Original Article

In situ concrete strength assessment: Influence of the aggregate hardness on the Windsor probe test results

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ABSTRACT Experimental research was carried out to investigate the influence of aggregate hardness on Windsor probe test results. A series of concrete specimens prepared from aggregates having a variety of Mohs' hardness values and also specimens using an aggregate with a consistent class of Mohs' hardness were prepared. The models once prepared were subjected to penetration tests. After conducting the penetration tests, cores were extracted from the specimens. A comparison between penetration tests and the core strength was carried out. These show that the Windsor method is more reliable when only one class of Mohs' hardness is contained in the specimens. In this case the results can be considered acceptable. The uncertainties grow as the number of classes of Mohs' hardness increase. When testing during the presence of aggregates with different classes of hardness, it is necessary to construct suitable curves of calibration.

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INTRODUCTION

The study of non-destructive testing (NDT) represented a deep development in the 1970s and 1980s, when most of the non-destructive techniques used in the field of civil constructions were created (Malhotra and Carino, 1991; Pucinotti, 2006). During this period a large amount of work was finalised with respect to the correct interpretation of *in situ* NDT. This was driven by the production of improved test instruments, which were easier to use and produced clearer results (by drawing up tables and standard correlation curves that were sufficiently reliable) (Law and Burt, 1969; Malhotra and Painter, 1971; Arni, 1972; Malhotra and Carino, 1991). However, further development declined in the subsequent decade.

Recently, due to numerous collapses that have occurred without an obvious cause, the appropriate conduction of non-destructive tests on concrete structures and the correct interpretation of the results have reawakened the interest of the scientific community

(Di Leo *et al*, 1983; Viola *et al*, 1984; Malhotra and Carino, 1991; Braga *et al*, 1992; Pascale *et al*, 2003; Pucinotti 2005, 2006).

Within the recent Italian order n. 3274 (OPCM 3274, 2003) of 20 March 2003 containing 'First elements of the general principles for the seismic classification of the national territory and technical rules for the constructions in a seismic zone' published on the G.U. (suppl. no. 72 to no. 105 of 8 May 2003) is emphasised the importance of the 'health' state control for existing buildings. This is recommended to be done through the prescription of *in situ* tests and surveys corresponding to various levels of knowledge and by consequently utilising different methods of analysis and acceptable safety coefficients.

Degradation of structural elements can have many causes, for example: (1) of chemical type, mainly because of the attack of chemical agents such as sulphates, sulphides, chlorides and carbon dioxide; (2) of physical type, owing to hygrothermic variations; (3) of accidental type, because of the effects produced from explosions, vibrations, impacts and earthquakes; (4) of technological type, owing to the use of low-quality concretes, and inadequacy of the concrete cover or insufficient controls in execution phases; (5) because of faulty design, reported for those structures that were realised without structural calculations or using inadequate structural calculations.

This paper deals with Windsor probe testing of concrete. Experimental research was carried out, involving both destructive and non-destructive methods applied to different concrete mixes with compressive strengths varying from 25 to 30 MPa, by using aggregates that had varying values of Mohs' hardness (inert of fluvial origin) and by using aggregates with only one class of Mohs' hardness (crushed aggregate).

The experimental research is aimed at appraising the influence of the aggregate's hardness on Windsor probe test results. Correlation curves have shown that the Windsor method is more reliable when only one class of Mohs' hardness is contained in the specimens.

THE WINDSOR PROBE SYSTEM

The penetration resistance method is well known. The Windsor probe system, introduced in the US in 1960, is based on the determination of the depth penetration of a steel pin fired into the concrete. The depth of penetration of the pins is correlated with the compressive strength of the concrete. Subsequently, in 1970, Arni (1972) reported the results of a detailed investigation into the evaluation of the Windsor probe. The Windsor probe (Pucinotti, 2005), like the rebound hammer, is basically a hardness tester that provides a quick means of determining the relative strength of the concrete. The exposed length of the probe is measured by a depth gauge and related by a calibration table to the compressive strength of the concrete. For each exposed length value of the depth gauge, different values for the compressive strength of concrete are given, depending on the hardness of the aggregate. This hardness is measured by the Mohs' scale. The correlations published by several researchers working upon concrete made with different types of aggregates, but having similar Mohs' hardness values, had, however, shown different relationships (Law and Burt, 1969; Malhotra and Painter, 1971; Arni, 1972; Malhotra and Carino, 1991; Pucinotti *et al*, 2003a, b; Pucinotti, 2005, 2006). However, as mentioned earlier, the calibration table furnished with the Windsor probe equipment does not always give satisfactory results (Malhotra and Carino, 1991; Pucinotti, 2005).

