TRANSPORT RESEARCH LABORATORY

Use of non-destructive testing for the assessment of newly-constructed concrete pavements

Prepared for Quality Services, Civil Engineering Division, Pavement Engineering Group, Highways Agency

A R Halliday

TRL REPORT 329

First Published 1998
ISSN 0968-4107

This report has been produced by the Transport Research Laboratory, under/as part of a Contract placed by the Highways Agency. Any views expressed are not necessarily those of the Agency.

TRL is committed to optimising energy efficiency, reducing waste and promoting recycling and re-use. In support of these environmental goals, this report has been printed on recycled paper, comprising 100% post-consumer waste, manufactured using a TCF (totally chlorine free) process.

Transport Research Foundation Group of Companies
Transport Research Foundation (a company limited by guarantee) trading as Transport Research Laboratory. Registered in England, Number 3011746.

TRL Limited. Registered in England, Number 3142272.
Registered Offices: Old Wokingham Road, Crowthorne, Berkshire, RG45 6AU.

CONTENTS

Executive Summary

This report contains the details of a full-scale trial designed to assess the ability of selected near-to-surface tests to provide accurate measures of the in-situ strength of a range of cast concrete materials typical of those currently used in highway construction applications. Their ease of use and ability to provide earlier indications of the quality of cast materials, and on a broader scale than is currently provided by 7-day cube and core assessment procedures, was also to be assessed. The work forms part of a wider study of the performance of non-destructive test methods in contract situations being undertaken for the Pavement Engineering Group of the Highways Agency under project reference E086A/HM: Standardisation of non-destructive testing.

The near-to-surface tests examined in the trial included the Schmidt Rebound Hammer, CAPO (cut and pull-out), BOND (surface pull-off) and Windsor Probe (Penetration resistance) tests.

Ten concrete slabs, each of 200mm nominal thickness and 5 metre square section were cast end to end on a prepared 150mm thick CBM3 base. The mix designs of the concretes were selected to allow an examination of the influence of aggregate type (flint and limestone), aggregate size (20mm and 40mm) and the inclusion of selected hydraulic binder additives (microsilica, pulverised fuel ash (pfa) and ground granulated blast-furnace slag (ggbs)) on the accuracy of the in-situ strengths measured using each of the near-to-surface test methods.

Twenty-eight day in-situ strengths indicated by each of the near-to-surface tests were compared with the concrete compressive strength indicated by cores extracted from each of the concretes and crushed in accordance with procedures published in both British Standard 1881 and ISO/DIS 7034 documents. Measures of the 3-day strength were also obtained and compared with the compressive strengths indicated by 3-day cube specimens which were cured on-site under ambient conditions. The 7-day and 28-day strengths of cube specimens, prepared from each of the mixes and cured in the laboratory at 20^{o}C, were also obtained for comparative purposes.

An analysis of the data collected has shown that each of the near-to-surface tests provide broadly similar measures of early-life concrete strength to those indicated by 3-day ambient cured cubes. Each of the near-to-surface tests is also of sufficient accuracy to enable it to be used to indicate any large-scale variability in the 28-day strength of the material. For individual concretes, however, near-to-surface tests may predict strengths 30-40 per cent greater than the in-situ strength indicated by crushing cores. Pre-test calibration could improve the accuracy of prediction associated with each of the test methods.

For the range of concretes used in the trial, the Schmidt Rebound Hammer and CAPO tests were found to correlate more closely with in-situ strength than either the BOND or Windsor Probe tests. The Schmidt Rebound Hammer was also found to be the quickest and easiest of the tests to perform. Because it causes little damage to the concrete, this device could be used to provide an intensive examination of large areas of concrete and locate areas of poor quality material. It could also be useful for determining when concrete slabs have gained the minimum strength necessary to allow them to be opened to traffic.

1 Introduction

The currently adopted procedure for assessing the quality of concretes used in highway engineering applications is based on a measurement of compressive strength, obtained by a laboratory test performed on cube specimens prepared from the freshly produced material. Cube specimens are made, cured and tested in accordance with procedures published in British Standard 1881: Parts 108, 111 and 116 (British Standards Institution, 1983), respectively. Prepared to optimum density and cured under ideal temperature and environmental conditions, cube strength reflects the optimum achievable for the mix.

Together with a measure of material density, performed in accordance with procedures published in British Standard 1881: Part 114 (British Standards Institution, 1983), on core specimens taken in accordance with procedures published in BS 1881: Part 120 (British Standards Institution, 1983), laboratory strength measurements are sufficient to characterise the material and provide the necessary confidence of a likely satisfactory in-service performance. Additional crushing tests, performed both on the core specimens and on cube specimens prepared from successive batches of the mix, provide additional confirmation of the quality and consistency of the cast material and also ensure that the necessary quality control is being maintained at the batching plant.

Although an approved and effective procedure, it attracts criticism on account of the lengthy delays which the preparation and testing of cubes and, to a lesser extent, core specimens introduces into the quality control process. In addition, the number of core samples made available for in-situ density assessment is restricted because of the detrimental effect of this activity on the structural integrity of the cast material. Consequently, although the procedure characterises the material in the sample adequately, the quality of the majority of the placed material can only be assumed.

In an ‘Appraisal of end-performance tests for concrete and cement bound materials’, Harding (1995) concluded that tests performed on core samples might offer the only reliable method of determining the properties of the in-situ material that can be related back to the design thickness curves and specified concrete strengths. As noted above, however, coring is by nature a destructive process and this restricts its wide-scale use as an assessment tool.

Alternative techniques, ideally of a non-destructive nature, which could be applied soon after casting to provide an accurate measure of the in-situ strength of concrete materials would, consequently, be of value both to contractor and customer alike. With the impending introduction of contracts based on end-performance criteria, and the ensuing non-standard mix designs likely to evolve with such contracts, these types of test might be of particular relevance, particularly if results obtained at an early age could be used to provide a warning of poor quality material, and so reduce the amount of expensive longer term corrective action otherwise necessary, and a prediction of the probable in-situ cured strength of the materials. Such techniques could also assist in minimising traffic delays by allowing roads of concrete construction to be re-opened to traffic at the earliest opportunity following maintenance.

Several different techniques which claim to provide a measure of the near-to-surface strength of concretes are currently available for engineering application purposes and recommendations for their use are documented in British Standard 1881: Part 202: 1986 and Part 207: 1992 (British Standards Institution, (1986) and (1992)) respectively.

Four tests of this type, possessing either non-destructive or mildly-destructive qualities, have been evaluated in a field trial. Each was used to measure the in-situ strength of a range of pavement quality concretes and the results were compared with material strengths determined by laboratory crushing test performed on laboratory and site-cured cube specimens, and also on cores removed from the materials.

The work described in this report forms part of a wider study of the performance of non-destructive test methods in contract situations being undertaken for the Pavement Engineering Group of the Highways Agency under project reference E086A/HM: Standardisation of non-destructive testing.

2 Objectives of the research programme

The objective of the research was to examine, in a field trial, several currently available non-destructive or mildly-destructive near-to-surface strength measurement techniques, and to provide guidance to the customer on their potential to provide an early and accurate measure of the in-situ strength of a range of concrete materials typical of those currently used in highway construction applications. The ease of use and speed of application of each of the selected techniques were also to be included in the assessment.

3 Non-destructive tests

The four near-to-surface tests examined in the trial were the Schmidt Rebound Hammer and Windsor probe (penetration resistance), together with CAPO (cut and pull-out) and BOND (surface pull-off) tests.

The Schmidt Rebound Hammer was included because of its non-destructive nature, and because it offers the additional advantages of both simplicity of use and speed of application. Although the Windsor probe would also appear to offer speed of application, it does, by its very nature, possess a mildly destructive element resulting in material damage similar to that caused by both the CAPO and BOND tests. The damage is, however, minimal and confined to an area near to the surface of the material. All of the techniques examined require some preparatory work - grinding of the surface of the material to provide a smooth flat finish. Both the CAPO and BOND techniques, however, involve additional preliminary activities. Each of the tests is described in more detail below.

3.1 Schmidt Rebound Hammer

The Schmidt Rebound Hammer was developed in Switzerland (Schmidt, 1950). The device provides a measure of the superficial hardness of the surface of the concrete interpreted from the rebound height of a steel mass after hitting one end of a steel rod held in contact with the surface of the material. The initial energy is imparted to the steel mass by means of a standard spring. There is no fundamental relationship between this arbitrary measure of hardness and material strength. However, an empirical relationship between the two parameters does exist for concretes of similar type when tested under similar conditions. Although the Schmidt Rebound Hammer might therefore prove more suitable for locating areas of poor quality material rather than providing an accurate interpretation of absolute strength, this could be of considerable benefit in highway engineering applications. In addition, the ability to provide a quick and concentrated non-destructive assessment of large areas of construction makes it attractive and worthy, therefore, of inclusion in the trial.

3.2 Windsor Probe

The Windsor probe was developed in the USA in the 1960's and involves the firing of a ballistically driven steel probe into the surface of a hardened concrete by a consistent amount of energy (powder charge). The resistance to penetration by the probe can, it is claimed, be related to material compressive strength. After firing, the exposed length of probe is measured and correlated with compressive strength. Results are, apparently, dependent on the hardness of the aggregate which can be obtained from a standard mineral test (Mohs' hardness scale). To obtain a statistically meaningful result, it is recommended that three probes are set in a triangular pattern, the average value of the exposed heights of the probes being converted to strength by reading from a simple conversion table supplied by the manufacturer and accommodating the range of hardnesses of aggregates likely to be encountered.

3.3 CAPO Test

The CAPO test (Peterson, C.G. 1982), is a variant of the LOK test (Hansen, K. 1975), which has been developed to the stage where it is included in Danish Standards as a compliance test. The LOK test involves pulling a 25mm disc shaped steel insert out of the hardened concrete against the counter pressure of a ring of 55 mm internal diameter. The required pull-out force has been demonstrated to correlate well with the compressive strength of the material.

