Reliability Of Partially Destructive Tests To Assess The Strength Of Concrete On Site

By J. H. Bungey and M. N. Soutsos

Synopsis: The range of available tests for assessing the strength of insitu concrete based on measurements of surface zone properties is examined, together with developments in supporting documentation. Attention is concentrated upon a number of recent research programmes, including work undertaken as part of the European Concrete Building Project. These focus primarily upon pull-out and pull-off techniques and encompass applications to early age strength assessment, lightweight and high strength concretes, and testing of repairs.

Keywords: Concrete; Early-age; In-place; Near-surface; Partially-destructive, Strength; Testing; Variability.

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INTRODUCTION

There has been recognition of the need to test in-place concrete to estimate strength for more than 70 years, but it is in the last 30 years that the most significant developments of commercially available systems have occurred. Dozens of techniques have been proposed in an attempt to overcome the problems of damage and time associated with cutting, preparation and testing of cores.

Whilst acceptance testing of concrete has traditionally involved compression testing of cylinders or cubes, these may not adequately reflect the compaction or curing received by the insitu concrete and, of necessity, relate only to a small proportion of the concrete placed. In-place testing may be used to overcome some of these difficulties. In the majority of current applications, however, testing is for one or two reasons:

- Evaluation of an existing structure (new or old).
- Monitoring strength development during new construction.

Use of in-place tests for acceptance is, at present, limited but increased awareness of the importance of the surface zone in terms of durability has stimulated interest.

A number of test methods have become established, and standardised either in Europe or North America, which involve the measurement of a surface zone property which can then be related to strength by means of an appropriate correlation. They typically cause localised surface damage which, although less than that associated with cores, must be considered at the planning stage. Consequently the term 'Partially-Destructive' is sometimes used to describe these methods.

Research at the University of Liverpool has focused over recent years upon the interpretation of results provided by a number of these methods, including correlation procedures, and taking account of within member strength variations. This work has encompassed both laboratory and field studies and has considered the suitability of techniques for:

- Early age testing.
- Use with 'normal concretes' with a range of aggregate types.
- Use with Lightweight and High Strength concretes.
- Testing repairs.

The scope of these investigations and key findings are considered in this paper, together with future prospects for this group of techniques.

AVAILABLE TESTS AND DOCUMENTATION

Principal test methods are described and discussed in detail by the Principal Author [1] and the American Concrete Institute [2] together with other related techniques. Surface zone insitu strength tests which are standardised in the USA and UK are listed in Table 1 together with an indication of key features, whilst those forming the basis of this investigation are briefly detailed below. Standards for many of these techniques also exist in other countries. It should be noted that Break-off methods have received little attention in the UK and are not considered in this paper.

Rebound Hammer - This simple test is probably the most widely known and most commonly used of all the test methods. It involves an assessment of localised surface hardness by means of a hand-held mechanically operated device, although electronic digital-recording versions are available [3]. Energy levels are relatively low and this method is very sensitive to a large number of factors which effectively limits usage to comparative applications for which it is a valuable preliminary to other forms of testing.

Probe Penetration Resistance - Measurements are made of the depth of penetration of a metal rod or pin that is forced into the surface of the hardened concrete by a driver unit. This is available in two basic forms:

- *Pin-penetration test* in which a 3.56mm diameter hardened steel pin is driven by a spring-loaded device to create a hole up to 7.6mm deep in the mortar. This is not recommended [2] for compressive strengths above 28MPa.
- *Probe-penetration test*, commonly known as the 'Windsor Probe' test in which a larger rod (6.35mm diameter for normal weight concrete) is fired from a specially designed gun using a smokeless powder charge producing a constant energy level. Penetration may be up to about 40mm depending upon the strength of the concrete and correlations to compressive strength are known to be influenced by aggregate hardness. Measurements are usually based on the exposed probe length.

Theoretical analysis is complex and relates to the absorption of the initial kinetic energy by the concrete. No rigorous studies have been reported, but it is generally accepted that most energy is absorbed by a cone-shaped fracture zone as illustrated in Fig. 1. There may be a risk of cracking slender members and safety regulations may apply.