In earlier studies (Pucinotti and De Lorenzo, 2003; Pucinotti, 2005) a series of non-destructive tests were performed *in situ* with the purpose of investigating the mechanical characteristics of materials of 'ancient' reinforced concrete structures; the correlation

Figure 1: Correlation between core strength and 'Windsor' strength (Pucinotti, 2006).

Figure 2: Windsor Probe System equipment.

between the values of experimental strengths were determined using the Windsor Probe System with satisfactory core strengths (Figure 1). The strength values in the rectangular window refer to a very old concrete, and in this case the tests indicate a higher strength than actually exists in the structure. In this case where the actual strength is less than approximately 15 MPa, the correlation between the probe penetration and *in situ* strength becomes more uncertain. In fact, the degree of carbonation present considerably affects the accuracy of the probe penetration, and hence indicates the concrete strength for some structural elements in reinforced concrete buildings.

THE TEST EQUIPMENT

The equipment used consists of a powder-actuated gun that drives a hardened alloy-steel probe (needle) into the concrete. The instrumentation used is known as the 'Windsor Probe System'. The parameter that characterises the method is called the penetration index and is represented by the length of the part of probe that has not penetrated the concrete. Calibration tables are furnished with the Windsor probe equipment. A view of the Windsor probe equipment is shown in Figure 2, and consists of a driver unit (A in Figure 2), a series of probes for concrete and power loads (B in Figure 2), a locating template used to locate the probes at the corners of a 178-mm equilateral triangle (C in Figure 2) and a depth gauge electronic measuring device (D in Figure 2).

Figure 3: Geometrical property of probe.

Figure 4: Failure of concrete during probe penetration.

The electronic measuring device is menu driven and programmed for selection according to the following parameters: aggregate hardness; and light weight, normal or HP concrete; American or Metric units of measurement can be selected. For determining the hardness of the aggregates, the Mohs' scale is accepted. It distinguishes between 10 classes and is characterised by a variable number from 1 to 10. The number 1 refers to talc, the more tender element, while the number 10 refers to a diamond. The probes

Figure 5: A view of the Windsor probe operation.

(Figure 3) have a tip diameter 7.9 mm and a length of 79.4 mm, with a conical point. The test points cannot be placed at distances lesser than 178 mm, and at a distance lesser than 102 mm from the corner of the test elements (ASTM C 803M-97; BS 1881-207, 1992); moreover, the surface around the test point must be sufficiently smooth.

Penetration of the probe causes the concrete to fracture within a cone-shaped zone below the surface, with cracks propagating up to the surface (Figure 4). Therefore, it is reasonable to suppose the existence of a correlation between the depth of penetration of the probe and a destructive parameter as being the compressive strength of concrete.

The method of testing is relatively simple and is given in the manual supplied by the manufacturer. The driver unit is used to deliver a probe into the concrete (Figure 5). The exposed length of the individual probe is subsequently measured by a depth gauge. For every test three probes are used and the result of the test is constituted from the average of the three measures obtained. The reliability of the result depends on the gap between the three values obtained. In general, the measured average value of exposed probe length is used to estimate the compressive strength of concrete by means of appropriate correlation data. The manufacturers of the Windsor probe test system have published tables related to the exposed length of the probe with the compressive strength of concrete. These are based on empirical relationships established in the laboratory. However, preceding investigations (Law and Burt, 1969; Malhotra and Painter, 1971; Arni, 1972; Malhotra and Carino, 1991; Pucinotti, 2005) indicate that the manufacturer's tables do not always give satisfactory results.