The CAPO test offers a similar measurement to that provided by the LOK test and was developed to avoid the need to insert the steel discs into the concrete whilst the material is being cast. However, the preparatory work, which involves the drilling of a 25mm diameter hole and under-reaming of a groove to accept a special expanding bolt, is more arduous and time consuming. The test, which causes minor damage only to the in-situ material in the form of a cone shaped fracture in the top 30mm of the concrete, could be used as an alternative to coring.

3.4 BOND Test

Finally, the BOND test was examined in the trial as it could offer a less time-consuming alternative to the CAPO test. The test is based on the concept that the tensile force required to pull a steel block of 75mm diameter and 30mm thickness, together with a layer of concrete, from the surface to which it has been attached is related to the strength of the material. The test is made possible by the development of fast curing, high bond strength adhesives, which are used to attach the metal block to the surface of the in-situ material. A criticism of the test has been the large scatter in results, possibly associated with a concentration of high mortar content material close to the surface of the in-situ material, although greater consistency can apparently be obtained by partially coring the concrete around the periphery of the block to encourage the fracture plane to occur deeper in the concrete. Unlike the other near-to-surface tests described above, the BOND test provides a direct measure of the tensile strength of the material under examination; derivation of its equivalent compressive strength requires calibration involving both pull-off and laboratory compressive strength tests, performed on cube specimens specially prepared from the same mix.

4 Site trial

4.1 Selection of site

The construction of ten concrete sections, and all subsequent testing, was undertaken by Trafalgar House Construction (Regions) Ltd, (now Kvaerner), under a contract agreement let by the Transport Research Laboratory (TRL) on behalf of the Highways Agency. With the kind permission of the British Airports Authorities (BAA), the trial was allowed to proceed on the Western Aprons Development site at Heathrow Airport. Trafalgar House's involvement in apron construction work at Heathrow had required the installation of an on-site batching plant at the Western Aprons site. Advantage was to be taken of this plant to supply all of the concrete materials called for by the TRL contract, and in so doing, alleviate concern regarding the transportation over long distances of the air-entrained concretes, which would have occurred had the trial been conducted at the TRL site at Crowthorne.

4.2 Pavement construction

The trial sections, each 5 metre square, were placed end to end and constructed between rigid forms. Each of the required 200mm thick pavement quality (PQ) concretes was prepared in a single 6 cubic metre volume mix in the on-site 'Elba 60' batcher operating on automatic cycle. The trial sections were cast on a prepared 150mm thick CBM3, complying with the requirements of the Specification for Highways Works (SHW) (Department of Transport et al, 1991) and the two layers were separated by 1000 gauge polythene sheet.

The mix constituents of each of the concretes in the trial sections, limitations on their mix parameters and the procedures adopted for their manufacture and placement were to comply with the requirements of Clauses 1001 to 1034 of SHW, unless otherwise stated in the TRL contract specification.

Each pavement quality concrete was manufactured to achieve the required C40 strength using either all Portland cement to British Standard 12 (British Standards Institution, 1996), or Portland cement in combination with different hydraulic binders. These alternative hydraulic binders were used to replace the cement on a weight basis and consisted of: microsilica to BBA Certificate No 85/1568 (British Board of Agrement, 1990) at 10% of total cementitious content, pulverised-fuel ash (pfa) to British Standard 12: Part 1 (British Standards Institution, 1993) at 25% of total cementitious content and ground granular blastfurnace slag (ggbs) to British Standard 6699 (British Standards Institution, 1992) at 35% of total cementitious content, respectively.

All of the mixes incorporated a Thames Valley Grade M sand conforming to British Standard 882 Specification (British Standards Institution, 1992). Each mix was air entrained, except for that containing the Portland cement/ microsilica blend of hydraulic binder, which incorporated a super-plasticiser instead of the air entraining agent.

Thames Valley flint aggregates were selected and used in nine of the sections. In eight of these a 20mm maximum size flint aggregate was used and in two sections, one incorporated a 40mm maximum size flint aggregate, and the other a 20mm maximum size carboniferous limestone aggregate. All aggregates conformed to British Standard 882.

Consequently, five sections (1-5), which were to act as controls, were constructed using the same concrete mix. Of the remainder, two sections (6 & 7) enabled the effects of different aggregate grading (40mm flint) and aggregate type (limestone) to be examined, and sections (8-10) allowed an examination of the effects of the inclusion of additional hydraulic binder additives in the paste (microsilica, pfa & ggbs), respectively.

The mix designs of the concretes selected for the trial, together with their section identification numbers, are presented in Appendix A, Table A1. A summary of the material sources is included in Table A2. The compacting factors, with a target value of 0.88, and air contents for each of the mixed concretes are presented in Table A3.

All ten sections were hand laid. The placed concrete was compacted using 75mm vibrating pokers prior to the application of a triple roller paver followed by a wire brush finish. Poker vibration was omitted on section 2 in an attempt to produce an under-compacted material.

Eight of the trial sections were cast during the period 24th to 28th October 1994. One objective of the investigation was to examine the influence of ambient temperature on the rate of development of in-situ strength and its effect on the near-to-surface 3-day and 28-day strength correlations. Consequently three sections (3-5) were cast at one week, one month and two months intervals respectively following casting of the first section, (section 1). Unfortunately, ambient temperatures recorded during the months of November and December were little different from those experienced in late October so this effect could not be investigated.

4.3 Measurements

The four selected near-to-surface techniques were employed to obtain a measure of the 28-day in-situ strength of each of the ten concretes. Three-day in-situ strength measurements were restricted to those concretes in trial sections 1 to 5 only. Measurements required by each of the techniques were made at similar positions on each trial section and are detailed in Appendix A, Figure A1 (section 1-5) and Figure A2 (section 6-10), respectively. A summary of the measurements programme, including the testing of both cubes and cores, is presented in Appendix A, Table A4.

Schmidt Rebound Hammer tests were performed using a Proceq Type N Hammer operated in the vertical orientation and in accordance with both the manufacturers instructions and British Standard 1881: Part 202 (British Standards Institution, 1986) recommended procedures. Rebound values obtained at 12 positions distributed over the area of each of the trial sections were averaged and values for 3-day and 28-day equivalent in-situ cube compressive strength determined by referring to the ‘rebound number/strength’ conversion table provided by the equipment manufacturer. The effect on indicated strength of rejecting rebound values falling outside of the range ±5 of the mean value was also examined.

Windsor Probe tests were performed in accordance with the appropriate clauses in British Standard 1881: Part 207 (British Standards Institution, 1992). Equipment used for the measurements comprised a James W600 Windsor Probe firing silver coded cartridges. Three ‘single shot’ tests were performed at separate positions on each trial section. Average values of ‘exposed probe height’ were calculated and converted to equivalent compressive strength using the ‘probe height/strength’ conversion table provided by the equipment manufacturer.

CAPO and BOND tests were provided under a sub-contract let to Construction Materials Management Ltd who supplied the specialised equipment necessary for these types of test. CAPO tests were performed at 4 pre-determined positions on each of the trial sections and in accordance with the appropriate clauses in British Standard 1881: Part 207 (British Standards Institution, 1992). BOND tests were performed at 6 pre-determined positions on each trial section, again in accordance with the appropriate clauses in British Standard 1881: Part 207 (British Standards Institution, 1992).

Three-day and 28-day strength predictions obtained using the near-to-surface techniques were to be compared with strength values determined by laboratory crushing test performed both on 3-day age site-cured cube specimens manufactured from the fresh concrete mixes, and also on 28-day age core specimens removed from the trial sections 25 days after casting.

In total, eight 150mm cubes were made from each mix. Four cubes were made, cured and tested under laboratory conditions in accordance with the requirements of British Standard 1881: Part 120 (British Standards Institution, 1983). Two of these were tested for compressive strength at 7-day age and the other two at 28-day age, in line with currently adopted practises. The remaining four cubes were left to cure ‘on-site’ under prevailing ambient conditions. Two of these cubes were tested in the laboratory for compressive strength at 3-day age, the remaining two being tested at 28-day age.

In addition to cubes, 12 full-depth core specimens of 150mm diameter were cut from each of the trial sections. Six of these were obtained when the materials had attained 3-day age and the remainder when each of the materials had attained 25-day age. In total, one hundred and twenty cores were made available for compressive strength testing purposes. Of these, half were prepared, stored and tested at 28-day age in accordance with the requirements of British Standard Specification 1881: Part 120 (British Standards Institution, 1983). The remainder were prepared, stored and tested, again at 28-day age, but in accordance with current ISO/DIS 7034 recommended procedures (International Organisation for Standardisation, 1983). The selected core positions, which were similar for each trial section, are indicated in Appendix A, Figures A1 & A2 respectively.

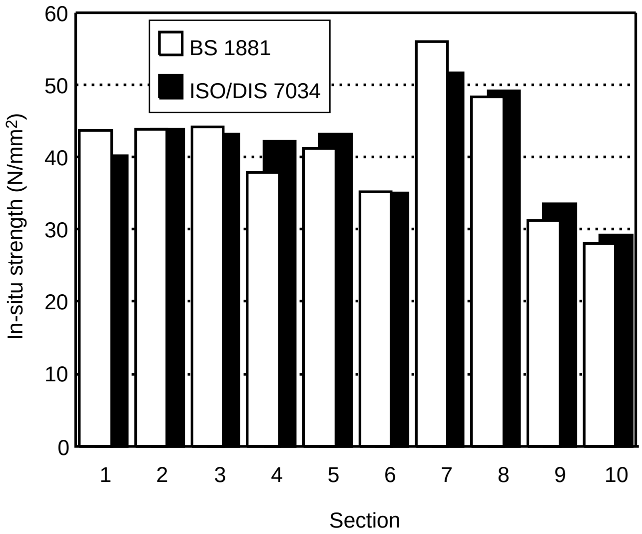

Figure 1 28-day in-situ strength — BS 1881 and ISO/DIS 7034 Procedures

5 Results

The purpose of the trial was to examine the ability of selected near-to-surface tests to provide accurate measures of the 28-day in-situ strengths of a range of concrete materials, and typical of those currently used in highway construction applications. Ease of use, and their ability to provide early indications of the quality of the materials, and on a broader scale than is currently provided by 7-day cube and core assessment procedures, was also to be examined. A contractor's report was presented to TRL Ltd on completion of the trial. All relevant data were extracted from the report and are presented in Appendix A.