Pull-Out - Measurements are made of the force required to pull an embedded metal insert with an enlarged head from a concrete surface. The pulling load is applied by a tension jack bearing against the concrete surface through a reaction ring concentric with the insert. Failure involves the fracture, and often removal, of an approximately cone shaped portion of concrete. A common feature of pull-out tests is that correlation with compressive strength is relatively insensitive to mixture characteristics such as cement and aggregate type (except lightweight), size and proportions. They are thus particularly useful when assessing a concrete of unknown composition.

Several forms of this type of test have been developed:

- *Internal fracture test* developed in the UK in which a 6mm diameter expanding wedge anchor bolt is inserted to a depth of 20mm in a predrilled hole as shown in Fig. 2. The pulling force may in this case be provided by a torquemeter device. The method was developed specifically for testing existing slender prestressed concrete elements and although the equipment is inexpensive and relatively quick to use, variability is high.
- *Lok-test* which has emerged as the most commonly used technique involving an insert placed in the concrete surface during construction. This may be fixed to formwork or a flotation cup and the head will typically be located 25mm below the surface. The basic configuration is shown in Fig. 3. Preplanning is obviously required, thus restricting the method to new construction. Many studies have been undertaken to analyse theoretically the mechanisms associated with this test, but there is no firm agreement concerning that governing the ultimate failure load. It is generally recognised however that well defined experimental correlations can be established with compressive strength. The method is particularly suitable for strength development monitoring.
- *Capo-test* has been developed as a version of the Lok-Test that can be applied to existing concrete. Drilling and under-reaming operations are required to provide a groove into which a compressed steel ring can be expanded to provide a similar test configuration, see Fig. 4. Load is applied by means of a similar jack, but the test is obviously slower to perform. It is claimed however [4], that identical correlations with compressive strength may be utilised.

Pull-Off - This measures the direct tensile force required to pull a metal disk, together with a layer of concrete, from the surface to which it has been bonded. Where it is desired to avoid surface effects, such as carbonation, the failure may be caused at some depth below the surface by partial coring, see Fig. 5. This method is particularly suitable where a tensile strength value is required, such as testing bonding of repairs, but may be correlated empirically to compressive strength for a particular mix. Many forms of this test are available commercially [3] but that most widely used in the UK is the 'Limpet' system developed at The Queens University of Belfast.

Temperature Measurement Methods - Although outside of the scope of this paper, attention must be drawn to the maturity method (ASTM C 1074) in which insitu strength may be estimated on the basis of a time and temperature maturity function for a specific concrete mixture. This is particularly suitable for strength estimation at early ages and most commonly utilises a temperature sensor located at an appropriate position within the pour, although chemically based inserts (COMA-meter) are also available. In the UK, attention has also been paid to Temperature Matched Curing (BS 1881 pt 130), in which cubes are stored in a water-tank whose temperature is controlled by a sensor in the pour to ensure an identical temperature history to the insitu concrete. Both of these methods suffer potential practical disadvantages including vulnerability to power supply failure or vandalism [5], but may be particularly useful when used in combination with other tests, the pull-out method in particular.

STRENGTH DEVELOPMENT MONITORING

Two major programmes involving field testing have been undertaken to assess the suitability of different test methods for early age testing.

Cooling Tower Study

This was aimed primarily at cooling tower construction with site work at Drax in North Yorkshire supported by extensive laboratory work. The objective was to enable formwork to be removed with confidence, even in cold weather, to enable construction schedules to be maintained. These studies demonstrated that surface hardness tests are unreliable at early ages, whilst ultrasonic pulse velocity measurements can yield good strength estimates but usage is usually limited by the need for access to two opposite forces for reliable measurements. Penetration resistance (Windsor Probe) is quick and suitable for large members such as slabs, but was shown to be unreliable at low strength values. Internal fracture tests are similarly unsuitable at early ages because of their high variability. It was concluded [5] that pull-out testing, maturity testing and temperature matched curing are the most reliable and practicable techniques for use at low strength levels, although it should be noted that pull-off tests were not considered in this programme.