THE EXPERIMENTAL PROGRAM

A total of 18 specimens were prepared in the Laboratory of the Department of Mechanics and Materials of the Mediterranean University of Reggio Calabria. Concrete slabs of dimensions 600 mm × 600 mm × 200 mm were cast to obtain two different strength classes of concrete: C20/25 ($f_{ck} = 20$ MPa, $R_{ck} = 25$ MPa) and C25/30 ($f_{ck} = 25$ MPa, $R_{ck} = 30$ MPa). The concrete mixes were prepared with four different water–cement ratios. A curing regime of $22 \pm 2^\circ\text{C}$ and 95 ± 5 per cent of relative humidity (RU) was adopted. f_{ck} is the characteristic compressive strength of standard specimens, while R_{ck} is the cubical characteristic compressive strength of 150 mm × 150 mm × 150 mm specimens.

The WSF specimens: Fluvial aggregate naturally crushed

Commercially available aggregates with a nominal maximum size of 25 mm sourced from the locality of the Valanidi River in Reggio Calabria were used to prepare the 12 specimens of dimensions 600 mm × 600 mm × 200 mm. Six of them had a nominal strength class of C20/25 and the remaining six had a nominal strength class of C25/30. The different nominal strengths of concrete were obtained by varying the W/C

Figure 6: The aggregates employed.

Figure 7: The granulometric curves of aggregates utilised.

Table 1: WSF specimens – Concrete mix proportions

<i>Cement</i>	<i>Water–cement ratio</i>	<i>Additive</i>	<i>Aggregates</i>
Concrete of strength class C20/25 32.5 N of Portland-limestone cement CEM II/A-LL 42.5 R including 6–20% limestone, 80–94% clinker and other secondary components according to EN 197-1 were used (EN 197-1, 2000)	W/C=0.41; 13.4 N of water for every cubic meter of concrete was employed	The Superplastifier Sika ViscoCrete® 3073-I (VP), which reduces the water content in the mix, increases the workability of the fresh concrete and improves compressive strengths at early and long-term age was used; dosage: 0.8% of the cement contents	Commercial, locally available sand and coarse aggregate with a nominal maximum aggregate size of 25.00 mm was used
Concrete of strength class C25/30 33.5 N of Portland-limestone cement CEM II/A-LL 42.5 R including 6–20% limestone, 80–94% clinker and other secondary components according to EN 197-1 were used (EN 197-1, 2000)	W/C=0.37; 12.3 N of water for every cubic meter of concrete was employed	Superplastifier Sika ViscoCrete® 3073-I (VP); dosage: 1% of the cement contents	Commercial, locally available sand and coarse aggregate with a nominal maximum aggregate size of 25.00 mm was used

Table 2: WSS specimens – Concrete mix proportions

<i>Cement</i>	<i>Water–cement ratio</i>	<i>Additive</i>	<i>Aggregates</i>
Concrete of strength class C20/25 43.4 N of Portland-limestone cement CEM II/A-LL 42.5 R including 6–20% limestone, 80–94% clinker and other secondary components according to EN 197-1 were used (EN 197-1, 2000)	W/C=0.46; 20.0 N of water for every cubic meter of concrete was employed	Sika ViscoCrete® 3073-I (VP); dosage: 0.8% of the cement contents	Commercial, locally available sand and coarse aggregate with a nominal maximum aggregate size of 25.00 mm was used; based on petrographic analysis, it was composed of 98% of limestone and of 2% of marl
Concrete of strength class C25/30 45.0 N of Portland-limestone cement CEM II/A-LL 42.5 R including 6–20% limestone, 80–94% clinker and other secondary components according to EN 197-1 were used (EN 197-1, 2000)	W/C=0.42; 18.9 N of water for every cubic meter of concrete was employed	Sika ViscoCrete® 3073-I (VP); dosage: 1% of the cement contents	Commercial, locally available sand and coarse aggregate with a nominal maximum aggregate size of 25.00 mm was used; based on petrographic analysis, it was composed of 98% of limestone and of 2% of marl

(water/cement) ratio. Figures 6 and 7 show coarse aggregate and granulometric curves used for casting the WSF specimens.

Table 1 reports the concrete mix proportions of WSF specimens of nominal strength classes C20/25 and C25/30.