5.1 Compressive strength from cores

In-situ compressive strength values of each of the concretes, determined by laboratory crushing tests on core specimens performed in accordance with British Standard 1881: Part 120 (British Standards Institution, 1983), are presented in Appendix A, Table A5.1. These include the 28-day strength values suggested by cores removed from the trial sections both 3-days and 25-days after placing together with their corresponding densities measured after applying the sulphur capping. Similarly, in-situ compressive strength values for each of the concretes, determined by laboratory crushing test performed on core specimens in accordance with ISO/ DIS 7034 recommended procedures (International Organisation for Standardisation, 1983), are presented in Appendix A, Table A5.2, together with their corresponding densities, again measured after capping.

Strength tests on cores taken from the concrete slabs should accurately reflect the in-situ strength of a concrete. Figure 1 shows the similarity in strength indicated by the two different procedures and this, in the absence of a definitive method, provides some indication of the confidence which can be placed on core crushing to provide an accurate measure of the in-situ strength of these materials.

The results compared are those obtained from cores extracted from each of the concretes at 25-day age and tested at 28-days. In each case the results from crushing cores have been converted to their equivalent estimated cube strength values and referred to hereafter as the in-situ strength.

The in-situ strengths illustrated in Figure 1 show that sections 1 to 5 inclusive are very similar, the range being from 38N/mm^2 to 44N/mm^2. Although the placing of these sections was deliberately extended over a period of 2 months in anticipation that the curing conditions would be different, there was, in fact, little overall variation in ambient temperature during this period. Section 2, which was deliberately under-compacted, proved to be the strongest of these mixes and, consequently, the resulting in-situ strength of this particular material was similar to that of the other four sections. Sections 6 to 10 inclusive were found to be more variable with in-situ strength varying in the range 28N/mm^2 to 56N/mm^2.

The 28-day in-situ strength results are as expected from these mixes and can therefore be used as a basis against which the other methods of strength assessment can be compared. As the two methods of testing cores give very similar results, those obtained using the British Standards procedures were used for the comparisons with the compressive strengths obtained by crushing cubes and by near-to-surface tests.

5.2 Compressive strength from laboratory cured cubes

The mix quality of concrete used for highway construction is currently determined by crushing tests performed on cube specimens, which are prepared, cured and tested under laboratory conditions in accordance with procedures published in British Standard BS1881: Parts 108, 111 and 116 respectively (British Standards Institution, 1983). Consequently, cube specimens were prepared, cured and subsequently tested in accordance with these procedures to enable both 7-day and 28-day compressive strength values to be determined for each of the concrete mixes employed in the trial.

The results of these tests are presented in Appendix A, Table A6, and illustrated in Figure 2(a) together with the in-situ strength determined by crushing cores; they demonstrate clearly that each of the concrete mix designs achieved their target 40N/mm² design strengths. The strong relationship existing between the strengths of the 7-day and 28-day cubes illustrated in Figure 2(a) is reinforced by the regression analysis presented in Figure 2(b) which has a correlation coefficient of 0.95 and confirms that, as expected, a high degree of confidence can be placed on a 28-day material strength prediction based on the 7-day cube test. Moreover, this currently adopted method of determining, at an early age, the mix quality and achievable strength of a concrete would appear to be relatively insensitive to variations in mix design typical of concretes currently used for highway construction examined in the trial. The degree of consistency in the 28-day strengths of each of the control concretes (Sections 1-5), which were manufactured intermittently over a period of 2 months, also provides a useful insight into the longer term mix control attainable by a batching plant.

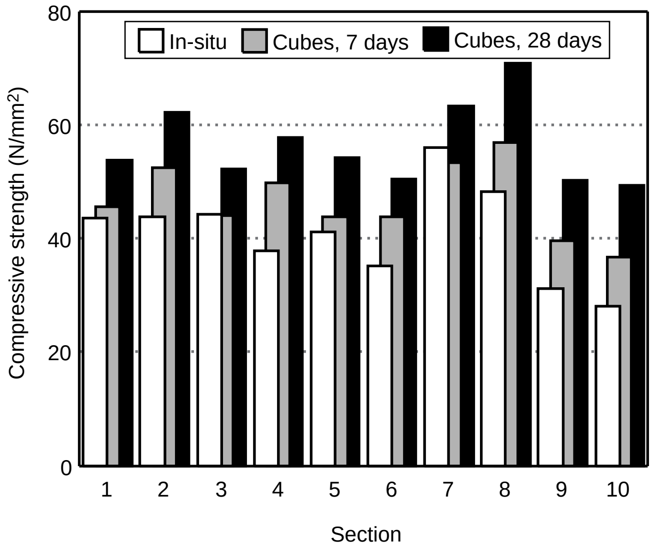

Figure 2(a) Compressive strength of cubes cured at 20°C compared to in-situ strength

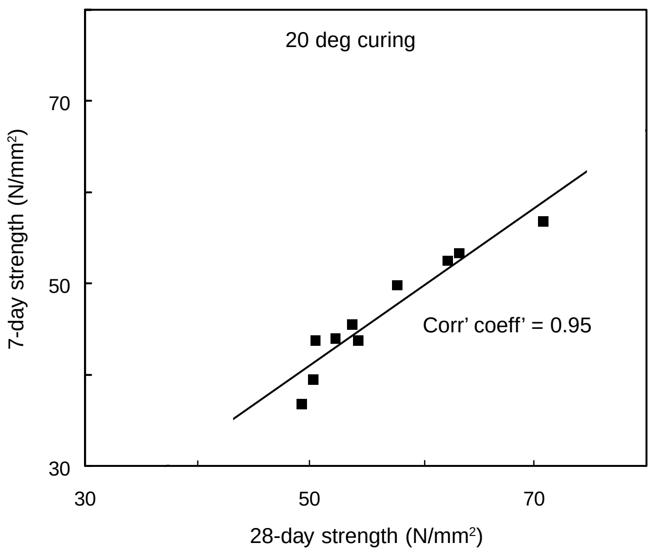

Figure 2(b) 7 v 28-day cube strength correlation (Sections 1–10)

In contrast, it is also evident from Figure 2(a) that, for most of the concretes, the 28-day in-situ strength is less than that suggested by the 28-day cube test, and also less than that indicated by the 7-day cube test. Laboratory prepared cubes provide a measure of the optimum achievable strength of a concrete when compacted to optimum density and cured under ideal, controlled laboratory conditions. The in-situ strength of the materials will be predictably less than optimum because of the lower in-situ density and the influence of less favourable curing conditions on site. Consequently, differences in the cube and in-situ strength relationships found to exist were probably to be expected.

For illustrative purposes, the relationship, expressed in percentage terms, between the average density of the 12 core specimens extracted from each of the materials to allow a more precise measure of the in-situ strengths of these materials to be made, and that of the 4 laboratory prepared cube specimens manufactured from each of the concrete mixes, is presented in Figure 2(c) and indicates the lower density typically associated with a cast material.

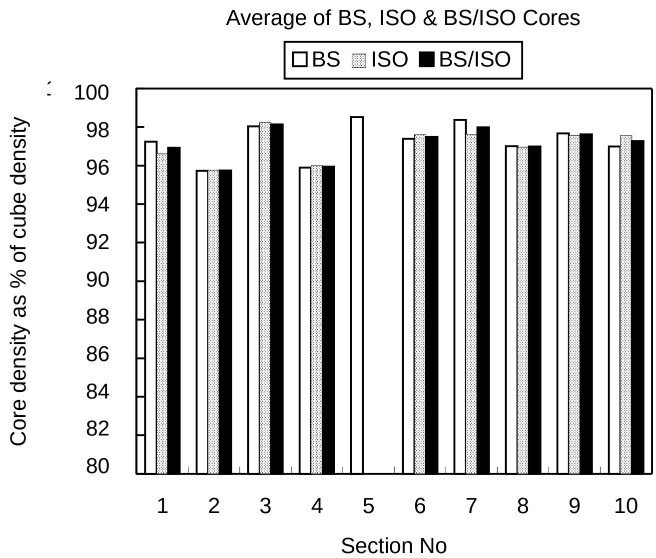

Figure 2(c) Core/cube density relationship

Similarly, the influence of differences in the curing conditions found on-site and in the laboratory is demonstrated by Figure 2(d) in which, for each of the materials, the average 28-day strength of cores extracted at 25-day age and those extracted at 3-day age and subsequently cured for a further 25-days, prior to test, under controlled laboratory conditions at a constant temperature of 20°C, are compared. The resulting strength relationships are also expressed in percentage terms. For completeness, the relationships presented in Figures 2(c) and 2(d) include the densities associated with cores selected for test in accordance with both British Standard BS 1881: Part 120 and ISO/DIS 7034 recommended procedures (British Standards Institution, 1983 and International Organisation for Standardisation, 1983, respectively) and the core strengths determined using each of these procedures.

