Afyon Kocatepe Üniversitesi
FEN BİLİMLERİ DERGİSİ

Özel Sayı
147-154

Afyon Kocatepe University
JOURNAL OF SCIENCE

USE OF COMBINED NON-DESTRUCTIVE METHODS TO ASSESS THE STRENGTH OF CONCRETE IN STRUCTURES

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ABSTRACT

The standard and non-destructive tests were performed on totally 144 cubes and 24 beam specimens produced from different concrete mixtures. The results of the non-destructive tests carried out on beams were correlated with cube compressive strength values. The effects of aggregate's type and its maximum size on the results of ultrasonic pulse velocity and rebound hammer tests were investigated. Simple charts were obtained from the test results and the use of these charts for the quality control of concrete in structural elements cast by locally available materials was discussed. Strength estimations were made using five combined models proposed by various investigators. The estimated strength values were compared with experimental values.

Keywords: Concrete Strength, Non-Destructive Methods, Ultrasonic Pulse Velocity.

1. INTRODUCTION

Quality control of concrete in structures is often performed by testing standard specimens. Thus, the direct determination of concrete strength requires preparation and testing of prepared specimens [1-5]. The standard test method gives an idea about the potential concrete strength [1]. However, the standard tests may not reflect the actual strength of concrete since the compaction and curing regimes applied in situ and in standard method are quite different [6]. Therefore, non-destructive tests are widely used to assess the strength of concrete in structures. Furthermore, as their name implies, non destructive tests do not give any damage to the material and do not affect the structural behavior [1]. These methods can also be employed for the efficient planning of the construction works in huge infrastructure projects, in which it may be necessary to know in-situ strength of concrete in order to determine the removal time of formwork, the stressing or releasing time for the wires in pre-stressed members, the loading time for the system in post-tensional elements or the time for opening the structure to service safely [7-9]. There are various non-destructive techniques in order to assess the strength of concrete in structures. The ultrasonic pulse velocity (UPV) and rebound hammer tests are the most widely used ones due to their simplicity. These methods can also be employed to confirm the uniformity of the material from one part to another, or to assess the relative quality of concrete in the structure [1-4].

The ultrasonic pulse velocity 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 in different parts of the structural member or in different parts of the structure itself, or to indicate the presence of voids or internal cracks and to determine the changes in the properties of concrete in a structure [10-13]. UPV test is prescribed in ASTM C 597 and BS 1881: Part 203 [14, 15]. The test is not yet involved in Turkish Standards. Although there is no statistical difference between the results obtained from direct and indirect transmission [10], generally the direct one is preferred in the test application. The test results are affected by a number of factors such as properties of aggregates, mix proportions of concrete, and the presence of steel reinforcement, voids or cracks. [9, 13, 16-19]. Although there are several proposals, it may not be possible to develop a unique relationship between the strength and ultrasonic pulse velocity [5, 9, 17].

Rebound hammer test is one of the oldest non-destructive tests and still commonly used owing to its simplicity. The test is prescribed in TS 3260, ASTM C 805, and BS 1881: Part 202 [20-22]. It is based on the principle that the rebound of an elastic mass depends upon the surface hardness, against which the mass impinges. A spring loaded mass having a fixed amount of energy is released and the distance traveled by the mass is expressed as a percentage of the initial spring extension. It is called as rebound number (RN) generally indicated by a rider moving along a graduated scale [1]. The measured rebound numbers are very sensitive to local variations in concrete. For example, presence of large pieces of aggregate just under the plunger may result in abnormal higher values, conversely, presence of a crack or void under the plunger will cause lower rebound numbers. Moreover, the rebound numbers also depend on the type and the properties of the aggregate, mix proportions, surface texture and surface wetness of the concrete. It is clear that the rebound number reflects only the concrete surface properties [1-5].