Pull-out (Lok) tests were conducted through cut-out panels in the timber shutters on 175mm thick wall panels at ages commencing at 15 hours. On site, tests were performed in groups of three within 400 x 250mm removable formwork panels. This dimension was constrained by formwork design considerations and limited the clear spacing between inserts to 165mm. This is less than the minimum recommended by Standards, but trials indicated that at the low strength levels associated with such tests no significant influence was detectable. In the laboratory, wall panels 1.5m high and 2.0m long with the same thickness and identical reinforcement were fabricated. In this case pull-out tests were made through individual circular cut-out panels at each test point.

Correlation tests were made on 225mm cubes to give adequate edge distances, in conjunction with 150mm cubes for crushing at strengths as low as 1MPa. Tests were performed on all 6 faces of the 225mm cubes and analysis showed that mean values were virtually identical to those obtained if the top and bottom surface tests were discarded. Variability within the group of results was however greater than when just the 4 side faces were considered. Correlations were achieved by testing the gravel aggregate mixtures at varying ages, and by varying the mixture designs. Results of these tests are shown in Fig. 6a in which each correlation point represents the average of 6 Lok-tests and 3 cube compressive strengths. For strengths up to 10MPa, all points lie within 1MPa of the mean line, but at higher strengths the sensitivity of the pull-out force to changes in cube strength is reduced and scatter increases. A further feature of concern was that the time taken to carry out a test at very low strength may be significantly less than that specified by Standards. This was addressed by comparative tests on 225mm cubes which indicated that neither magnitude of force nor variability will be affected provided the load rate is such that the test exceeds 20 seconds.

Wall-pour results shown in Fig. 6b represent the average of 6 Lok-tests together with cube strength values estimated from maturities computed from appropriately located temperature sensors using a temperature-time factor with -11^{0}C datum [2]. The generally close agreement between both laboratory and site wall pour results and correlation tests, especially at very low strength levels, can be seen and is most encouraging given the uncertainties introduced by the use of maturities in determining insitu strengths. It is surprising to note that the greatest discrepancies, which cannot be easily explained, occur with the laboratory wall panels whilst on site no strengths of less than 10MPa were encountered despite cold weather. A key feature emerging from the insitu temperature measurements was the extent of the in-place differentials across the height of the wall. The peak temperature was found to occur at approximately mid-height of the 1.5m high lift at about 12-15 hours after casting. This was typically 20^{0}C higher than that experienced 100mm below the top surface of the pour and will lead to significant early age strength differences.

Cardington Study

This recent study has been based on the European Concrete Building Project at the Cardington Laboratories of the Building Research Establishment in the UK. This project involved the construction of a 7 storey insitu reinforced flat slab building frame, Fig. 7, utilising a range of construction methods with the aim of improving speed, reducing costs and improving the quality of such construction. See http://www.bre.co.uk/bre/cardington/cardlab1.html for further details on this project. The structure provided the basis for a number of construction-phase research projects including that undertaken jointly by the University of Liverpool and Queens University of Belfast [6]. In this project, pull-out testing was extended to include the Capo-test and the Pull-off test was also considered, supported by maturity measurements and temperature matched curing to assist insitu strength estimates. Air-cured and water cured cubes were also available, with results for early ages in addition to 28 days to support the aim of seeking to estimate 28 day strengths from early age insitu tests, as well as enabling comparisons of insitu strengths with cubes experiencing differing curing regimes.

A range of concrete mixtures incorporating different aggregate types (Gravel and Limestone) and admixtures (plasticiser and superplasticiser) with nominal cube compressive strengths of 37 and 85MPa were used. The six different mixtures covered in this study are detailed in Table 2. Some adjustments were made during construction by the concrete supplier to maintain target mean strengths (C37N-10 and C37N-11), as is common practice during construction of a large project.

Tests were performed on columns at different heights (top, middle and bottom), and on slabs, both adjacent to columns and in mid bay (top and soffit). The selected test methods were each used at similar locations to permit comparison of their practicality on site; for example speed, relative cost, disruption and accuracy, and to assist determination of an optimum balance between insitu and cube testing.

The insitu tests using the Pull-off, Lok and Capo methods, were undertaken at 1 day (or as soon as practicable), 3 days, 7 days and 28 days after casting. Temperature measurements were available from the time of casting at several locations on columns at a depth of 25mm below the surface and on slabs at 25mm above soffits and 50mm below top surfaces. Results for corresponding temperature-matched cured cubes were based on sensors at a depth of 50mm below the tops of slabs midway between columns. High strength Lok-test inserts uniformity of stress distributions at the base of the cored portion, although this may be reduced for steel disks.