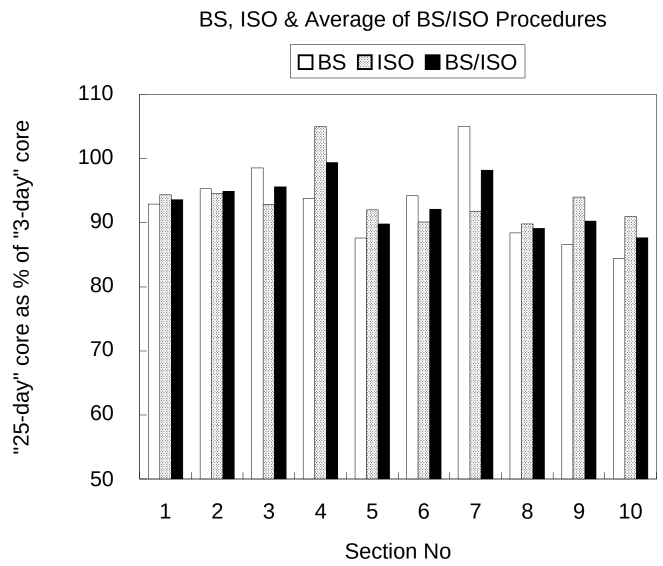

Figure 2(d) Core strength relationship (25-day v 3-day in-situ curing)

5.3 Compressive strength from ambient cured cubes

Three-day and 28-day strength values of 'site-cured' cube specimens prepared from the same mixes are also included in Appendix A, Table A6 together with their corresponding saturated densities. The resulting cube strengths are illustrated in Figure 3 together with the 28-day in-situ strength values determined by crushing cores.

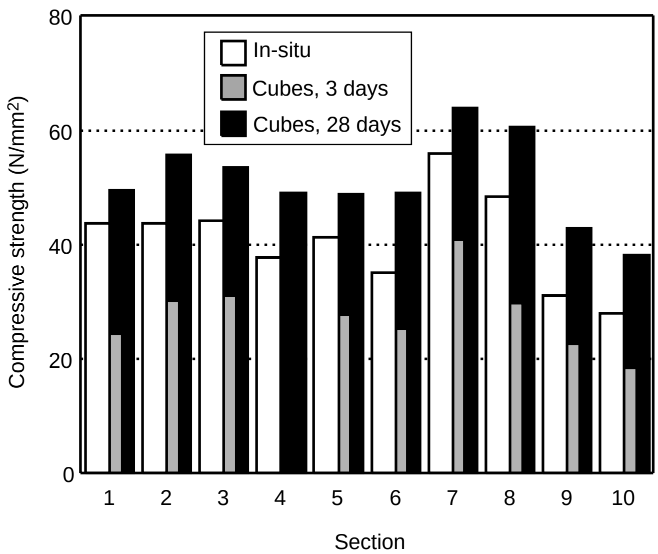

Figure 3 Compressive strength of cubes cured at ambient compared to in-situ strength

Figure 3 shows clearly that 28-day compressive strength values obtained from cubes cured at ambient temperature relate more closely and are therefore more representative of the in-situ strength than the compressive strengths reflected by cubes cured in the laboratory at 20°C. Although, again, some difference is to be expected due to differences in density, a strong correlation was found to exist between the strengths indicated by ambient cured cubes and in-situ strength, even for the cubes tested at 3-day age. This is not unexpected, as concrete gains strength more quickly initially, so that a significant proportion of the 28-day strength will have been achieved 3-days into the curing cycle, as is demonstrated by Figure 3.

5.4 Compressive strength from near-to-surface test techniques

In-situ concrete compressive strength values measured by each of the near-to-surface techniques are presented in Appendix A, Tables A7 to A10 inclusive. The 3-day and 28-day strength values associated with Schmidt Rebound Hammer are presented in Tables A7.1 and A7.2 respectively, while those pertaining to Windsor Probe, CAPO and BOND tests are presented in Tables A8, A9 and A10 respectively. Summaries of the 3-day and 28-day test results are presented in Tables A11a and A11b respectively.

Recommendations on the use of near-to-surface tests for concrete strength assessment purposes are published in British Standard Documents, for rebound hammers in British Standard BS 1881: Part 202 (British Standards Institution, 1986), and for other near-to-surface techniques examined in the trial in British Standard BS 1881: Part 207 (British Standards Institution, 1992). The recommendation for pre-test calibration of the devices, for improved accuracy, was beyond the scope of the trial and, consequently, in the case of Schmidt Rebound Hammer and Windsor Probe tests, standard manufacturers conversions appropriate to the hardness of the selected aggregates have been used to provide equivalent in-situ cube compressive strength values. This approach also served to allow an examination of the sensitivity of Schmidt Rebound Hammer and Windsor Probe tests in particular, to differences in the mix constituents.

In contrast to other near-to-surface techniques, the BOND test measures the tensile strength of a material, for which there is no standard manufacturers conversion to equivalent compressive strength. To enable the spread of results to be compared to those of the other near-to-surface techniques, BOND tensile strengths were converted to equivalent cube compressive strength using the following technique. The average ratio of BOND tensile strength results to estimated in-situ cube strength was found for Sections 1 to 5, which are the same concrete mix. This calibration was then applied to the results obtained for each of the sections, including the different concrete mixes used in Sections 6 to 10.

The near-to-surface results for tests conducted on the 3-day age concretes are presented in Figure 4, together with the 3-day compressive strength values determined from the ambient-cured cubes, with the exception of Section 4 cube results which unfortunately failed prematurely during the crushing process. Cubes were used as a substitute for cores which could not be removed from the slabs and prepared in readiness for testing at 3-day age. The 28-day in-situ strength is also included, for comparison.

Figure 4 shows that the 3-day near-to-surface tests gave broadly similar strengths to those indicated by the 3-day ambient cubes. Near-to-surface tests, by their very nature, provide a measure of the surface strength of a cast material. Consequently, this would suggest that each of the

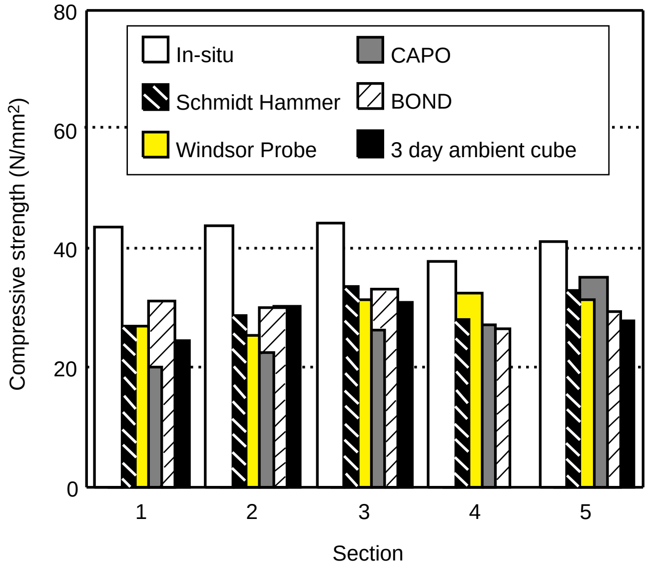

Figure 4 Compressive strength from 3-day near-to-surface tests compared to 3-day ambient cubes and 28-day in-situ strength

near-to-surface tests is able to provide a reasonable indication of the strength of the near-to-surface material, which might be expected to cure at a similar rate to that of the ambient cubes.

Similarly, the near-to-surface results for tests conducted on each of the ten 28-day age concretes are presented in Figure 5, together with the 28-day in-situ strength values.

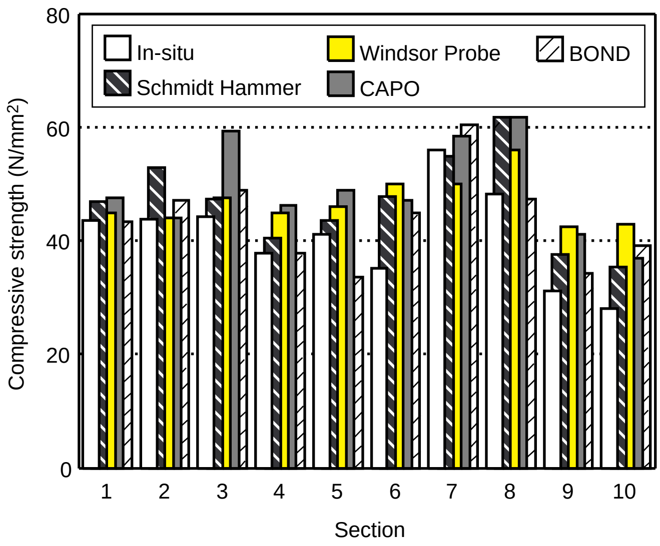

Figure 5 Compressive strength from 28-day near-to-surface tests compared to 28-day in-situ strength

Figure 5 shows that each of the near-to-surface tests is of sufficient accuracy to enable it to be used to indicate large-scale variability in the strength of the material under test. However, for individual sections the near-to-surface tests may predict strengths 30-40 percent greater than the in-situ strength indicated by crushing cores.

Concrete strengths suggested by each of the near-to-surface techniques represent the average of a number of individual measurements obtained from locations distributed within each of the slabs. The variability associated with these measurements was examined and compared with that associated with the cores. The 95% confidence limits, expressed as a percentage of the mean strengths, were calculated and are presented in Table 1. Core strength variability was determined using all available core specimens, whether tested in accordance with British Standard or ISO/DIS recommended procedures.

Because of the random nature of the variability of the results used in this analysis, and the varying numbers of samples associated with each of the different strength assessment techniques, it is not possible to ascertain whether the variability shown in Table 1 is predominantly associated with the measurement techniques themselves, including core crushing, or to strength variations within each of the concrete slabs.

5.5 Comparison of methods of obtaining in-situ strength

Linear regression analysis was used to determine the extent to which the 28-day in-situ strength could be estimated by the strength obtained by crushing cubes or near-to-surface tests. The degree of correlation between the in-situ strength and the other methods of strength assessment is summarised in Table 2.

