural aggregate bearing concretes, respectively.



*d=core diameter

Fig.9. Core/cube strength for natural aggregate bearing concretes



*d=core diameter

Fig.10. Core/cube strength for higher strength concretes

In the present study the concrete mixtures designated by MIX-I, J, K, and L were produced to investigate the influence of strength level of concrete on core/cube strength. It can be seen from Fig.10 that core/cube strength generally increased as the concrete strength increased. The effect was more significant for 46 mm diameter cores.

4.3. Ultrasonic pulse velocity (UPV) tests results

Ultrasonic pulse velocity (UPV) tests results are presented in Figs.11-13. As it was expected, UPV values increased with increase in concrete age. It was also found that UPV values increased with increase in maximum aggregate size in concrete mixture. This was most probably caused by the increase in the coarse aggregate volume as well as aggregate/cement paste ratio with increase in aggregate size. The effect of aggregate size upon UPV value was found to be more pronounced for seven days age. It should also be noted that somewhat higher UPV values were measured on crushed limestone aggregate concrete (Figs.11 and 12).

Fig.13 illustrates the relationship between the cube compressive strength and UPV value obtained from MIX-I, J, K, and L. It is clear that there is a linear relationship between the cube strength and UPV value. The regression equation and R^2 value is shown in the figure.

