ASSESSMENT OF INSITU CONCRETE STRENGTH

OVERVIEW OF TEST PROCEDURES

J.H. Bungey - University of Liverpool

1. STRENGTH OF CONCRETE IN STRUCTURES

In-place strength will vary within a member due to

(a) variations of mix supplied – assumed to be random

(b) compaction differences

(c) curing differences

(b) and (c) - follow well defined patterns according to member type

Construction technique will be important, but in general there is a tendency for water to rise during compaction and for aggregate to settle. This leads to the general pattern of reduced strength towards the top of a pour depending upon the member type as shown in figure 1. This figure should only be regarded as indicative of the general types of strength distribution, since individual cases are affected by member size and other factors. Strength differences of 5-10% may also typically be expected between surface zone and interior of concrete members due to differences in curing effectiveness.

In-place strength is also likely to be less than that of standard control specimens because of less efficient compaction and curing. This represents the difference between in-situ cube strength and potential strength considered in core testing. Quoted values for this vary, but may be assumed to typically be between about 50% to 75% according to the member type, leading to overall in-place vs standard cube relationships of the type shown in figure 2.

Moisture differences and age may combine with these effects since standard specimens are tested saturated at 28 days whilst in-place concrete is likely to be dryer and older, with both of these factors tending to increase in-place values relative to standard specimens.

It is important that the above factors which are identified in BS6089 (1981) are considered when planning and interpreting the results of in-place strength testing.

2. PLANNING AN INVESTIGATION

The essential first step of planning is to establish the aims and purpose of the investigation. This will influence the locations and numbers of test points as well as the methods employed, and will also affect the interpretation procedures which must be agreed before testing commences.

Information about the insitu strength of concrete may be required for both newly cast and old concrete. For new concrete the most commonly occurring circumstances include:

(a) Non-compliance of the material supplied in terms of works control specimen test results or other specified requirements.

(b) Uncertainties concerning the level of workmanship involved in construction operations affecting the hardened properties of the insitu concrete.

(c) Quality control of construction or manufacture.

(d) Monitoring of strength development in relation to formwork removal, curing, prestressing, load application or similar purposes.

Older concrete may need to be examined when:

(a) There is suspected deterioration of the concrete due to factors such as external or internal chemical attack or change, fire, explosion or other environmental effects.

(b) An assessment is to be made of the load carrying capacity of an established structure for change of ownership or insurance purposes, or in relation to proposed change of use or alteration.

Positioning and interpretation of tests must take account of the likely variations of properties within particular member types as well as the anticipated differences between in-situ strength and that of standard specimens. The positions of test locations will be influenced by the purpose of testing, and the need to establish either average values (as for specification compliance) for a member or values relating to a critical region (as for structural adequacy assessment). The degree of representativness of surface zone values must also be considered when using some methods. The number of locations to be tested will vary according to circumstances and the accuracy of overall strength estimates required (see section 6), but may typically be between 5 and 8.

The different stages of planning an investigation are shown in figure 3. Maximum benefit will be obtained if interpretation is ongoing, thus permitting modifications of the programme in the light of the results obtained. Whilst some tests may seem straightforward, all are affected by many complex influences and it is essential that planning, testing and interpretation are undertaken by suitably experienced and skilled personnel. Documentation should always be prepared on the basis that litigation may follow.

3. SELECTION OF TEST METHOD

Important considerations will include

(a) The availability and reliability of correlations.

(b) The effects and acceptability of surface damage

(c) Practical limitations such as member size and type, surface condition, depth of test zone required, location of reinforcement and access to test points.

(d) Economic consideration of the value of work under investigation and the cost of delays in relation to the cost of the test programme.

Preliminary comparative surveys using non-destructive methods of relatively low cost are often worthwhile where the investigation is concerned with material properties or conditions. In this way, greatest benefit can be obtained from a limited number of higher precision but more expensive or disruptive tests. Examples of this includes rebound hammer or Ultrasonic Pulse Velocity surveys to establish the most worthwhile locations for cores or partially-destructive tests. For early age strength testing it may also be helpful to use maturity measurements as a preliminary to direct physical tests such as pull-outs.

Available methods are summarised in Table 1 and described below. Further practical details relating to the most widely used surface zone partially-destructive methods are also given in Table 2. Fuller descriptions will be found in Bungey and Millard (1996) and CIRIA TN 143 (1992).

4. COMPARISON OF AVAILABLE METHODS

4.1. Cores

The most reliable method of obtaining an estimate of the strength of concrete in a structural element is the cutting of cores for subsequent preparation and crushing in a laboratory. The cores are cut by means of a diamond tipped cutter which is clamped to the concrete surface and normally requires a water supply. However, to achieve a worthwhile accuracy, these cores should be at least 100 mm in both diameter and length, and at least three cores are required from a given location. The diameter should also be at least three times the size of the largest aggregate particles. It is generally accepted that an estimate of actual insitu cube of strength is unlikely to have an accuracy better than $\pm 12/\sqrt{n}\%$ where n is the number of samples tested. Sometimes it is impracticable to obtain cores of this size and smaller diameter cores may be used. In this case a much greater number of samples is required to achieve comparable accuracy due to increased scatter of results, but it is generally accepted that similar calculation procedures may be adopted down to 50 mm diameter. BS 1881 pt 120 (1983) provides basic guidance concerning interpretation of core results including allowance for specimen shape, proportions and orientation, whilst more extensive information on this subject is provided by Concrete Society Technical Report No 11 (1987), which is under revision.