These results were obtained from extensive laboratory experimental studies, supported by finite-element modelling. It is thus particularly important that only standardised equipment is used or alternatively that the configuration is specified together with the minimum acceptable test value. A laboratory based study in the USA [14] has also confirmed the suitability of the method for assessing the bonding of highway overlays, and the effects of freezing and thawing cycling and de-icing salts.

DISCUSSION

The results presented have confirmed that pull-out and pull-off tests can be successfully applied to concrete in structures to yield estimates of insitu strength. The pull-out method in particular offers advantages of being able to utilise a general strength correlation as provided by the Manufacturer. Concrete mixtures used on site may not be finalised until just before the start of construction, thus hampering the development of specific correlations. Similarly, with existing concrete precise details of the composition may be unknown and expensive, disruptive coring may be the only effective means of producing a specific correlation.

For new construction, the Lok-test has been shown to be easy to use and reliable over a very wide range of strengths. If it is possible to develop a specific strength correlation, possibly during construction, this may be used to improve the accuracy with which insitu strength estimates may be made. For lightweight concretes a general correlation based on Fig. 16 can be used, noting that this is different to the Manufacturer's correlation which relates only to concretes made with dense natural aggregates.

When testing is required on existing structures Windsor Probe, Pull-off and Capo tests may be considered. Although simple to use, the Windsor Probe requires specific correlation for the aggregate and doubts have been cast upon reliability both at low strength levels and above 50MPa. Pull-off tests require surface preparation and careful bonding but are otherwise quick and straightforward to use. Specific correlations must be developed for the concrete under investigation, but the work at Cardington has confirmed that concrete with strengths up to 100MPa can be successfully tested with strength estimation accuracies generally of the order of ±10% based on the average of 6 No. tests. This value is comparable to that associated with pull-out tests (4 No.) using specific correlations. Capo-testing is not simple and requires considerable skill to successfully perform the coring and under-reaming operations. Nevertheless it is most encouraging that work reported here confirms the ability to use the same general correlation as the Lok-test with similar likely accuracies (±20% based on 4 No. results). This method thus offers the significant benefits noted above associated with the ability to avoid the development of a specific strength correlation. It can also be used as a back-up to the Lok-tests, if required, but the need to use a covermeter to avoid reinforcement should be noted.

The application of statistics to assess the reliability of insitu strength estimates is fraught with difficulties. This issue has been considered at length by Carino and others in the USA with findings summarised by ACI 228 [2]. The subject has also been considered by RILEM Committee TC 126-In Place Testing. Unfortunately there are seldom enough in-place test results to establish statistical confidence, whilst the number of strength levels available when preparing a strength correlation will have a large effect upon the uncertainty of estimated strength. ACI 228 [2] recommend that six to nine strength levels should be used in performing correlations, providing a balance between precision and cost. Work at Cardington has highlighted the difficulties of achieving this in practice, even on a carefully planned project. Where it is necessary to develop correlations from cores taken from an existing structure, the difficulties escalate. Few reports exist of reliable and systematic comparisons of in-place tests with cores taken from structures [4], thus it has to be recognised that commonly quoted 'accuracies' are effectively based on confidence limits (typically 95%) of laboratory correlations. It may well be that it would be more realistic to quote 'lower-bound' estimates of insitu strength.

The work described above has further highlighted the significance of insitu strength variations due to location within an element. This effect is especially marked at early ages due to temperature differentials, and must be considered when establishing test locations. Care must be taken when using large correlations specimens (eg. 200mm cubes) to ensure that temperature histories match those of specimens used for crushing (eg. 100mm cubes).

The use of early age tests to predict later age strength is potentially a valuable application of testing. Analysis of results from the Cardington Project continues, but preliminary findings suggest that predictions based on Lok-tests at 3 days may be sufficiently accurate to identify situations requiring remedial action. If combined with maturity measurements, confidence in later age predictions can be increased.