The WSS specimens: Artificial crushed aggregate

Using artificial crushed aggregate from the Basilicata Region, six additional specimens were prepared, also of 600 mm × 600 mm × 200 mm dimensions. Three had a nominal strength class of C20/25 and the remaining three had a nominal strength class of C25/30. Selected limestone aggregates with a nominal maximum size of 25 mm were used. Figures 6 and 7 show coarse aggregate and granulometric curves used for casting the WSS specimens.

The mix design and the materials of WSS specimen casting are summarised in Table 2.

EXPERIMENTAL RESULTS AND COMMENTS

All the experimental tests were executed using 28-days-old concrete (RILEM 43 CD, 1993; prEN 13791, 2003). The correlation curves are shown in Figure 8 with reference to WSF and WSS specimens, together with the 95 per cent confidence limits for individual values.

Note that two different relationships have been obtained for concrete that differ only for the type of aggregate. In fact, in the case of WSF specimens, the correlation curve is

$$R_c = 1.4525 \cdot L_e - 27.047 \text{ MPa}$$

where R_c is the compressive strength; L_e is the exposed probe length; and $r^2 = 0.9736$ is the correlation coefficient.

In the case of WSS specimens the correlation curve assumes the following expression:

$$R_c = 2.003 \cdot L_e - 57.843 \text{ MPa}$$

$$r^2 = 0.9706$$

For an exposed length of 43 mm (1.69 in.) two different values of concrete strength were obtained by the two correlation curves: 35.41 and 28.29 MPa.

Figure 9 shows the same relationships together with the correlation curve extracted from manufacturer's tables of the instrument used. In fact the manufacturers of the Windsor probe have published tables relating the exposed length of the probe to the compressive strength of the concrete. For different values of exposed length, different values of compressive strength are given depending on the Mohs' hardness of the aggregates. It is easy to note that the manufacturer's tables are not satisfactory, based on the correlation curve of WSF specimens (drawn for a Mohs' hardness equivalent value of 3.15).

Instead, the correlation curve relative to the WSS specimens (with only one class of Mohs' hardness of aggregate) were drawn for a Mohs' hardness value of 4.5, and presented the same slope and trend of the correlation curves as the instrument tables.

This confirmed that the Windsor Probe System is reliable when aggregates belong to a single class of Mohs' hardness.

Figure 8: WSF and WSS specimens: Relation between penetration and compressive strength of concrete.

Figure 9: WSF and WSS specimens: Relation between exposed probe length and compressive strength of concrete.

Figure 10: Relationship between exposed probe length and compressive strength of concrete as obtained by different investigators.

Figure 11: Relationship between exposed probe length and compressive strength of concrete as obtained by different investigators.

Figure 10 shows the correlations obtained by various investigators. The considerable differences tend to support the marked influence of the aggregate type. Note the different relationships obtained for concretes with aggregates having similar Mohs' hardness values (Law & Burt Cherth and Arni Traprock).

Figure 11 shows the correlation curves obtained by various investigators together with the correlation curve extracted from the manufacturer's tables for the instrument used. Note that only the curve drawn for Pucinotti, Limestone, Mohs' hardness 4.5 presents the same slope and trend of the correlation curves as the instrument tables.

CONCLUSIONS

A series of concrete specimens cast using aggregates containing various Mohs' hardness values (inert of fluvial origin) and using an aggregate with only one class of Mohs' hardness (crushed aggregate) has been tested in the Laboratory of the Department of Mechanics and Materials of the Mediterranean University of Reggio Calabria, Italy, and the correlations between penetration tests and core strength analysed.

The study has shown that the Windsor method is more reliable when only one class of Mohs' hardness is contained in the specimens; in this case the method results can be considered acceptable. However, the uncertainties increase when aggregates of varying Mohs' hardness values are present. In the case of the presence of more than one type of aggregate with different classes of hardness, a reconstruction of suitable curves of calibration is necessary. In fact, the study has evidenced, in the case of concretes containing fluvial aggregate, that there is a necessity to calibrate the resistance obtained using non-destructive methods with cylindrical strength of cores extracted from the specimens. In this case, the use of Windsor methods is generally justifiable only if a reliable correlation for a particular type of concrete is developed before the evaluation of the subject quality concrete.

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