After trimming and grinding or capping to provide parallel end faces, cores should be stored under water for at least 48 hours prior to test to standardise moisture conditions unless it is specifically required that they are tested dry. Density and excess voidage assessment should also be made to assist interpretation of crushing test results. It is vital that cores are clearly marked and identified, and care must be taken to remove unrepresentative end portions during trimming, unless these are specifically required to be included in the tests. Reinforcement should be avoided if possible, otherwise corrections must be made to allow for bars present in the core.

4.2. Partially-Destructive Tests

Frequently, the damage caused and the delays whilst the cores are cut, prepared and tested are unacceptable. The 'partially-destructive' techniques that are available for assessing strength of surface zone concrete are generally less reliable than cores, but cause substantially less damage and give instant results. These include established methods such as penetration resistance (Windsor probe), pull-out (Lok & Capo), internal fracture, break-off, and pull-off methods. All have the important characteristic that they directly measure a strength-related property and strength correlations are therefore not as sensitive to such a wide range of variables as the truly non-destructive methods. These methods are covered by BS1881 pt 207 (1992)

4.2.1. Penetration resistance testing. (Figure 4.)

The most common commercially available form is the Windsor Probe Test in which a hardened steel alloy probe (typically approx 80mm long and 6.3mm diameter) is fired into the concrete surface by a driver using a standardised powder cartridge. The depth of penetration, which will usually lie between 20mm and 40mm, is measured and the mean of three readings is related empirically to compressive strength by calibration charts. After measurement, the probe may be pulled from the surface leaving a conical damage zone approximately 75mm in diameter. Although unsuitable for slender members because of the danger of cracking, the test is quick and useful where access may be difficult.

Two different 'power levels' are available according to the strength range of the concrete under test, and different probe types are used for concrete made with normal and 'lightweight' aggregates.

The principal factors influencing the relationship between exposed probe length and compressive strength are aggregate hardness and type, and it has also been suggested that curing conditions and age are important. It is thus essential that specific correlation are prepared, since those supplied with the equipment do not account for all of these variables and usually overestimate the actual cube strength of the insitu concrete. Particular difficulty may be encountered in predicting strengths in the range 20-50 N/mm^2 at ages greater than one year. (Typical test C. of V. = 5%).

A smaller spring-operated Pin-Penetration method is also available for early age testing at strengths up to about 25 N/mm^2. This uses a pin approx. 30mm long and 3.5mm diameter, but published results are very limited and the method is not generally used in the UK.

4.2.2 Pull-out tests. (Figures 5 and 6)

A circular steel insert is located below the concrete surface and pulled by means of a calibrated hydraulic jack against a reaction ring bearing on the surface. The configuration is such that failure is dominated by compression of the concrete between the insert and reaction ring and is relatively independent of other properties.

Two versions are commercially available; the Lok-test which uses a 25 mm diameter insert cast into the concrete at a depth of 25mm; and the Capo-test in which a steel ring is expanded into a groove undercut from an 18mm diameter drilled hole to provide a similar configuration. The latter is intended for strength assessment of existing concrete. In both cases a hand operated jack is used with a 55mm diameter reaction ring, and the average of four readings would normally be used for correlations against compressive strength using a relationship which, for practical purposes may be regarded as 'general' for concretes made with natural aggregates. This is essentially bi-linear in nature and accuracy of insitu strength prediction may be improved by using a correlation which is specific to the concrete mix in use. (Typical test C. of V. = 7%.) Lok-test inserts are either fixed to the shutter panels (removable cut-outs can be used) or to a flotation –cup (for upper surfaces). Special high-strength Lok-test inserts are available for strengths above 70 N/mm^2.

The Lok-test is primarily useful in monitoring insitu strength development but may also be used for pre-planned long term monitoring in situations where strength deterioration is anticipated. The Capo-test, which may take up to half an hour to perform, requires skill and experience to successfully achieve the drilling, under-reaming and ring expansion but is most valuable for insitu strength estimation where specific calibration is not possible. Correlations with strength may be considered to be the same as for Lok-test for practical purposes, but with an upper limit of 55 N/mm^2 due to equipment details. Both methods will cause a damage zone 55mm in diameter.