It is clear from the Authors' experience that simplicity is the key to increased usage of in-place testing. Combining methods can be valuable, especially at early ages (eg. maturity and pull-out) but can seldom be justified except on major projects. Bickley [15] has demonstrated the economic benefits of in-place testing during new construction, and experience both at Drax and Cardington has confirmed the value of testing in conjunction with formwork renewal and speed of construction. It is in this area that the greatest scope for increased usage lies at present, since in most parts of the world there is little will to move away from cube or cylinder testing for acceptance purposes.

CONCLUSIONS

It has been demonstrated that Partially-Destructive tests provide a viable approach to estimation of insitu concrete strength for a range of concrete types and circumstances. Cast-in pull-out tests have been shown to be particularly suitable, both in terms of ease of test and reliability, for early age testing. Pull-out and Pull-off tests may also be reliably applied both to lightweight and high-strength concretes in structures. The Pull-off test, with partial coring, is valuable in assessing the bonding of repairs but results may be influenced by the test configuration.

Development of a reliable correlation with compressive strength is a critical aspect influencing reliability of insitu strength predictions, which are difficult to define statistically. Use of results of inplace testing must furthermore take account of insitu strength variations, including surface/interior effects.

Results confirm that the drilled version of the pull-out method (Capo-test) produces results which may be regarded as comparable to the cast-in version (Lok-test) and this may be a worthwhile method to use when assessing unknown existing concretes.

There is considerable scope for future development and usage related to new construction, where test simplicity and reliability are the key issues. Long-term strength predictions from early age Partially-Destructive tests alone are not yet, however, regarded as sufficiently accurate for acceptance purposes.

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Table 1 STANDARDISED TEST METHODS

Method	Standards		Principal Features
	ASTM	BS 1881	
Rebound Hammer	C805	202	Existing concrete, best used comparatively.
Probe Penetration	C803	207	Existing concrete, pin or probe. Strength correlation specific to aggregate.
Pull-Out			
Internal Fracture	-	207	Existing concrete, high variability.
Cast-in	C900	207	New construction (Lok-test) - general strength correlation possible.
Drilled	C900	207	Existing concrete (Capo-test) care with drilling and underreaming.
Pull-off	-	207	Existing concrete, surface or partially cored, care with bonding, strength correlation specific to mix.
Break-off	C1150	207	New construction (formed) or existing concrete (drilled), strength correlation specific to mix and test type.

Table 2 CONCRETE DETAILS

	CONCRETE TYPES AND DRY BATCH WEIGHTS (per m^3)					
	C85MS Microsilica	C85MK Metakaolin	C37N-10 Normal	C37N-11 Normal	C37P Plasticised	C37F Flowing
Location	Columns	Columns	Columns	Columns & Slab	Slab	Slab
Portland Cement (kg)	400	400	380	355	330	335
Sand (kg)	732	717	755	785	815	810
5-20mm Coarse Aggregate (kg).						
Limestone	1170	1146				
Gravel			1025	1025	1010	1010
Admixtures (ml)						
Plasticiser	1232	1232			990	
Superplasticiser	8800	8800				5000
Cement Replacements (kg)						
Microsilica	40					
Metakaolin		40				
Free W/C	0.25	0.32	0.50	0.53	0.52	0.52
Target						
Slump (mm)			100	100	100	
Flow (mm)	550	600				550

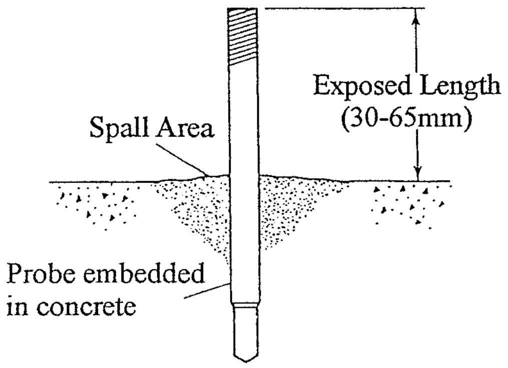


Figure 1: Probe Penetration Test.