Sometimes, the ultrasonic pulse velocity and the rebound hammer methods are used together for better estimations of concrete strength. This is very convenient since the two techniques are sensitive to the variations in the concrete properties of especially in opposite directions. For instance, increase in moisture content of concrete raises the pulse velocity but lowers the rebound number. Therefore, the combination of two methods will reduce the errors produced by using one method alone and thus, will yield more reliable results [1, 3-5]. There are several equations established for predicting concrete strength by combined non-destructive tests [23]. However, most of the equations require previous knowledge of concrete constituents in order to obtain reliable and predictable results [5]. In the present study, the relationships between non-destructive test results and the cube compressive strength were established. Five different combined models involving RN and UPV were used to estimate the strength of concrete. The estimated results were compared with experimental values [23].

2. RESEARCH SIGNIFICANCE

Non-destructive tests such as ultrasonic pulse velocity (UPV) and rebound hammer are widely used to assess the concrete properties in structures. Although the application of such techniques is simple and easy, the interpretation of the test results is very difficult due to a number of factors affecting the test results. This paper investigates the effects of mix proportions of concrete on the UPV and RN values measured on beams cast by different concrete mixtures. The possible combined uses of UPV and rebound hammer tests were also searched.

3. EXPERIMENTAL STUDY

In this study, the effects of maximum size of aggregate (D_{max}) and aggregate type on the compressive strength of concrete obtained by standard and non-destructive testing methods were investigated. For this purpose, 150 mm standard cubes and 250x300x650 mm prismatic beams were cast from eight different concrete mixtures. The specimens were wet cured with burlap in laboratory up to the testing time. Table 1 shows the proportions and some properties of the concrete mixtures used in this investigation. The slump values of all the mixtures were kept constant as 150±20 mm.

Table 1. Constituents and some properties of concrete mixtures

Mix	Mix Proportions (kg/m^3)				Some Properties		
	SSD* Coarse Aggregate	SSD Fine Aggregate	Cement	Water	w/c Ratio	Aggregate Type	Maximum Aggregate Size (mm)
MIX-A	696	1043	356	215	0.6	Crushed Limestone	10
MIX-B	729	1094	331	200			15
MIX-C	1034	846	315	190			22
MIX-D	1128	752	315	190			30
MIX-E	507	1259	356	195	0.55	Natural Aggregate	10
MIX-F	833	994	331	181			15
MIX-G	1158	706	315	173			22
MIX-H	1300	565	315	173			30

*SSD: Saturated surface dry

Two different aggregates were used and, four different maximum aggregate sizes ranging from 10 mm to 30 mm were selected for each type. The proportions of fine and coarse aggregate particles were chosen in accordance with TS 802 “Design of Concrete Mixtures” standard requirements. An ordinary Portland cement conforming to the relevant Turkish standard was used in all the mixes. The compressive strength test was applied on cubes and UPV and rebound hammer tests were performed on beams. The tests were performed at the ages of 7, 28, and 90 days. For each age, six cubes were crushed and the average of these was taken as the cube compressive strength. Fig.1 illustrates the beam prepared for the non-destructive tests. The ultrasound measurements were performed through 9 paths by direct transmission and the average of these was taken as UPV for the corresponding beam. In each rebound test 12 readings were taken and the hammer was horizontally applied in all readings. For non destructive tests 3 beams were prepared from each mixture. The average of these was recorded as test result.

Fig. 1. Beam used for non-destructive testing

4. RESULTS AND DISCUSSIONS

The results of the experiments are summarized in Figs. 2-5. Figs. 2 and 3 present the relationships between the UPV and the cube strength of concrete mixtures produced from crushed limestone and natural aggregate, respectively. Irrespective of aggregate type, for a given cube strength, UPV was increased with the increase in maximum aggregate size. This may be caused by higher aggregate content as well as lower air and paste contents of the mixtures including aggregates of smaller maximum size. The effect was more pronounced at 7 days where the porosity of paste was higher due to insufficient cement hydration. Besides, a given UPV was recorded in mixtures containing aggregates with lower D_{max} at somewhat later ages and correspondingly, somewhat higher strength levels. The type of aggregate had not a marked effect on UPV values.