4.2.3 Internal fracture test (Figure 7)

This was developed in the UK to permit testing of High Alumina Cement Concrete in slender members, but has subsequently been extended to more general applications. A 6mm diameter hole is drilled approximately 35mm deep into the concrete surface using a masonry drill. An expanding wedge anchor bolt is fixed into this hole to a depth of 20mm and pulled against an 80mm diameter reaction tripod by a torque-meter acting on a greased nut. The peak torque is observed and the average of six tests may be related to compressive strength with the aid of a correlation curve. The scatter of results may be lower if a direct-pull load application method is used although no purpose-made equipment is currently available. Failure is initiated by internal fracturing of the concrete, but the necessary load is sensitive to loading technique, which must be carefully standardised. It is recommended that a correlation curve is developed individually by the operator for the particular equipment and loading technique in use. The failure mode is complex and the scatter of results is high. A surface damage zone approximately 18mm diameter will remain. (Typical test C. of V. = 15%).

4.2.4 Pull-off tests. (Figure 8)

A circular metal disc is bonded to the surface of the concrete by an adhesive. This is then pulled-off, along with an attached mass of concrete, by applying a direct tensile force using hand operated equipment bearing on the concrete surface. The peak load is measured, enabling a tensile strength to be calculated, and an equivalent cube strength is estimated with the aid of a correlation graph. Partial coring may be used to overcome surface skin effects, or when assessing the bonding of repairs (for which the method is becoming very popular). The use of a correlation which is appropriate to the aggregate type is necessary, and care is required to ensure good bonding between the disc and the surface. The test depth will be within a few millimetres of the surface unless partial coring is used, and a small damage zone will remain. Many different versions of equipment are currently available, with disk characteristics and load rate varying widely. (50mm diameter disks are most commonly used in the UK). It is important that these are standardised if results are to be meaningfully compared (see BS 1881 pt 207). (Typical test C. of V. = 10%)

4.2.5 Break-of test. (Figure 9)

This method, which has been developed in Scandinavia, measures the force required to break off a 55mm diameter core which has been formed within the concrete to a depth of 70mm. This may be achieved by a disposable tubular plastic sleeve inserted into freshly placed concrete, or by drilling if existing concrete is to be tested. An enlarged slot is formed near to the surface into which a load cell coupled to a hydraulically operated jack is inserted to provide a transverse force to the top of the core. This will cause a flexural failure at the base of the core and the break-off force may be related to bending strength by means of appropriate calibration charts. The mean of five tests would normally be required for this purpose, although the tests are quick to perform. (Typical test C. of V. = 10%)

Data concerning scatter of results and accuracy of insitu strength prediction is limited, but a specially prepared correlation is required for the concrete in use. A sizeable damage zone is left, and the method is not commonly used in the UK.

4.3. Non-Destructive Tests

The position and extent of suspect concrete may be identified comparatively by non-destructive techniques such as ultrasonic pulse velocity and surface hardness measurements, but unless specifically developed calibrations are available these methods should not be used for absolute strength estimates. Correlation between the measured parameter and strength is complex for both cases, although it may sometimes be possible to develop strength correlations by the use of carefully located cores in conjunction with insitu NDT results. Other non-destructive methods which are particularly valuable for strength development monitoring of newly cast concrete are outlined below.

4.3.1 Surface hardness Measurements

A rebound hammer is used, in which a mass impacts the concrete surface with a standardised energy and causes localised crushing. The amount of rebound of the mass is measured and expressed as a 'Rebound Number'.

A number of instruments are available to suit particular concrete types. The results are affected by conditions within about 30mm of the surface and may be greatly influenced by localised carbonation hardening in concrete more than about three months old, and by member regidity. Determination of uniformity of young concrete represents the most reliable field application with a coefficient of variation of better than 4% to be expected on uniform concrete. Detailed test procedures (including equipment calibration) and applications are described in BS 1881 Pt 202.

This is a well established, quick and simple test, but results are influenced by a great many factors, and the method is not recommended for absolute strength assessment. General strength correlations provided with equipment should not be used unless confirmed by calibration trials for the conditions of use. Some minor surface marking is likely, especially with young concrete and a group of ten or twelve readings is usually required at a location.

A great many factors influence strength correlations including mix characteristics, maturity, moistsure conditions and nature of surface finish. Instrument orientation (horizontal, vertical etc.) is also critical. Erroneous readings may be caused by surface carbonation hardening, inadequate member rigidity, test located on aggregate particle at the surface, or reinforcing steel close to the surface.

4.3.2 Ultrasonic Pulse Velocity Testing

Measurements are made of the transit time of a high-frequency pulse (typically 54kHz) over a measured path length between transducers placed on the concrete surface. This is a well-established method which is quick to use and reflects the characteristics of the interior of a concrete member.

Careful measurement is required since most concretes have pulse velocities which lie within a narrow range (approximately 3.8 to 4.6km/s) but are closely related to elastic modulus. A pulse cannot cross an air gap. This technique is well documented and is covered in detail in BS 1881 Pt 203 which describes requirements for equipment and test procedures as well as applications. The most reliable applications are for the determination of concrete uniformity and the location of internal defects, but in some cases strength estimation may be possible with the aid of specially prepared correlation charts. Such correlation is necessary since strength is not directly related to Elastic Modulus, and strength correlations are influenced by a large number of features associated with the mix and insitu conditions (including moisture).