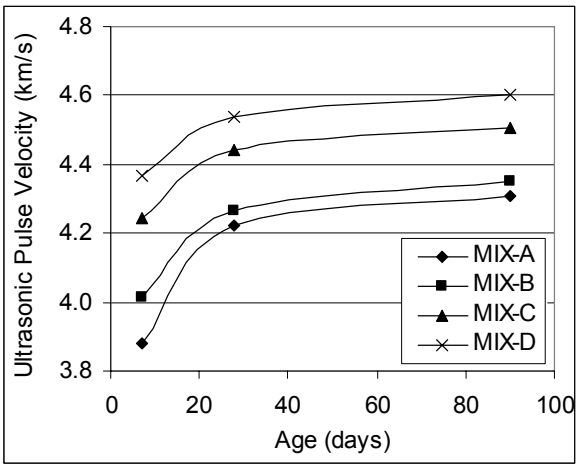


Fig.11. UPV values measured on crushed limestone containing concretes

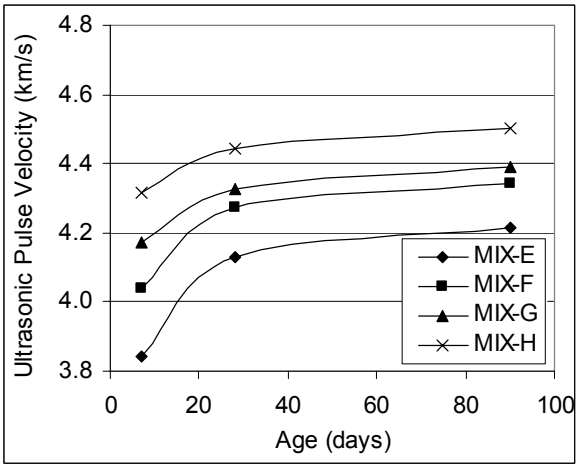


Fig.12. UPV values measured on natural aggregate containing concretes

ISSN 1313-2539, Published at: http://www.scientific-publications.net

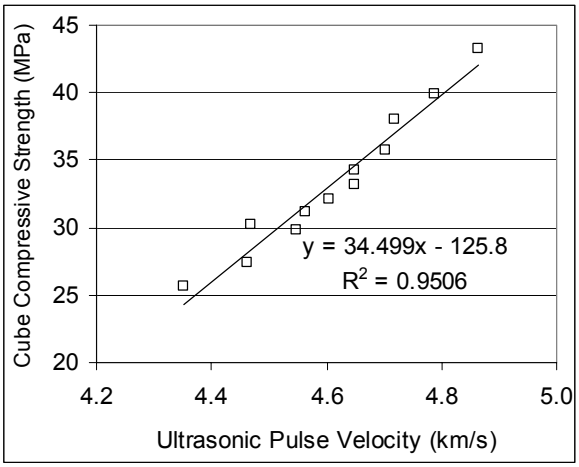


Fig.13. Relationship between UPV value and cube strength

4.4. Rebound hammer tests results

The results of the rebound hammer tests are depicted in Figs.14-16. It is clearly seen from Figs.14 and 15 that RN value increases with increase in concrete age. It should also be noted that RN value increases as the aggregate size increases. This is mainly attributed to the fact that the possibility presence of an aggregate just under plunger of the hammer increases with increase in aggregate size. Fig.16 illustrates the relationship between the cube compressive strength and rebound number. According to the figure, the cube strength linearly increases with increase in rebound number. The corresponding regression equation and R^2 value are shown in the figure.

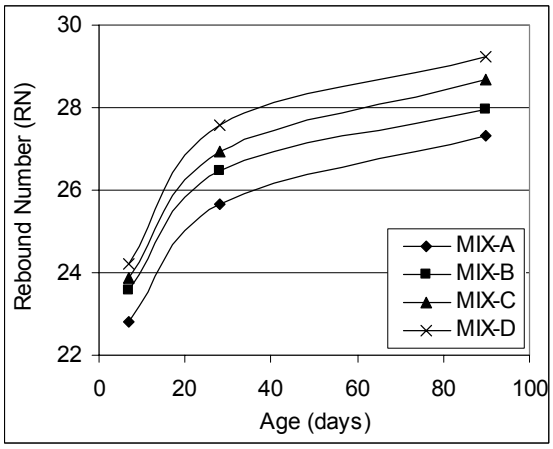


Fig.14. Rebound numbers measured on crushed limestone containing concretes

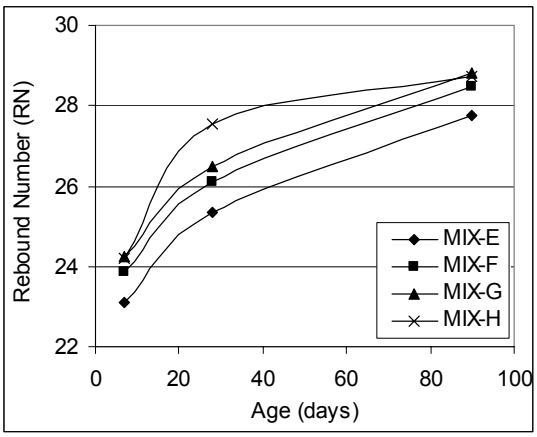


Fig.15. Rebound numbers measured on natural aggregate containing concretes

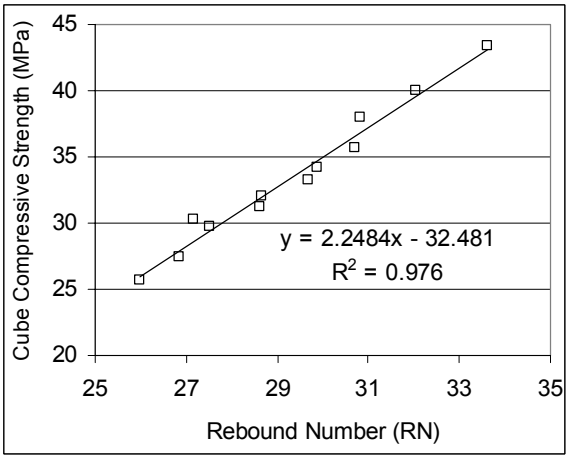


Fig.16. Relationship between rebound number and cube strength

5. CONCLUSIONS

The following results can be drawn from this experimental study;

1. As it was expected, the compressive strength of concrete increased gradually with the decrease in w/c ratio and with the increase of concrete age.
2. Core strength was significantly affected by maximum size of the aggregate used in the concrete production. The effect was more pronounced for smaller diameter cores.
3. Core/cube strength raised as the concrete strength increased. The effect was more significant for 46 mm diameter cores.
4. UPV value increased with increase in concrete age.
5. UPV value increased with increase in maximum aggregate size in concrete mixture for nearly equal cube strength.