Figs. 4 and 5 depict the linear relationships between the RN and the cube strength of the mixes. In both crushed aggregate and natural aggregate-containing mixtures, for a given strength, RN increased slightly as the maximum aggregate size was increased. The effect was more pronounced for both natural aggregate-bearing mixtures and early ages. The increase of RN in mixtures containing larger aggregate sizes may be caused by the fact that the possibility of presence of an aggregate particle under the plunger of hammer increases with the increase in maximum size of aggregate. Moreover, for equal compressive strength, mixtures containing crushed limestone showed rebound numbers 1-2 points lower than that made with natural aggregate. Similar result was reported by Klieger as cited by Malhotra [24]. However, in the present study, the effect of aggregate type on RN is not as high as the value reported by Kliger. According to Klieger, for equal compressive strengths, concretes made with crushed coarse aggregate show rebound numbers approximately 7 points lower than those made with gravel coarse aggregate, representing approximately 7 MPa difference in compressive strength. The difference between the results of this study and that of Kliger may be arisen from the differences of fine aggregates used in concrete mixtures. For a given RN value, mixtures containing crushed limestone indicated a little higher cube strength than natural aggregate- bearing mixtures.

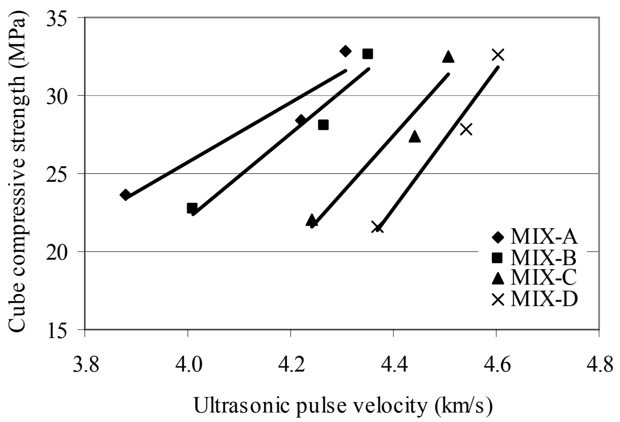

Fig. 2. Relationship between UPV and cube strength for concrete mixes containing crushed limestone aggregate

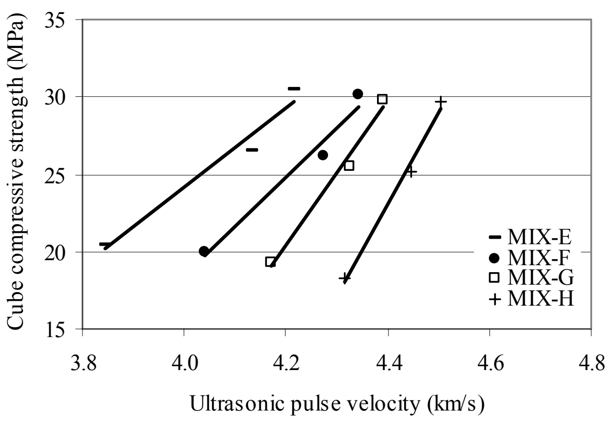

Fig. 3. Relationship between UPV and cube strength for concrete mixes containing natural aggregate

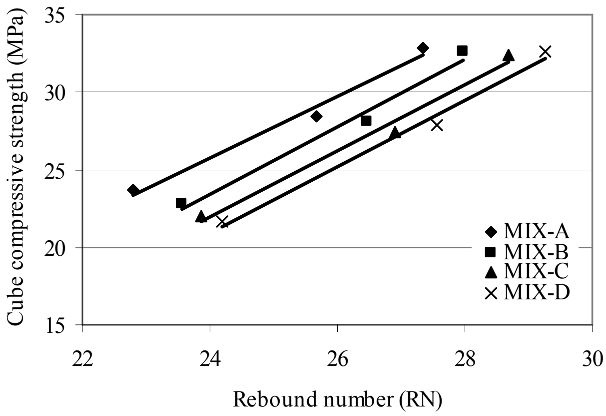

Fig. 4. Relationship between RN and cube strength for concrete mixes containing crushed limestone aggregate