Access is required to opposite faces of the concrete member for the most reliable results, and surface staining may result from the use of some couplants. Erroneous results may be caused by poor surface coupling, internal air-filled cracks or voids, reinforcing bars, small path length or small lateral dimensions. Corrections may be made for the presence of reinforcing bars close to the pulse path if these cannot be avoided. A 2% change in pulse velocity is often regarded as indicative of a significant difference in concrete properties.

Robust equipment is commercially available for pulse velocity measurements, while additional useful information may sometimes be gained from a study of pulse waveform and attenuation using more specialised equipment.

4.3.3. Maturity measurement.

This approach is based on a record of temperature measurements taken at the interior of the concrete element to evaluate a maturity as a function of temperature above a predetermined datum (typically -10°C or -11°C) and time. For a particular concrete mix, it is possible to establish a single relationship between strength and maturity. Several different forms of this relationship have been proposed but at early maturities the influence of temperature on strength is generally underestimated. Also, maturity cannot be simply summed or integrated for fluctuating curing temperatures because temperatures occurring at different ages affect strengths differently. (ASTM C1074).

The typical form of maturity relationship is given by

$$M(t) = \sum (Ta - To)\,\Delta t$$

Where M(t) is maturity at time t in degree hours or degree days

Δt is time interval in hours or days

Ta is average concrete temperature during time interval Δt

To is datum temperature.

A typical strength/maturity relationship is given in Figure 10 for a specific concrete mix.

The method may be used to monitor insitu strength development where this may be critical, provided that the early age temperatures of the concrete used to develop the maturity-strength relationship are similar to those occurring on site. The approach also relies upon the use of the correct concrete mix, which introduces significant uncertainty in practice and it is unlikely that this method alone would be relied upon unless substantial margins for error are built-in to calibrations. The greatest value is as a preliminary indicator prior to some other form of testing.

Measurements are most reliably obtained from thermocouples or temperature measurement devices embedded at appropriate locations within a pour, which are coupled to automatic recording equipment. Sensor location is critical, as for temperature matched curing (see below). Equipment is commercially available which automatically integrates temperature and time to give a direct output of maturity. Simple disposable temperature-dependent chemically based devices are also available for casting into surface zone concrete to give an approximate indication of maturity at early ages.

4.3.4 Temperature matched curing. (Figure 11)

This involves the use of a temperature sensor located at a critical position within the pour to control the temperature of a water tank in which standard concrete control specimens are placed. The curing regime of the specimens thus follows that of the pour as closely as possible and they may be tested by crushing as appropriate. British Standard BS1881pt 130 (1996) offers guidance on these procedures, and in particular emphasis the need for a record to be available of both pour and tank temperatures to ensure correct functioning of the equipment.

This technique can be extremely valuable in monitoring early age strength development in situations when this is critical to subsequent construction procedures. Particular care is necessary to establish the location of the controlling sensor since considerable within pour temperature differentials are likely to exist within the first few days from casting. The technique is also vulnerable to disruption by power failures or vandalism

5. EARLY AGE ASSESSMENT

Studies at Liverpool have demonstrated that surface hardness tests are unreliable at early ages, whilst ultrasonic pulse velocity measurements can yield good strength estimates but are limited to cases where access is available to two opposite faces for reliable measurements. Windsor Probe tests are quick and suitable for large members such as slabs, but have been shown to be unreliable at low strengths. Internal fracture tests are similarly unsuitable at early ages because of their high variability, whilst pull-off tests are liable to bonding problems at very early ages. Pull-out, maturity and temperature matched curing are clearly the most reliable and practicable tests for use at low strength levels – especially used in combination. This confirms findings of CIRIA Report 73 (1987) relating to assessment of formwork stiking times. Reliable results have been achieved with pull-out tests in particular at equivalent cube strengths as low as 2 N/mm^2 and at an age of 15 hours.

6. ANALYSIS OF RESULTS

Accuracy of insitu strength assessment will depend upon the variability of the test method and the reliability of correlations, but is unlikely to be significantly better than the values given in Table 2. (Note that 3 standard cores would give $\pm 7\%$).

Particular attention must be paid to the differences between laboratory conditions (for which correlation curves will normally be produced) and site conditions. Differences in maturity and moisture conditions are especially relevant in this respect. Also, the tests may not be so easy to perform or control on site due to adverse weather conditions, difficulties of access or lack of experience of operatives. Calibration of non-destructive and partially destructive strength tests by means of cores from the insitu concrete may often be possible and will reduce some of these differences, but is time consuming and disruptive since a wide strength range is desirable.

Accuracy of strength estimation may sometimes be improved by mathematical combination of results of two separate types of non-destructive or partially destructive tests, each with their appropriate strength correlations, although this approach tends not be used to any great extent in practice at present.