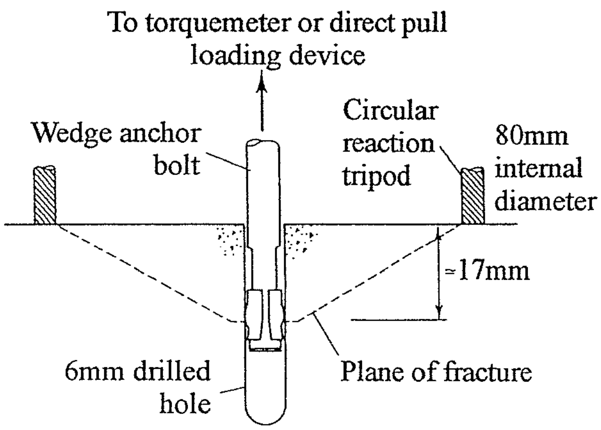


Figure 2: Internal Fracture Test.

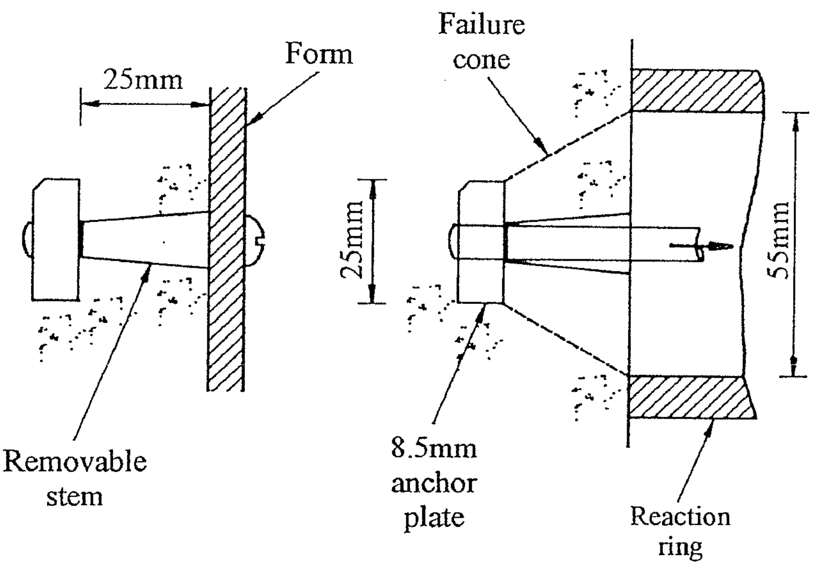


Figure 3: Pull-out (Lok) Test.

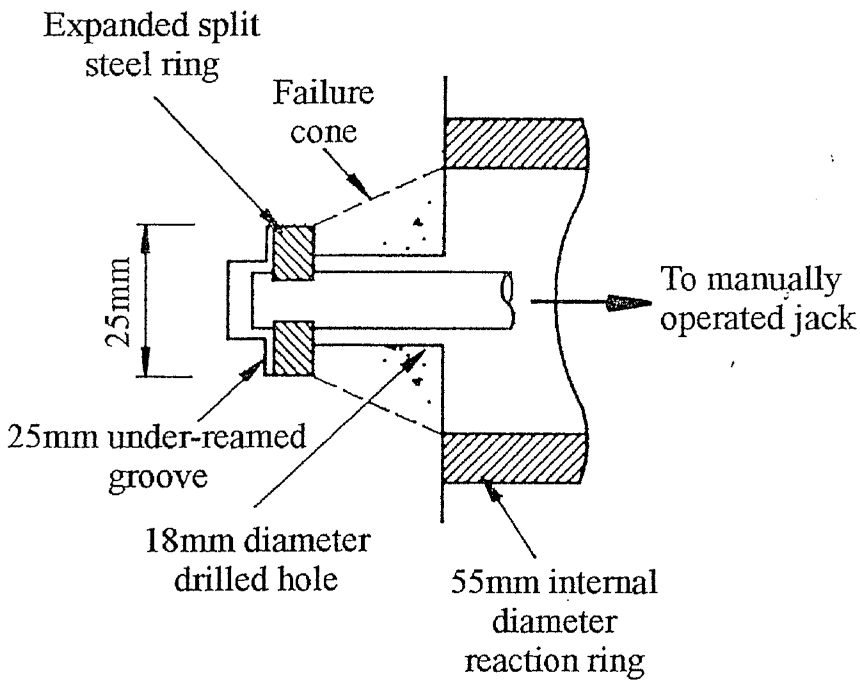


Figure 4: Pull-out (Capo) Test.