The results of the regression analysis, which are presented in detail for each of the near-to-surface tests in Figures 6 to 9 inclusive, indicate that the 28-day Windsor Probe and BOND tests correlate least well with in-situ strength, with correlation coefficients of 0.60 and 0.72 respectively. Twenty-eight-day Schmidt Rebound Hammer and CAPO tests show a reasonable correlation with in-situ strength, returning a correlation coefficient of 0.83, which, although better than that associated with laboratory cured cubes, is not as strong as the correlation with ambient cured cubes.

The core strength values used in the presentations made in Figures 6-9 represent the average of those determined using both British Standard and ISO/DIS procedures.

Table 1 Variability of near-to-surface and core strength measurements – 95% confidence limits as % of mean strength

Section	*1* ±	*2* ±	*3* ±	*4* ±	*5* ±	*6* ±	*7* ±	*8* ±	*9* ±	*10* ±
Schmidt Hammer	12%	18%	12%	13%	13%	20%	7%	11%	10%	17%
Windsor Probe	4%	2%	11%	2%	8%	11%	22%	12%	8%	6%
CAPO Pull-out	21%	21%	10%	30%	16%	19%	7%	13%	17%	24%
BOND Pull-off	18%	14%	7%	18%	10%	7%	11%	12%	20%	19%
Core 25-day	17%	9%	11%	21%	11%	6%	10%	10%	13%	15%
Core 3-day	20%	7%	10%	15%	7%	9%	12%	7%	7%	11%

Table 2 In-situ strength correlations

Method	*Correlation coefficient, r*
28-day in-situ strength (from cores)	1.00
28-day cube cured at 20°C	0.74
7-day cube cured at 20°C	0.81
28-day cube cured at ambient	0.95
3-day cube cured at ambient	0.92
28-day Schmidt Rebound Hammer	0.83
28-day Windsor Probe	0.60
28-day CAPO	0.83
28-day BOND	0.72

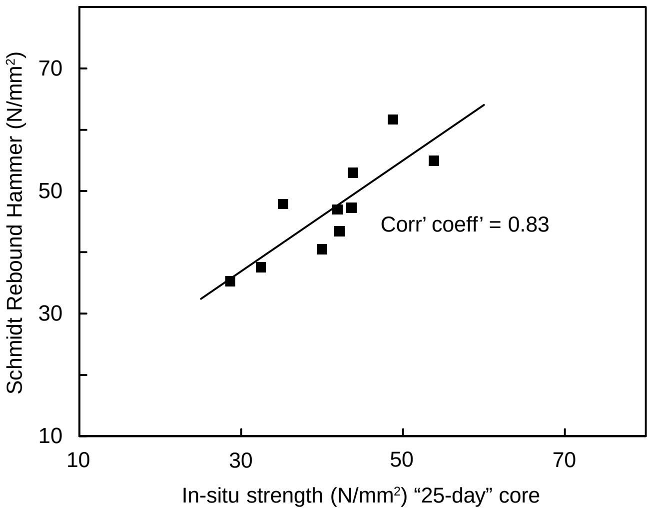

Figure 6 Linear regression analysis Schmidt Rebound Hammer 28-day test (Sections 1–10)

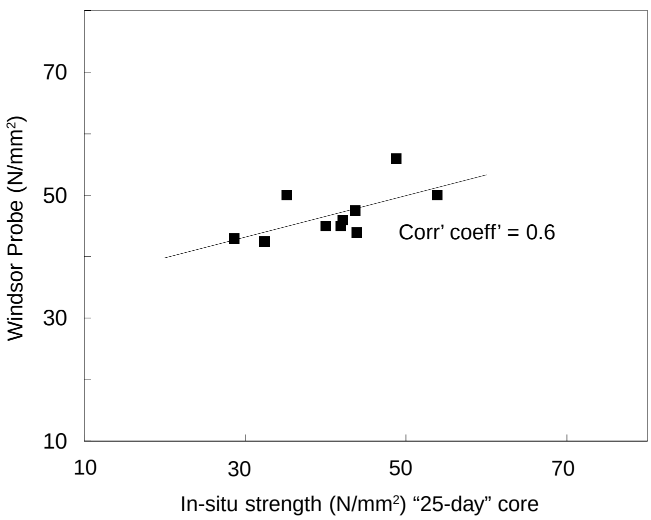

Figure 7 Linear regression analysis Windsor Probe (penetration resistance) 28-day test (Sections 1–10)

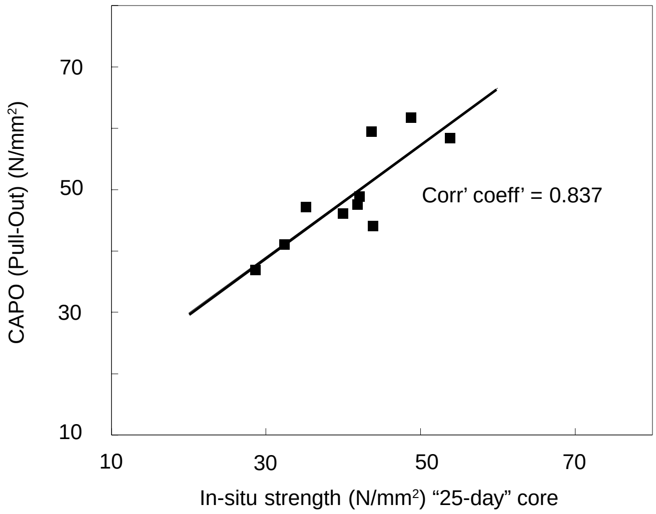

Figure 8 Linear regression analysis CAPO (pull-out) 28-day test (Sections 1–10)

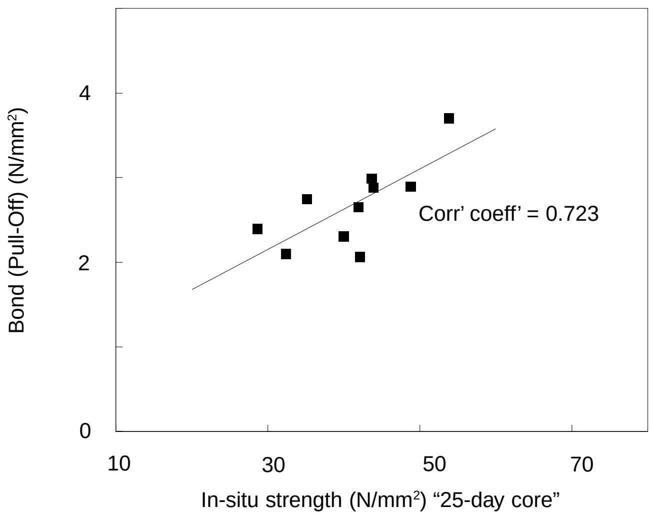

Figure 9 Linear regression analysis BOND (pull-off) 28-day test (Sections 1–10)

BOND test results have been retained in units of tensile strength to avoid the introduction of errors associated with their conversion to compressive strength.

Insufficient variation in the strength of the concretes in Sections 1 to 5 precluded the development of correlations between 3-day strength indicated by each of the near-to-surface techniques and the 28-day in-situ strength determined by crushing cores.

6 Comments on practical aspects of near-to-surface tests

6.1 Schmidt Rebound Hammer

As discussed in Section 3 of this report, some near-to-surface tests are easier and quicker to perform than others. The Schmidt Rebound Hammer is one of the quickest and easiest of the tests to perform and demands the minimum of skill. Also, little or no damage is caused to the concrete. The 12 individual readings required to estimate material strength can be spread over a relatively large area and so enable a comprehensive examination of the cast material. For the range of concretes examined in the trial, the 28-day results obtained using the Schmidt Rebound Hammer show one of the highest correlations with in-situ strength (correlation coefficient 0.83). This device could, therefore, prove to be useful for checking on a broad scale for significant variation in the strength of concrete on a highway.

6.2 CAPO and BOND

Although the CAPO test correlated equally well with in-situ strength, this method, being slower to perform, could not, in practice, be used to provide as intensive an examination of the strength of a given area of concrete as that offered by the Schmidt Rebound Hammer.

The BOND test returned a poorer correlation with in-situ strength than the Schmidt Rebound Hammer and CAPO tests. The additional activity of coring of the surfacing of the concrete around the periphery of the attached disc, in order to encourage the fracture plane to occur deeper in the concrete, resulted in the speed of the test being little quicker than that of the CAPO test. Although of little consequence when used in its principal function of comparing the strengths of existing and reinstated concretes, a quality assessment based on a measure of a material's tensile strength would be a significant departure from traditional practise.

6.3 Windsor Probe

This penetration resistance test proved to be the most poorly correlated of the near-to-surface tests examined. Difficulty in achieving satisfactory penetration of the ballistically fired pin was experienced during the tests. This could be associated with localised concentrations of larger-size aggregate occurring close to the surface of the concrete.

Insufficient variation in the strength of the concretes examined at 3-day age precluded the development of a correlation between 3-day strength measured by the near-to-surface techniques and 28-day in-situ strength, and, consequently, an assessment of the ability of near-to-surface tests to provide an early, accurate indication of the quality of in-situ concretes. Their suitability for this application will, however, depend on the sensitivity of a relationship between early-life concrete strength and curing temperature, which, if significant, as suggested by Klieger (1958), could introduce additional calibration and temperature monitoring requirements which could detract from this method of material strength assessment.

7 Conclusions

From this evaluation and analysis of techniques for the prediction of the 28-day in-situ strength of newly laid concrete, the following conclusions can be drawn.

1 Each of the four near-to-surface strength measurement techniques examined in the trial can be used to detect any large-scale variability in the 28-day strength of a range of concrete materials typical of those currently used in highway construction. For individual concretes, however, near-to-surface tests may predict strengths 30-40 per cent greater than the in-situ strength indicated by crushing cores.

2 Each of the near-to-surface strength measurement techniques provided similar measures of in-situ strength to those indicated by 3-day ambient cured cubes.