6. The effect of aggregate size upon UPV value was more pronounced for seven days age.
7. Somewhat higher UPV values were measured on crushed limestone aggregate concrete.
8. There was a linear relationship between the cube strength and UPV value. UPV increased as cube strength increased.
9. RN value increased with increase in concrete age.
10. RN value increased as the aggregate size in concrete mixture increased for approximately equal cube strength.
11. Cube strength linearly increased with increase in rebound number.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial and technical supports supplied by Scientific Research Projects Commission of Anadolu University, Turkey (Projects: 03 02 23 and 04 02 01).

REFERENCES

Abdel-Halim, MAH, Al-Omari, MA&Iskender, MM 1999, 'Rehabilitation of the spillway of Sama El-Serhan Dam in Jordan, using roller compacted concrete', *Engineering Structures*, vol. 21, pp. 497-506.

Arioglu, E&Arioglu, N 1998, *Testing of Concrete Core Samples and Evaluations*, 2nd Edition, Evrim Publisher, Istanbul.

Arioz, O, Yildiz, D, Nalcaci, M, Karaesmen, E&Erkay, C 2004, 'Economical aspects of concrete quality of reinforced-pre-stressed concrete structures', *Concrete 2004 Congress*, Istanbul, Turkey, pp. 131-140.

ASTM C 39, *Standard test method for compressive strength of cylindrical concrete specimens*, Annual Book of ASTM Standards, 1994.

ASTM C 192-90a, *Standard practice for making and curing concrete test specimens in the laboratory*, Annual Book of ASTM Standards, 1994.

ASTM C 42-90, *Test for obtaining and testing drilled cores and sawed beams of concrete*, Annual Book of ASTM Standards, 1994.

ASTM C 597-83, *Standard Test method for Pulse Velocity through Concrete*, Annual Book of ASTM Standards, 1994.

ASTM C 805-85, *Standard test method for rebound number of hardened concrete*, Annual Book of ASTM Standards, 1994.

Bartlett, FM 1979, 'Precision of in-place concrete strengths predicted using core strength correction factors obtained by weighed regression analysis', *Structural Safety*, vol. 19, pp. 397-410.

Bartlett, FM&Macgregor, JG 1993, 'Effect of moisture condition on concrete core strengths', *ACI Materials Journal*, vol. 91, pp. 227-236.

Bartlett, FM&Macgregor, JG 1994a, 'Effect of core length-to-diameter ratio on concrete core strengths', *ACI Materials Journal*, vol. 91, pp. 339-348.

Bartlett, FM&Macgregor, JG 1994b, 'Effect of core diameter on concrete core strengths', *ACI Materials Journal*, vol. 91, pp. 460-470.

Bartlett, FM&Macgregor, JG 1996, 'Statistical analysis of the compressive strength of concrete in structures', *ACI Materials Journal*, vol. 93, pp. 158-168.

Beek, VA, Breugel, VK&Hilhorst, MA 1997, 'In-situ monitoring system based on dielectric properties of hardening concrete', *Structural Faults and Repair*, vol. 2, pp. 407-414.

BS 1881: Part 108: 1983, *Method for making test cubes from fresh concrete*, British Standards, 1983.

BS 1881: Part 110: 1983, *Method for making test cylinders from fresh concrete*, British Standards, 1983.

BS 1881: Part 120: 1983, *Method for determination of the compressive strength of concrete cores*, British Standards, 1983.

BS 1881: Part 203: 1986, *Recommendations for measurement of velocity of ultrasonic pulses in concrete*, British Standards, 1986.

BS 1881: Part 202: 1986, *Recommendations for surface hardness testing by rebound hammer*, British Standards, 1986.

Bungey, JH 1979, 'Determining concrete strength by using small diameter cores', *Magazine of Concrete Research*, vol. 31, pp. 91-98.

Bungey, JH&Soutsos, MN 2001, 'Reliability of partially-destructive tests to assess the strength of concrete on site', *Construction and Building Materials*, vol. 15, pp. 81-92.

Chmielewski, T&Konopka, E 1999, 'Statistical evaluations of field concrete strength', *Magazine of Concrete Research*, vol. 51, pp. 45-52.

Davis, SG 1977, 'The effect of variations in the aggregate content of concrete columns upon the estimation of strength by the pulse-velocity method', *Magazine of Concrete Research*, vol. 29, pp. 7-12.