An examination of the variability of test results can provide valuable information. Even when few results are available, these can provide an indication of the uniformity of the construction and hence the significance of the results. Typical values of coefficient of variation.

$\left\{ = \frac{\text{Standard Deviation}}{\text{Mean}} \right\}$ are quoted above for results obtained from one location

on site for a well constructed member. Values significantly in excess of these are likely to indicate either deficiencies in testing or excessive material variability. The use of contour plots (figure 12) or histograms (figure 13) may be most useful when examining the variability and strength distribution within individual or similar members, but can only be applied when sufficient results are available.

The use of insitu strength test results poses problems in that specifications and calculations are almost always based upon characteristic strengths (f_{cu}) of standard specimens cured and tested at 28 days at 20°C under moist conditions. As discussed above, insitu results will be different from those achieved by standard specimens of the same concrete. In design, this is often allowed for by the use of a generalised partial factor of safety on concrete strength, but in practice, the differences vary according to member type and location within the member. Consequently, there is likely to be a considerable 'unproven' zone when considering strength specification compliance, even when test locations have been selected to give representative results for the member.. The number of insitu test results will seldom be sufficient to permit proper statistical analysis to determine the appropriate characteristic value. Hence, it is better to compare mean insitu strength estimates with the expected mean 'standard' test specimen result. This requires knowledge or an estimate of the likely standard deviation of standard specimens and is considered more fully by Bungey and Millard (1996) and CIRIA TN 143 (1992).

$$f_{mean} = f_{cu} + ks$$

where s = standard deviation of samples
k = a factor depending upon the confidence limits required and the number of samples tested

If a large number of results are available. k = 1.64 for 95% confidence limits. (If only a small number of results are available, the value of k increases substantially, e.g. for 4 results, k = 4.00, and for 8 results k = 2.23). ACI 228.1R provides more detailed information on statistical analysis.

Insitu strength values measured at a critical location for calculations of structural adequacy are similarly best used in the form of a mean value from the location with a factor of safety applied to this to allow for test variability, lack of concrete homogeneity and future deterioration. A factor of safety of not less than 1.2 is recommended by BS6089 for general use. If there is particular doubt about the reliability of the test results, or if the concrete tested is not from the critical location considered then it may be necessary to adopt a higher value.

7. REFERENCES

B.S. 1881 pt120 (1983): "Testing Concrete - Method for determination of compressive strength of concrete Cores".

B.S. 1881 Pt 207 (1992): "Testing Concrete – Recommendations for the assessment of concrete strength by Near-to-Surface Tests".

B.S. 6089 (1981) "Guide to the Assessment of Concrete Strength in Existing Structures".

B.S. 1881 pt 130 (1996): "Method for Temperature Matched Curing of Concrete Specimens".

Bungey, J.H. and Millard S.G. (1996): "Testing of Concrete in Structures" Blackie, 3rd ed, 286p.

C.I.R.I.A. TN143 (1992): "Testing Concrete in Structures" 87p.

CONCRETE SOCIETY TR11 (1987): " Concrete Core Testing for Strength", 58p.

ACI 228.1R (1995): "In place methods to determine concrete strength"

ASTM C1074 "Estimating concrete strength by the maturity method"

CIRIA Tech Rep73 (1987) "Formwork Stiking times – methods of assessment (Harrison T A) 40p

Method	Damage Level	Classification	Application
Cores	Significant	Sample for Laboratory testing	Localised Insitu Strength Assessment
Penetration Resistance Pull-out Internal Fracture Pull-off Break-off	Localised to surface zone	Partially Destructive	Surface zone Strength Assessment
Re-bound Hammer Ultrasonic Pulse Velocity	Minor surface marking or staining	Non-Destructive	Comparative Strength Survey
Maturity Measurement Temperature matched curing	Very minor	Non-Destructive	Insitu Strength Development Monitoring

TABLE 1 Summary of Strength Assessment Methods

Test Method	No. of individual results required to give mean value for a location	Useful Cube Strength Range (N/mm^2)	Likely 95% confidence limits for strength estimation with appropriate correlation	Correlation requirements	Minimum test spacing centre - to - centre (mm)	Minimum thickness of concrete (mm)
Penetration Resistance (Windsor Probe)	3	8-50	$\pm 20\%$	Specific to aggregate	200	150
Pull-out Cast-in (Lok)	4	1.5 - 130	$\pm 20\%$ $\pm 10\%$	General for natural aggregates Specific to mix	200	100
Drilled (Capo)	4	8 - 55			200	100
Drilled (Internal Fracture)	6	8 - 40	$\pm 30\%$	Specific to loading method and concrete type	150	75
Pull-off (Surface or partially-cored)	6	7 - 45	$\pm 15\%$	Specific to mix, test type, and disk details	100 (50mm dia. Disks)	75
Break-off (drilled or formed)	5	4 - 65	$\pm 20\%$	Specific to mix and test type	108 (20mm agg.)	100