3 Pre-test calibration would improve the accuracy of prediction of each of the near-to-surface strength measurement techniques.

4 28-day Schmidt Rebound Hammer and CAPO test correlated more strongly with 28-day in-situ strength (coefficient 0.83) than BOND (coefficient 0.72) or Windsor Probe (coefficient 0.6) tests.

5 Schmidt Rebound Hammer and CAPO test could be used to determine the 28-day strength of in-situ material at least as well as it can be determined by tests performed on cubes cured in the laboratory.

6 Schmidt Rebound Hammer and CAPO test could be used instead of coring and measuring density to check the 28-day strength of in-situ concrete.

7 Schmidt Rebound Hammer could be used to provide an intensive examination of large areas of concrete in order to locate any areas of poor quality material. It might also be of use in determining when concrete slabs have gained the minimum strength necessary to allow them to be opened to traffic.

8 Insufficient variation in the strength of the concretes examined at 3-day age precluded the development of a correlation between 3-day strength measured using the near-to-surface techniques and 28-day in-situ strength, and, consequently, an assessment of the ability of near-to-surface tests to provide an early, accurate indication of the quality of in-situ concretes.

In addition, the trial has also shown that:

a The in-situ strength of well compacted materials can be predicted more accurately by ambient cured cubes than by either near-to-surface tests or cubes cured in the laboratory.

b There is no significant difference in the indicated strengths of concrete cores tested in accordance with either BS or ISO/DIS procedures.

8 Recommendations for implementation

It is recommended that further work be undertaken at road construction and maintenance sites to enable a more extensive assessment of the potential of Schmidt Rebound Hammer, with an aim to developing a specification for its use. This would allow a more thorough examination of the potential of the device when used to predict the strength of in-situ concrete and to locate areas of poor quality material. The benefits associated with pre-test calibration and of omitting surface preparation activities in order to increase speed of use should also be examined.

9 Acknowledgements

This report was prepared in the Civil Engineering Resource Centre of the Transport Research Laboratory (Resource Centre Manager, Mr P G Jordan). The co-operation of Trafalgar House (Regions) Ltd for organising and undertaking the site trial and the British Airports Authority for allowing the trial to proceed at Heathrow Airport is gratefully acknowledged.

10 References

British Board of Agrement (1990). *Second issue. Elkem microsilica. Agrement certificate No 85/1568*. British Board of Agrement, Watford, Herts.

British Standards Institution (1983). *Testing concrete. Method for making test cubes from fresh concrete.* British Standard BS 1881: Part 108. British Standards Institution: London.

British Standards Institution (1983). *Testing concrete. Method of normal curing of test specimens (20°C method).* British Standard BS 1881: Part 111. British Standards Institution: London.

British Standards Institution (1983). *Testing concrete. Methods for determination of density of hardened concrete.* British Standard BS 1881: Part 114. British Standards Institution: London.

British Standards Institution (1983). *Testing concrete. Method for the determination of compressive strength of concrete cubes.* British Standard BS 1881: Part 116. British Standards Institution: London.

British Standards Institution (1983). *Testing concrete. Method for the determination of compressive strength of concrete cores*. British Standard BS 1881: Part 120. British Standards Institution: London.

British Standards Institution (1986). *Testing concrete. Recommendations for surface hardness testing by rebound hammer.* British Standard BS 1881: Part 202. British Standards Institution: London.

British Standards Institution (1992). *Testing concrete. Recommendations for the assessment of concrete strength by near-to-surface tests.*British Standard BS 1881: Part 207. British Standards Institution: London.

British Standards Institution (1992). *Specification for ground granulated blastfurnace slag for use with Portland cement.* British Standard BS 6699. British Standards Institution: London.

British Standards Institution (1992). *Specification for aggregates from natural sources for concrete.* British Standard BS 882: British Standards Institution: London.

British Standards Institution (1993). *Pulverised-fuel ash Part 1. Specification for pulverised-fuel ash for use with Portland cement.* British Standard BS 3892: Part 1. British Standards Institution: London.

British Standards Institution (1996). *Specification for Portland cements*. British Standard BS 12. British Standards Institution: London.

Department of Transport, Scottish Office Industry Department, The Welsh Office (Y Swyddfa Gymreig) and The Department of the Environment for Northern Ireland (1991b). *Manual of contract documents for Highway Works.* Volume 1 Specification for Highway Works. London: HMSO.

Harding H M (1993). *End-performance tests for concrete and cement bound layers: A literature review*. Project Report PR/H/25/93. Transport Research Laboratory, Crowthorne. (*Unpublished report available on direct personal application only*)

International Organization for Standardization (1983). *Cores of hardened concrete - Taking, examination and testing in compression.* Draft International Standard ISO 7034. International Organisation for Standardization.

Klieger P (1958). *Effect of mixing and curing temperature on concrete strength.* Journal of American Concrete Institute: Volume 54 Pages 1063-1081. June 1958.

Appendix A: Data tables

	A	B	C	D	E	F	G	H
1	ISO 1	SH 1	BS 2	SH 2	OFF 2		OUT 2	BS 2
2	OUT 1	SH 2	OFF 1	PR 2	SH 2	OFF 1	SH 1	SH 2
3	PR 1	OFF 2	BS 1	OUT 2	SH 1	ISO 2	OFF 2	ISO 1
4	OFF 1	SH 1	SH 2	SH 1	SH 2	OUT 1	PR 1	SH 1
5	SH 1	PR 2	OUT 1	SH 2	SH 1	SH 2	SH 1	OFF 1
6	BS 1	OFF 2	BS 2	SH 1	OUT 2	ISO 1	OFF 2	PR 2
7	SH 2	SH 1	OFF 1	SH 2	PR 1	OFF 1	SH 2	OUT 1
8	ISO 2	OUT 2		OFF 2	SH 2	ISO 2	SH 1	BS 1

Measurements area - 3.2 metres square
Individual measurement locations - 0.4 metres square

ISO denotes cores for strength testing - ISO/DIN 7034 procedure
BS denotes cores for strength testing - BS 1884 procedure

SH Schmidt Rebound Hammer test positions
OUT CAPO (pull-out) test positions
OFF BOND (pull-off) test positions
PR Windsor Probe (penetration resistance) test positions

Numbers relate to times of tests/extraction of cores
1 at 3-days
2 at 23/25-days (extraction of cores)
at 28-days (tests)

Figure A1 Measurements and core positions — Sections 1-5

	A	B	C	D	E	F	G	H
1	ISO 1		BS 2	SH 2	OFF 2		OUT 2	BS 2
2		SH 2		PR 2	SH 2			SH 2
3		OFF 2	BS 1	OUT 2		ISO 2	OFF 2	ISO 1
4			SH 2		SH 2			
5		PR 2		SH 2		SH 2		
6	BS 1	OFF 2	BS 2		OUT 2	ISO 1	OFF 2	PR 2
7	SH 2			SH 2			SH 2	
8	ISO 2	OUT 2		OFF 2	SH 2	ISO 2		BS 1

Measurements area - 3.2 metres square
Individual measurement locations - 0.4 metres square

ISO denotes cores for strength testing - ISO/DIN 7034 procedure
BS denotes cores for strength testing - BS 1884 procedure

SH Schmidt Rebound Hammer test positions
OUT CAPO (pull-out) test positions
OFF BOND (pull-off) test positions
PR Windsor Probe (penetration resistance) test positions

Numbers relate to times of tests/extraction of cores
1 at 3-days
2 at 23/25-days (extraction of cores)
at 28-days (tests)

Figure A2 Measurements and core positions — Sections 6-10

Table A1 Concrete mix design

	Section(s)					
Material	*1-5*	*6*	*7*	*8*	*9*	*10*
PC 42.5	360	350	375	320	270	235
pfa	-	-	-	-	90	-
ggbs	-	-	-	-	-	125
microsilica	-	-	-	32	-	-
40mm flint	-	670	-	-	-	-
20mm flint	755	375	-	780	755	755
20mm limestone	-	-	760	-	-	-
10mm flint	380	185	-	390	380	380
10mm limestone	-	-	380	-	-	-
Grade M sand	660	630	650	690	660	660
Air entrainer	400ml	400ml	400ml	-	500ml	400ml
Plasticiser	750ml	750ml	800ml	-	750ml	750ml
Superplasticiser	-	-	-	7000ml	-	-
Free water (litres)	155	145	161	133	155	155

Masses of solids are kg/m^3 of Saturated Surface Dry material

Table A2 Summary of material sources

Material	*Standard*	*Source*
PC 42.5N	BS 12	Blue Circle, Northfleet
pfa	BS 3892: Part 1	Ash Resources, Little Barford
ggbs	BS 6699	Civil & Marine, Purfleet
Microsilica	BBA 85/1568	Elkem 940, Elkem, High Wycombe
40mm flint	BS 882	Streeters, Harlington
20mm flint	BS 882	Streeters, Harlington
20mm limestone	BS 882	Wimpey Hobbs, Halecombe
10mm flint	BS 882	Streeters, Harlington
10mm limestone	BS 882	Wimpey Hobbs, Halecombe
Sand Grade M	BS 882	Streeters, Harlington
Air entrainer	BS 5075: Part 2	AE 88/2, Cormix, Warrington
Plasticiser	BS 5075: Part 1	P7, Cormix, Warrington
Superplasticiser	BS 5075: Part 3	SP6, Cormix, Warrington

Table A3 Concrete compacting factor and air content

Section	*Compacting factor*	*Air content %*
1	0.86	4.9
2	0.88	5.6
3	0.90	5.1
4	0.90	5.2
5	0.92	5.9
6	0.91	5.2
7	0.85	4.6
8	0.89	-
9	0.94	3.5
10	0.86	4.0