Elverly, RH&Ibrahim, LAM 1976, 'Ultrasonic assessment of concrete strength at early ages', *Magazine of Concrete Research*, vol. 28, pp. 181-190.

Erdogan, TY 2003, *Concrete*, 1st Edition, METU Publisher, Ankara.

Franco, L, Noli, A, Degiralamo, P&Ercolani, M 2000, 'Concrete strength and durability of prototype tetrapods and dolosse: results of field and laboratory tests', *Coastal Engineering*, vol. 40, pp. 207-219.

Haque, MN&Al-Khaiat, H 1997, 'Carbonation of concrete structures in hot dry coastal regions', *Cement and Concrete Composites*, vol. 19, pp. 123-129.

Hernandez, MG, Anaya, JJ, Izquierdo, MAG&Ullate, LG 2002, 'Application of micromechanics to the characterization of mortar by ultrasound', *Ultrasonics*, vol. 40, pp. 217-221.

Kenai, S&Bahar, R 2003, 'Evaluation and repair of Algiers new airport building', *Cement and Concrete Composites*, vol. 25, in press.

Miao, B, Aitcin, PC, Cook, WD&Mitchell, D 1993, 'Influence of concrete strength on in situ properties of large columns', *ACI Materials Journal*, vol. 90, pp. 214-219.

Mindess, S&Young, JF 1981, *Concrete*, Prentice-Hall, inc, New Jersey.

Neville, AM 1981, *Properties of Concrete*, Pitman Books Limited, London.

Qasrawi, HY&Marie, IA 2003, 'The use of USPV to anticipate failure in concrete under compression', *Cement and Concrete Research*, vol. 33, pp. 2017-2021.

Ohdaira, E&Masuzawa, N 2000, 'Water content and its effect on ultrasound propagation in concrete-the possibility of NDE', *Ultrasonics*, vol. 38, pp. 546-52.

Ohtsu, M&Watanabe, H 2001, 'Quantitative damage estimation of concrete by acoustic emission', *Construction and Building Materials*, vol. 15, pp. 217-224.

Price, WF&Hynes, JP 1996, 'In-situ strength testing of high strength concrete', *Magazine of Concrete Research*, vol. 48, pp. 189-197.

Taylor, WH 1977, *Concrete Technology and Practice*, McGraw-Hill Book Company, Sydney.

Tomsett, HN 1980, 'The practical use of ultrasonic pulse velocity measurements in the assessment of concrete quality', *Magazine of Concrete Research*, vol. 32, pp. 7-16.

Troxell, GE, Davis, HE&Kelly, JW 1968, *Composition and Properties of Concrete*, McGraw-Hill Book Company, New York.

TS 3260, *Determination of concrete strength by surface hardness method*, Turkish Standard Institute, Ankara, 1978.

TS 10465, *Test methods for concrete-obtaining samples and determination of compressive strength in structures (destructive method)*, Turkish Standard Institute, Ankara, 1992.

TS EN 12390, *Concrete-Testing hardened concrete-part 1:shape, dimensions and other requirements for specimens and moulds,* Turkish Standard Institute, Ankara, 2002.

TS EN 12504-1, *Testing concrete in structures-part 1: cored specimens-taking, examining and testing in compression*, Turkish Standard Institute, Ankara, 2002.

Van Hauwaert, A, Thimus, JF&Delannay, F 1998, 'Use of ultrasonics to follow crack growth', *Ultrasonics*, vol. 36, pp. 209-217.

Yaman, IO, Inci, G, Yesiller, N&Aktan, H 2001, 'Ultrasonic pulse velocity in concrete using direct and indirect transmission', *ACI Materials Journal*, vol. 98, pp. 450-457.

Ye, G, Van Breugel, K&Fraaij, ALA 2003, 'Experimental study and numerical simulation on the formation of microstructure in cementitious materials at early age', *Cement and Concrete Research*, vol. 33, pp. 233-39.

Zhu, W, Gibbs, JC&Bartos, PJM 2001, 'Uniformity of in situ properties of self-compacting concrete in full-scale structural elements', *Cement and Concrete Composites*, vol. 23, pp. 57-64.