TABLE 2 Some Features of Principal Partially Destructive Tests

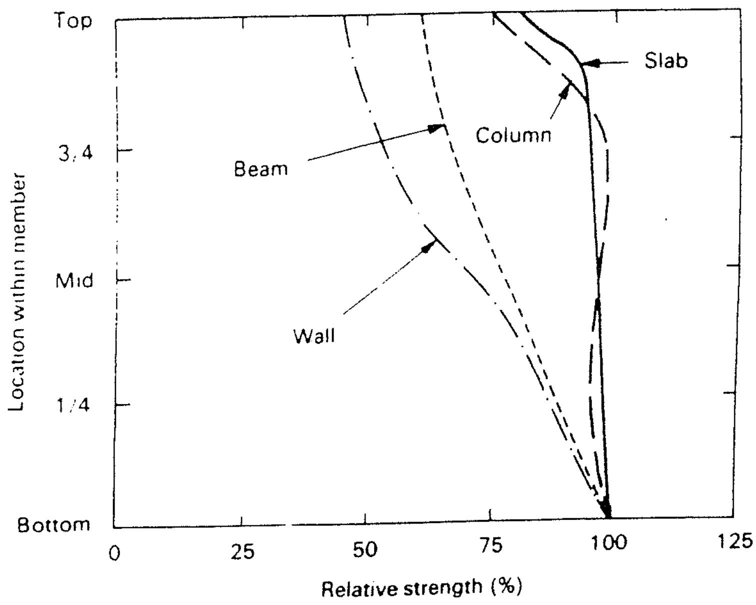

Fig 1. Typical Within-Member Strength Variations

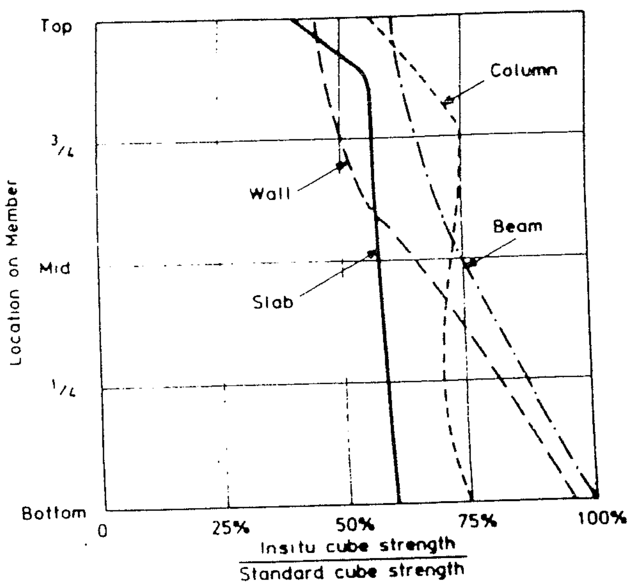

Fig 2. Typical Relationships between Insitu Strength and Standard Cubes

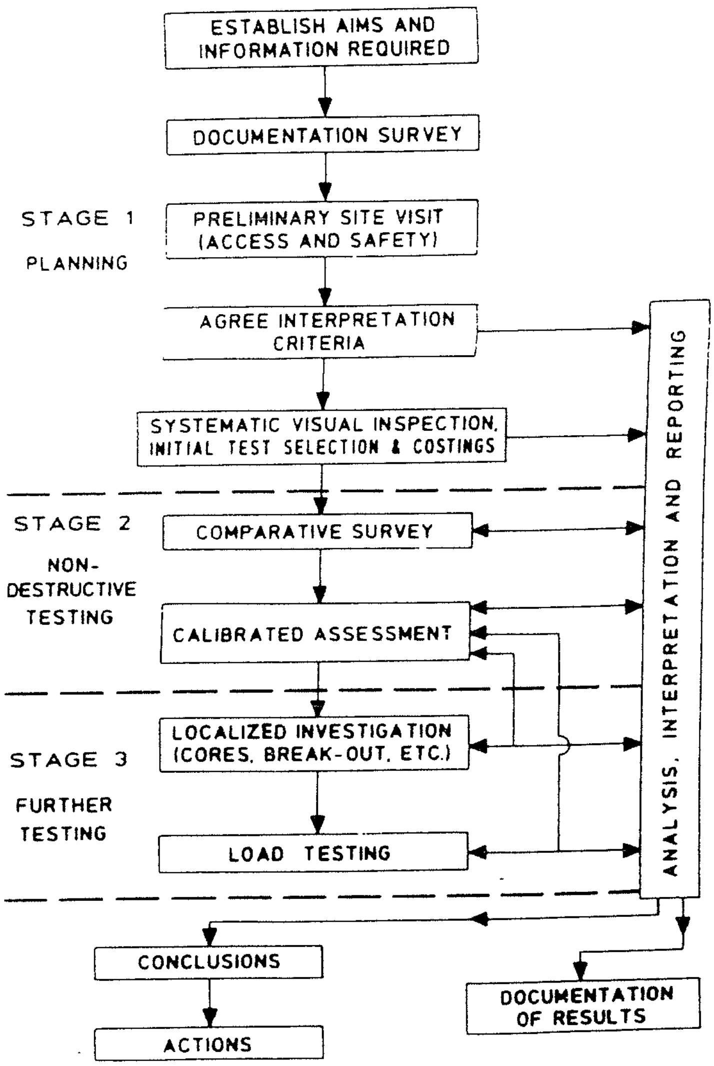

Fig. 3 Typical Stages of Test Programme