Table A4 Summary of proposed testing

	Section(s)					
	1-5	*6*	*7*	*8*	*9*	*10*
Age (days)	*3 7 28*	*3 7 28*	*3 7 28*	*3 7 28*	*3 7 28*	*3 7 28*
BS 1881 cores	- - 6	- - 6	- - 6	- - 6	- - 6	- - 6
ISO 7034 cores	- - 6	- - 6	- - 6	- - 6	- - 6	- - 6
BS 1881 cubes	- 2 2	- 2 2	- 2 2	- 2 2	- 2 2	- 2 2
In-situ cubes	2 - 2	2 - 2	2 - 2	2 - 2	2 - 2	2 - 2
Schmidt Hammer	12 - 12	- - 12	- - 12	- - 12	- - 12	- - 12
Windsor Probe	3 - 3	- - 3	- - 3	- - 3	- - 3	- - 3
Pull-out	4 - 4	- - 4	- - 4	- - 4	- - 4	- - 4
Pull-off	6 - 6	- - 6	- - 6	- - 6	- - 6	- - 6

Table A5.1 Core test results

	Cores tested to BS 1881: Part 120 at 28-days age					
	Cores cut at 3-days age			*Cores cut at 23/25-days age*		
Section	*Capped density (kg/m³)*	*Core compressive strength (N/mm²)*	*Estimated in-situ cube strength (N/mm²)*	*Capped density (kg/m³)*	*Core compressive strength (N/mm²)*	*Estimated in-situ cube strength (N/mm²)*
1	2259	45.0	45.0	2274	43.8	43.0
	-	52.0	53.5	2262	46.2	47.5
	2250	42.8	42.5	2282	40.8	40.5
2	2249	44.9	46.0	2272	45.5	46.5
	2267	46.5	47.5	2269	43.0	44.5
	2227	43.9	44.5	2242	39.0	40.5
3	2243	43.1	44.0	2292	44.9	45.5
	2281	45.0	45.5	2258	40.9	41.0
	2257	45.0	45.0	2276	45.9	46.0
4	2244	39.7	40.0	2255	39.5	39.5
	2294	39.6	40.0	2177	32.4	32.5
	2262	40.5	41.0	2297	41.1	41.5
5	2286	44.5	45.5	2269	41.9	43.0
	2293	50.7	50.0	2280	37.0	38.0
	2305	44.2	45.5	2298	41.3	42.5
6	2300	38.7	39.0	2312	33.9	35.5
	2265	34.3	35.5	2305	32.5	33.5
	2279	36.6	37.5	2283	36.8	36.5
7	2363	54.5	56.5	2386	53.7	55.5
	2304	46.7	49.5	2387	55.6	56.0
	2347	51.6	54.0	2369	55.6	56.5
8	2313	51.6	52.0	2324	45.9	45.0
	2310	54.4	56.0	2331	46.9	48.5
	2333	54.7	56.0	2306	51.2	51.5
9	2297	32.8	34.5	2306	28.6	30.0
	2310	36.1	36.0	2284	31.4	32.5
	2300	37.1	37.5	2294	30.6	31.0
10	2243	31.0	32.0	2226	28.2	29.0
	2302	33.0	34.0	2235	26.2	27.5
	2313	31.8	33.5	2226	26.8	27.5

Densities are 'as received densities'
Strengths are compressive

Table A5.2 Core test results

	Cores tested to ISO/DIS 7034 at 28-days age					
	Cores cut at 3-days age			Cores cut at 23/25-days age		
Section	Capped density (kg/m^3)	Core compressive strength (N/mm^2)	Estimated in-situ cube strength (N/mm^2)	Capped density (kg/m^3)	Core compressive strength (N/mm^2)	Estimated in-situ cube strength (N/mm^2)
1	2280	43.0	43.5	2286	42.5	43.5
	2257	41.5	42.4	2229	37.5	37.7
	2220	40.5	41.6	2222	39.0	39.1
2	2268	45.5	47.5	2255	41.5	43.3
	2255	47.5	47.5	2266	43.5	44.8
	2242	42.5	44.2	2245	42.5	43.5
3	2324	51.0	49.9	2258	41.0	41.4
	2263	41.5	43.5	2264	41.5	42.2
	2264	46.5	45.9	2261	45.0	45.7
4	2237	39.0	39.3	2238	40.0	41.6
	2216	36.5	35.7	2297	40.0	39.9
	2268	44.5	45.3	2288	44.5	44.8
5	-	50.0	47.1	-	42.0	43.1
	-	46.0	47.5	-	46.0	44.8
	-	44.5	45.8	-	40.0	41.3
6	2318	40.5	40.8	2297	34.0	35.3
	2293	37.0	38.3	2295	33.5	34.8
	2286	38.0	37.8	2285	34.0	35.2
7	2374	56.0	59.2	2358	51.5	54.1
	2345	56.0	56.5	2321	48.5	51.4
	2334	52.0	53.2	2316	47.5	49.5
8	2340	56.0	56.8	2307	46.5	46.8
	2313	53.0	54.0	2322	50.5	50.0
	2294	53.5	53.6	2334	49.0	50.8
9	2272	34.0	34.3	2275	31.0	31.1
	2300	34.0	35.9	2316	33.0	34.7
	2318	35.5	36.9	2293	33.5	34.9
10	2268	33.5	34.9	2239	24.5	25.7
	2266	29.0	30.3	2289	29.5	31.1
	2283	29.5	31.2	2279	29.0	30.9

Densities are 'as received densities'
Strengths are compressive

Table A6 Cube test results

Section	20 deg Curing: 7-Day Test: Density (kg/m^3)	20 deg Curing: 7-Day Test: Strength (N/mm^2)	20 deg Curing: 28-Day Test: Density (kg/m^3)	20 deg Curing: 28-Day Test: Strength (N/mm^2)	Ambient Curing: 3-Day Test: Density (kg/m^3)	Ambient Curing: 3-Day Test: Strength (N/mm^2)	Ambient Curing: 28-Day Test: Density (kg/m^3)	Ambient Curing: 28-Day Test: Strength (N/mm^2)
1	2327	46.0	2330	55.0	2284	24.5	2297	50.0
	2325	45.0	2329	52.5	2284	24.5	2294	49.0
2	2355	51.5	2354	63.0	2328	30.5	2324	56.5
	2359	53.5	2352	61.5	2329	30.0	2315	55.0
3	2308	43.5	2312	50.5	2320	32.0	2314	52.5
	2312	44.5	2321	54.0	2301	30.0	2314	54.5
4	2350	50.0	2356	57.5	-	-	2287	49.0
	2345	49.5	2355	58.0	-	-	2300	48.5
					-	-	2292	49.0
					-	-	2303	49.5
5	2321	44.0	2323	54.5	2278	25.5	2284	46.0
	2321	43.5	2327	54.0	2304	30.0	2296	51.5
6	2347	43.5	2366	50.5	2288	25.5	2327	48.0
	2356	44.0	2339	50.5	2306	25.0	2319	50.0
7	2400	52.0	2404	64.0	2399	40.0	2392	65.5
	2402	54.5	2388	62.5	2386	41.5	2394	62.0
8	2386	57.0	2396	70.0	2336	29.5	2358	62.0
	2391	56.5	2391	71.5	2344	30.0	2352	59.0
9	2349	40.0	2356	50.0	2317	22.5	2334	43.0
	2349	39.0	2358	50.5	2311	23.0	2328	42.5
10	2328	36.0	2326	48.5	2327	19.0	2304	38.0
	2326	37.5	2330	50.0	2287	18.0	2296	38.5

Densities are ‘saturated densities’
Strengths are compressive

Table A7.1 Schmidt Rebound Hammer — 3-day test results

Section Location	*1*	*2*	*3*	*4*	*5*
			Rebound number		
B1	27	28	33	42	39
G2	38	31	36	26	30
E3	29	29	32	25	55
B4	26	30	35	36	34
D4	35	29	29	30	30
H4	43	30	30	36	28
A5	27	28	34	21	33
E5	38	39	32	35	29
G5	32	32	41	26	29
D6	20	43	34	32	31
B7	30	27	33	24	40
G8	27	31	30	29	34
Mean 1	31.0	31.4	33.3	30.2	34.3
Standard deviation	6.45	4.78	3.22	6.18	7.56
Est' cube comp' strength (N/mm^2)	31.0	32.0	35.0	30.0	36.0
Est' cylinder comp' strength (N/mm^2)	26.5	27.0	29.5	25.5	30.5
Mean 2	28.1	29.5	32.5	29	32.1
Standard deviation	4.2	1.58	2.21	3.65	3.26
Est' cube comp' strength (N/mm^2)	26.9	28.7	33.6	28.1	33
Est' cylinder comp' strength (N/mm^2)	22.0	23.8	28.0	23.6	27.8

Strengths are compressive
Mean 1: Mean of 12 results
Mean 2: Mean of values falling with ± 5 of Mean 1

Table A7.2 Schmidt Rebound Hammer — 28-day test results

Section Location	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
	Rebound number									
D1	40	44	38	37	38	36	45	44	34	34
B2	45	42	45	36	39	40	45	45	33	39
E2	44	49	42	32	42	39	45	49	38	46
H2	40	51	42	40	41	44	38	49	44	32
C4	40	42	54	36	40	48	44	51	37	37
E4	49	46	39	44	35	35	49	43	36	32
D5	52	49	40	36	37	38	46	52	37	32
F5	42	47	46	40	35	51	45	49	35	32
A7	39	42	40	44	36	35	52	49	38	38
D7	40	52	38	38	41	44	43	53	34	32
G7	40	36	44	39	39	40	45	50	44	32
E8	37	45	42	36	41	45	55	49	34	37
Mean 1	42.3	45.5	42.5	38.2	38.7	41.8	45.9	48.8	37.0	35.3
Standard deviation	4.42	4.56	4.46	3.49	2.46	5.17	4.35	3.09	3.67	4.35
Est' cube comp'strength (N/mm^2)	49.5	55.0	50.0	42.5	43.5	49.0	56.2	61.5	40.5	37.3
Est' cylinder comp'strength (N/mm^2)	42.0	47.0	43.5	36.0	37.0	41.5	47.8	52.0	34.0	32.0
Mean 2	40.7	44.2	41.0	37.0	38.7	41.4	45.2	49.1	35.6	34.0
Standard deviation	2.36	3.94	2.4	2.4	2.46	4.07	1.64	2.66	1.84	2.87
Est' cube comp' strength (N/mm^2)	47.0	53.0	47.3	40.5	43.5	47.9	54.9	61.7	37.6	35.3
Est' cylinder comp'strength (N/mm^2)	40.0	45.0	40.5	34.0	37.0	40.5	46.5	48.5	33.0	30.0