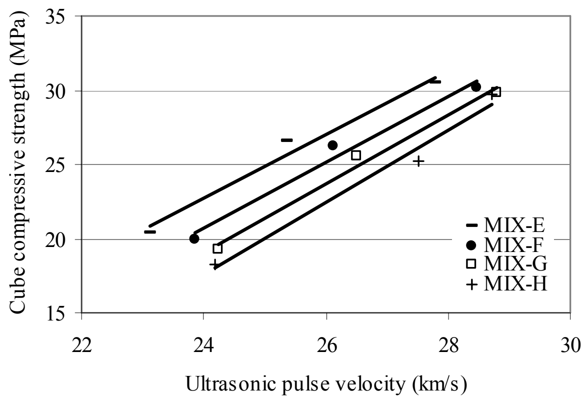

Fig. 5. Relationship between RN and cube strength for concrete mixes containing natural aggregate

The linear relationships between cube strength of concrete and RN or UPV values are summarised in Table 2. Although RN and UPV are measures of various properties of concrete, good correlations were found between them in all the mixtures (Table 3).

Table 2. Relations between cube compressive strength and non-destructive test parameters

Mix	UPV-Strength Equation	R^2 Value	RN-Strength Equation	R^2 Value
MIX-A	S=19.256 UPV* - 51.317	0.9018	S=1.9865 RN*- 21.892	0.9802
MIX-B	S=27.146 UPV - 86.461	0.9469	S=2.1778 RN - 28.806	0.9822
MIX-C	S=36.743 UPV - 134.24	0.9338	S=2.1142 RN - 28.738	0.9834
MIX-D	S=44.807 UPV - 174.46	0.9663	S=2.1403 RN - 30.435	0.9862
MIX-E	S=25.646 UPV - 78.418	0.9688	S=2.1496 RN - 28.785	0.9765
MIX-F	S=31.951 UPV - 109.36	0.9681	S=2.2040 RN - 32.165	0.9840
MIX-G	S=46.405 UPV - 174.50	0.9841	S=2.3133 RN - 36.442	0.9867
MIX-H	S=59.349 UPV - 238.02	0.9912	S=2.4297 RN - 40.772	0.9803

*RN is rebound number and UPV is ultrasound pulse velocity in km/s.

Table 3. Relations between the ultrasonic pulse velocity and rebound number

Mix	UPV-RN Equation	R^2 Value
MIX-A	UPV=0.0974 RN + 1.6739	0.9688
MIX-B	UPV=0.0784 RN + 2.1717	0.9903
MIX-C	UPV=0.0556 RN + 2.9231	0.9829
MIX-D	UPV=0.0472 RN + 3.2303	0.9955
MIX-E	UPV=0.0789 RN + 2.0593	0.8939
MIX-F	UPV=0.0652 RN + 2.5139	0.9091
MIX-G	UPV=0.0483 RN + 3.0152	0.9426
MIX-H	UPV=0.0411 RN + 3.3186	0.9978

There are several models proposed to estimate the concrete strength using combined methods involving both RN and UPV. Among these, the following five equations were selected.

$$f_c = -25.568 + 0.000635(RN)^3 + 8.397(UPV)$$ after Bellander [23]

$$f_c = -24.668 + 1.427(RN) + 0.0294(UPV)^4$$ after Meynink and Samarin [23]

$$f_c = -39.570 + 1.532(RN) + 5.061(UPV)$$ after Tanigawa et al. [23]

$$\log f_c = 3.077\sqrt{\log\left(RN^3 UPV^4\right)} - 6.680$$ after Yapi Merkezi [23]

$$fc = 0.00153\left(RN^3 UPV^4\right)^{0.611}$$ after Arioglu and Koyluoglu [23]

where f_c is 150 mm cube strength (MPa), RN is rebound number and UPV is ultrasonic pulse velocity (km/s).

The strength values obtained in this study were compared with estimated values found using the above combined models. The results are given in Tables 4-6.