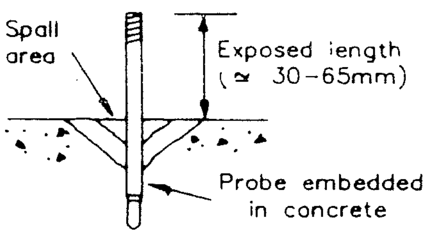

Fig. 4 Windsor Probe

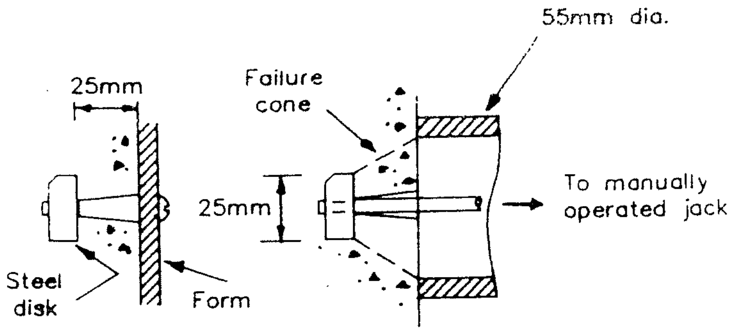

Fig. 5 Lok-Test

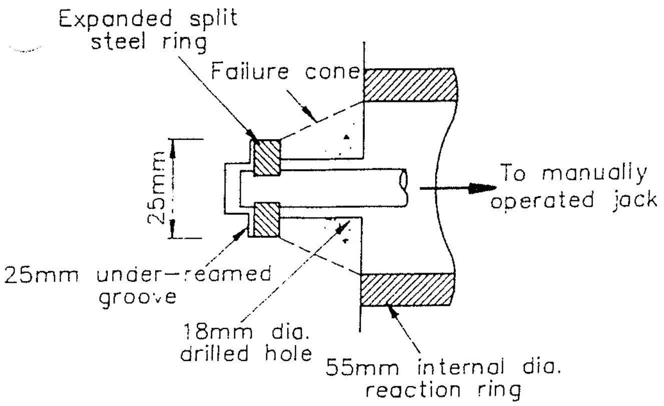

Fig. 6 Capo Test

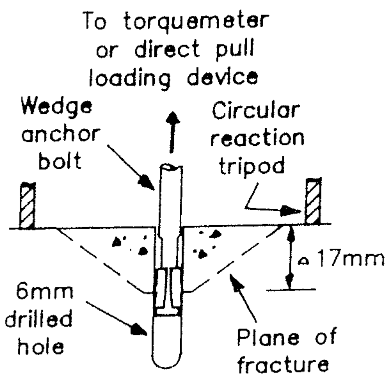

Fig. 7 Internal Fracture

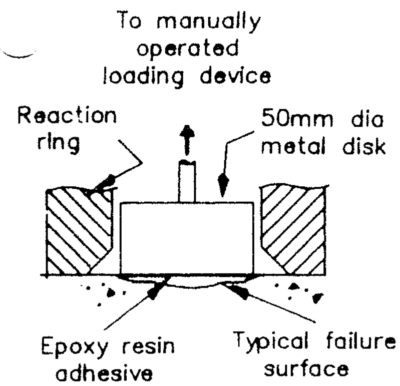

Fig. 8 Pull-Off

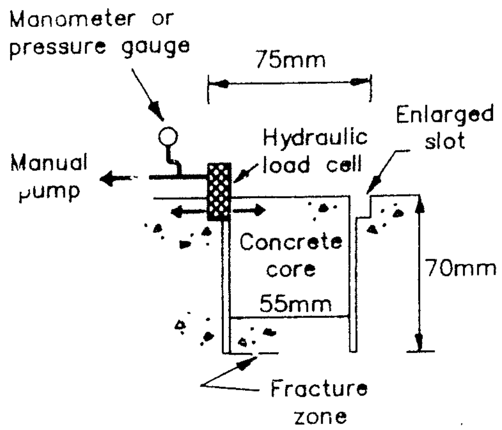

Figure 9. Break-Off