Strengths are compressive
Mean 1: Mean of 12 results
Mean 2: Mean of values falling with ± 5 of Mean 1

Table A8 Windsor Probe (penetration resistance) — 3 and 28-day test results

	3-day test						*28-day test*					
	Exposed probe height (mm)			*Mean*	*Standard*	*In-situ strength*	*Exposed probe height (mm)*			*Mean*	*Standard*	*In-situ strength*
Location	*A3*	*G4*	*E7*	*(mm)*	*deviation*	*(N/mm^2)*	*D2*	*B5*	*H6*	*(mm)*	*deviation*	*(N/mm^2)*
Section												
1	4.5	3.9	4.0	4.13	0.32	27.0	5.0	5.1	5.2	5.10	0.10	45.0
2	3.9	3.9	4.4	4.07	0.29	25.5	5.0	5.0	5.1	5.03	0.06	44.0
3	4.0	4.6	4.5	4.37	0.32	31.5	4.9	5.4	5.4	5.23	0.29	47.5
4	3.9	4.5	4.9	4.43	0.50	32.5	4.9	4.85	4.8	5.10	0.04	45.0
5	3.93	4.28	4.9	4.37	0.49	31.5	5.0	5.37	5.1	5.14	0.20	46.0
6	-	-	-	-		-	5.2	5.2	5.7	5.36	0.29	50.0
7	-	-	-	-		-	6.0	5.0	5.0	5.33	0.58	50.0
8	-	-	-	-		-	5.7	5.3	6.0	5.66	0.35	56.0
9	-	-	-	-		-	5.2	4.8	4.9	4.96	0.21	42.5
10	-	-	-	-		-	5.0	4.8	5.1	4.97	0.15	43.0

Strengths are compressive
Assessed 'Mohs'' hardness No for flint and limestone — No 4

Table A9 CAPO (pull-out) — 3 and 28-day test results

	3-day test							*28-day test*						
	Pull force (kN)						*Mean*	*Pull force (kN)*						*Mean*
Location	*A2*	*C5*	*F4*	*H7*	*Mean (mm)*	*Standard deviation*	*strength (N/mm²)*	*B8*	*D3*	*E6*	*G1*	*Mean (mm)*	*Standard deviation*	*strength (N/mm²)*
Section														
1	16.5	15.5	16.5	20.6	17.3	2.27	20.1	41.2	35.0	42.2	33.0	37.9	4.54	47.6
2	18.5	17.5	22.7	17.5	19.05	2.48	22.5	35.0	30.9	35.0	40.1	35.3	3.77	44.1
3	22.7	22.7	22.1	20.6	22.0	0.99	26.3	49.3	44.2	48.3	45.2	46.8	2.44	59.4
4	20.6	24.7	24.7	20.6	22.7	2.37	27.3	43.2	34.0	39.1	30.9	36.8	5.44	46.2
5	29.8	27.8	28.8	27.8	28.6	0.96	35.2	38.1	42.2	35.0	40.1	38.9	3.06	48.9
6								35.0	40.1	34.0	41.2	37.6	3.6	47.2
7								45.2	44.2	47.3	47.3	46.0	1.56	58.4
8								44.2	49.3	49.3	51.3	48.5	3.03	61.8
9								32.0	30.9	37.1	32.0	33.0	2.78	41.1
10								32.0	32.0	25.8	-	29.9	3.58	36.9

Strengths are compressive

Table A10 BOND (pull-off) — 3 and 28-day test results

	3-day test								*28-day test*							
	Bond strength (N/mm²)								*Bond strength (N/mm²)*							
Location	*A4*	*C2*	*C7*	*H5*	*F2*	*F7*	*Standard deviation*	*Mean*	*B3*	*B6*	*D8*	*E1*	*G3*	*G6*	*Standard deviation*	*Mean*
Section																
1	1.88	1.88	1.98	1.98	1.88	1.88	0.05	1.91	2.81	2.81	2.33	2.58	2.92	2.44	0.23	2.65
2	1.77	1.67	2.09	1.77	1.67	2.09	0.20	1.84	2.92	3.03	2.58	3.15	2.81	2.81	0.20	2.88
3	1.98	2.09	1.88	2.09	2.09	-	0.09	2.03	2.97	3.08	3.08	3.08	2.86	2.86	0.11	2.99
4	1.54	1.65	1.54	1.54	1.76	1.76	0.11	1.63	2.30	2.08	2.30	2.54	2.54	2.08	0.21	2.31
5	1.97	-	1.63	1.74	1.85	1.85	0.13	1.81	2.17	1.95	2.17	2.06	1.95	2.06	0.10	2.06
6									2.64	2.86	2.75	2.75	2.64	2.86	0.10	2.75
7									3.84	3.84	3.46	3.62	3.51	3.95	0.20	3.70
8									2.97	2.75	3.08	3.08	2.64	2.86	0.18	2.90
9									2.44	1.88	1.88	2.21	2.10	2.10	0.21	2.10
10									2.44	2.55	2.21	2.21	2.21	2.75	0.23	2.40

Strengths are tensile

Table A11a Summary of 3-day strength test results

	3-day cube	Schmidt Hammer Equiv' in-situ cube		Windsor Probe	Pull -out	Pull -off
	Ambient	*All meas'*	*Mean ±5*			
Section						
1	24.5	31.0	27.0	27.0	20.0	1.91
2	30.5	32.0	28.5	25.5	22.5	1.84
3	31.0	35.0	33.5	31.5	26.5	2.03
4	-	30.0	28.0	32.5	27.5	1.63
5	28.0	36.0*	33.0	31.5**	35.0	1.81**
6	25.5	-	-	-	-	-
7	41.0	-	-	-	-	-
8	30.0	-	-	-	-	-
9	23.0	-	-	-	-	-
10	18.5	-	-	-	-	-

3-day cube, Schmidt Rebound Hammer, Windsor Probe and Pull-out strengths are compressive (N/mm²)
Pull-off strength is tensile (N/mm²)
** 5-day strength ** 4-day strength*

Table A11b Summary of 28-day strength test results

	28-day cube		28-day core Equivalent in-situ cube 3-days		28-day core Equivalent in-situ cube 25-days		Schmidt Hammer Equiv' in-situ cube		Windsor Probe	Pull -out	Pull -off
	Ambient	*20°C*	*BS*	*ISO*	*BS*	*ISO*	*All meas'*	*Mean ±5*			
Section											
1	49.5	54.0	47.0	42.5	43.5	40.0	49.5	47.0	45.0	47.5*	2.65
2	56.0	62.5	46.0	46.5	44.0	44.0	55.0	53.0	44.0	44.0	2.88
3	53.5	52.5	45.0	46.5	44.0	43.0	50.0	47.5	47.5	59.5	2.99
4	49.0	58.0	40.5	40.0	38.0	42.0	42.5	40.5	45.0	46.0	2.31
5	49.0	54.5	47.0	47.0	41.0	43.0	43.5	43.5	46.0	49.0	2.06
6	49.0	50.5	37.5	39.0	35.0	35.0	49.0	48.0	50.0	47.0	2.75
7	64.0	63.5	53.5	56.5	56.0	51.5	56.0	55.0	50.0	58.5	3.70
8	60.5	71.0	54.5	55.0	48.5	49.0	61.5	61.5	56.0	62.0	2.90
9	43.0	50.5	36.0	35.5	31.0	33.5	40.5	37.5	42.5	41.0	2.10
10	38.5	49.5	33.0	32.0	28.0	29.0	37.0	35.5	43.0	37.0	2.40*

Schmidt Rebound Hammer, Windsor Probe and Pull-Out strengths are compressive (N/mm²)
Pull Off strength is tensile (N/mm²)
** 29-day strength*

Abstract

A programme of research was carried out to examine the ability of selected near-to-surface tests to provide early, accurate measures of the 28-day in-situ strength of a range of cast concrete materials typical of those currently used in highway construction applications. Their ease of use, and ability to forecast the quality of cast materials on a broader scale than is currently provided by the 7-day cube test and core assessment procedures, was also included in the study.

An analysis of the data has shown that each of the near-to-surface tests provide measures of early-life concrete strength broadly similar to those indicated by 3-day ambient-cured crushed cubes. Each of the tests is also sufficiently accurate to enable it to be used to indicate relatively large-scale variability in the 28-day strength of the material. For individual concretes, however, near-to-surface tests may predict strengths 30-40% greater than the in-situ strength indicated by crushing cores. Careful pre-test calibration could improve the accuracy of prediction associated with each of the tests.

From the point of view of their ease of use, and their output, the Schmidt Rebound Hammer appears to be the most suitable test to pursue.

Related publications

CT121 *Non-destructive testing (1994–1997).* (Current Topics in Transport: selection of abstracts added to TRL Library's database) (price £20)

RR250 *Non-destructive testing methods for concrete bridges* by R J Woodward. 1990 (price code B, £15)

CR156 *The non-destructive detection and mapping of ASR cracking in concrete* by R L Smith and M J Crook. 1989 (price code C, £15)

Prices current at April 1998

For further details of these and all other TRL publications, telephone Publication Sales on 01344 770783 or 770784, or visit TRL on the Internet at http://www.trl.co.uk.