Table 4. Comparison of the experimental and estimated 7-day strength values

Eq.No	Differences between experimental and estimated strength values (%)							
	MIX-A	MIX-B	MIX-C	MIX-D	MIX-E	MIX-F	MIX-G	MIX-H
1	-38.6	-27.8	-15.1	-6.9	-28.7	-15.1	-4.1	7.8
2	-38.7	-27.2	-14.1	-4.8	-27.9	-14.0	-2.4	9.9
3	-36.7	-26.1	-16.1	-9.2	-25.1	-13.0	-3.2	6.0
4	-44.1	-33.1	-19.0	-9.3	-35.0	-20.8	-8.7	4.3
5	-45.3	-34.3	-20.3	-10.5	-36.3	-22.3	-10.2	2.7

Table 5. Comparison of the experimental and estimated 28-day strength values

Eq.No	Differences between experimental and estimated strength values							
	MIX-A	MIX-B	MIX-C	MIX-D	MIX-E	MIX-F	MIX-G	MIX-H
1	-27.3	-21.6	-12.1	-7.1	-26.8	-17.3	-11.7	-0.8
2	-24.9	-18.7	-8.2	-2.4	-24.5	-14.3	-8.2	3.6
3	-25.5	-19.6	-11.9	-7.9	-24.2	-15.6	-10.3	-0.4
4	-29.3	-22.7	-10.3	-3.0	-29.9	-18.5	-11.9	1.8
5	-30.2	-23.5	-10.8	-3.1	-31.0	-19.4	-12.8	1.3

Table 6. Comparison of the experimental and estimated 90-day strength values

Eq.No	Differences between experimental and estimated strength values							
	MIX-A	MIX-B	MIX-C	MIX-D	MIX-E	MIX-F	MIX-G	MIX-H
1	-28.3	-23.7	-15.9	-11.3	-23.1	-15.4	-11.3	-8.0
2	-25.6	-20.9	-12.4	-7.3	-20.4	-12.5	-8.3	-4.3
3	-26.7	-22.4	-16.1	-12.6	-20.2	-13.8	-10.3	-8.3
4	-28.5	-23.0	-12.2	-5.3	-24.5	-14.7	-9.5	-4.0
5	-29.0	-23.4	-12.1	-4.8	-25.2	-15.1	-9.7	-4.0

As it can be clearly seen from Tables 4-6, none of the models gave accurate strength estimations in A, B, E and F mixtures which contain either crushed or natural aggregates of 10 and 15mm D_{max} values. However, irrespective of aggregate type, the differences between experimental and estimated strength values decreased for grater D_{max} values. It seems that in estimating concrete strength by any combined method, D_{max} of the aggregate plays greater role than its type.

5. CONCLUSIONS

The following conclusions could be drawn from the experimental study carried out:

1. For the same cube strength, the increase in maximum aggregate size and resulting increase in aggregate/paste ratio raises the ultrasonic pulse velocity and rebound number.
2. For an equal cube strength, both ultrasonic pulse velocity and rebound number of natural aggregate-bearing mixtures are slightly higher than those of crushed aggregate-bearing mixtures.
3. Irrespective of the aggregate type or maximum aggregate size, strong correlations are found between cube strength-UPV, cube strength- RN and UPV-RN values.
4. All of the five combined models, proposed by various investigators, give reasonable strength estimates when the maximum aggregate size is greater than 10 mm or even 15 mm.

6. FURTHER RESEARCHES AND RECOMMENDATIONS

The findings of this experimental investigation are based on a scientific research on the determination of concrete strength by destructive and non-destructive methods. In this study, the concrete mixtures are designed for the same strength level. Another research can be performed to investigate the properties of higher strength concrete by means of various non-destructive techniques. The findings of the further investigation can be effectively used for the inspection of the concrete structures constructed by high strength concrete.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge for the financial and technical supports supplied by Anadolu University, Turkey. This investigation has been supported by the project numbered as 030223 accepted by Anadolu University, Commission of Scientific Research Projects.

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