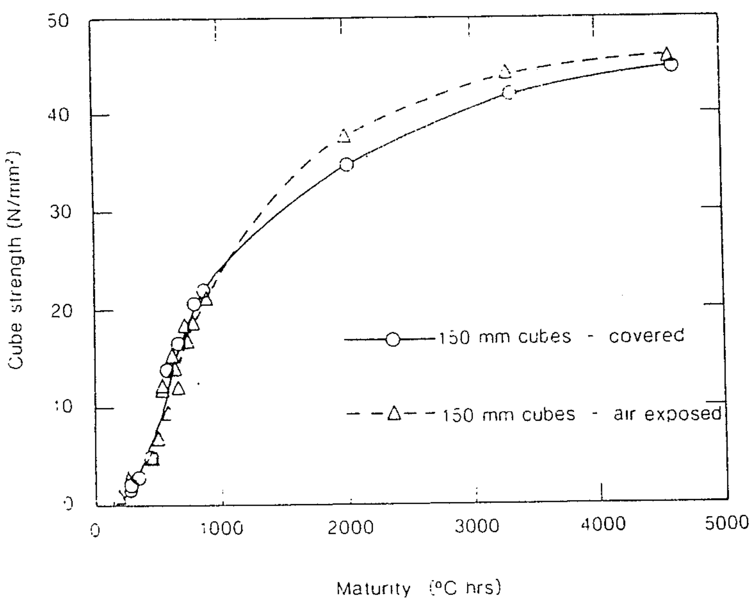

Fig. 10 Typical Strength-Maturity relationship

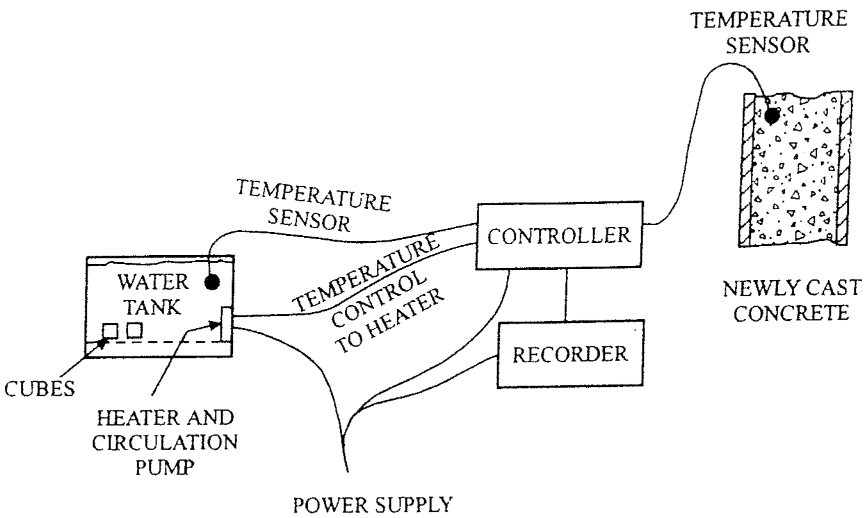

Fig. 11. Temperature-Matched Curing

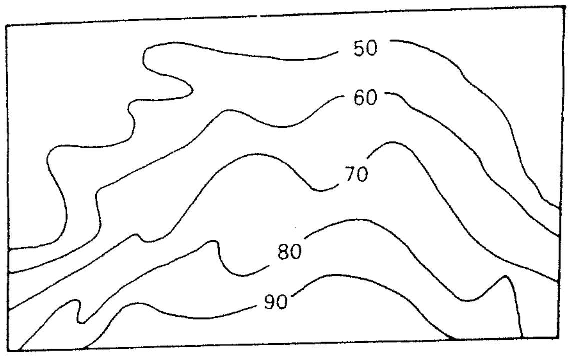

Fig. 12 Typical relative percentage strength contours for a wall

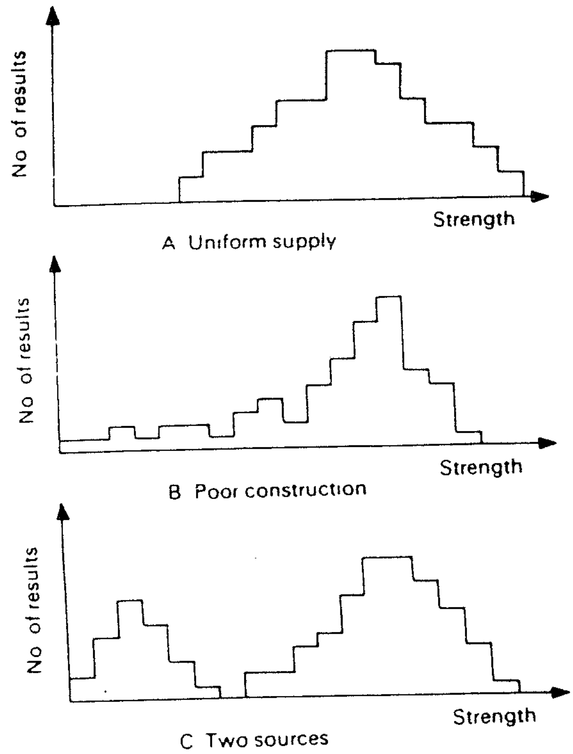

Fig. 13 Typical histogram plots of in-situ test results