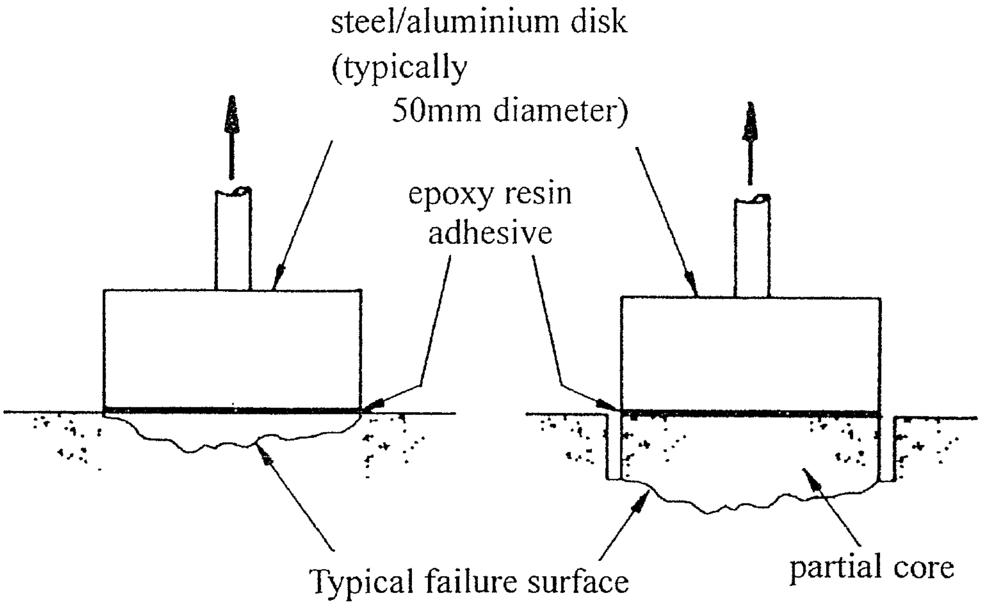


Figure 5: Pull-off Test.

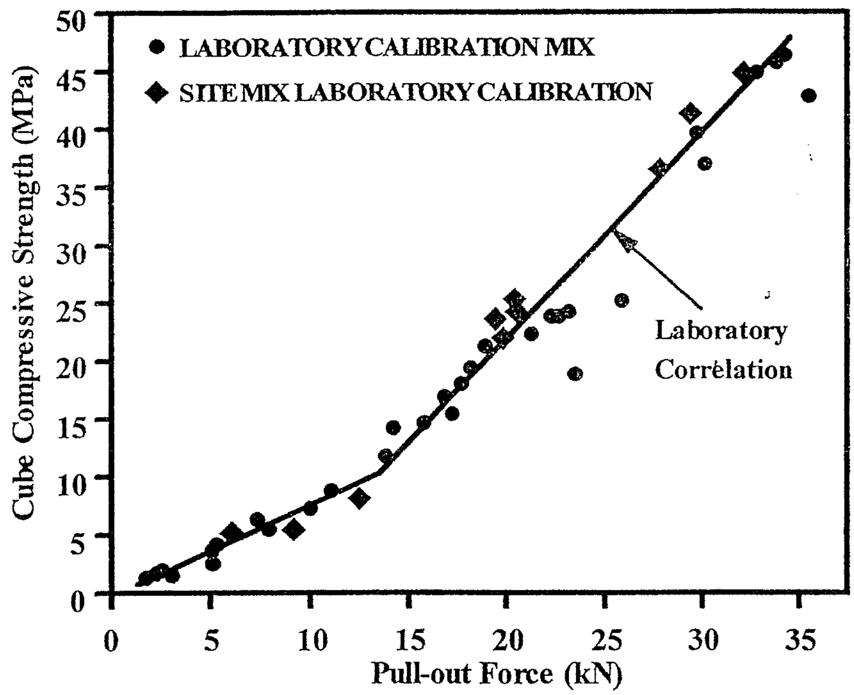


Figure 6a: Laboratory Pull-out Strength Correlation.

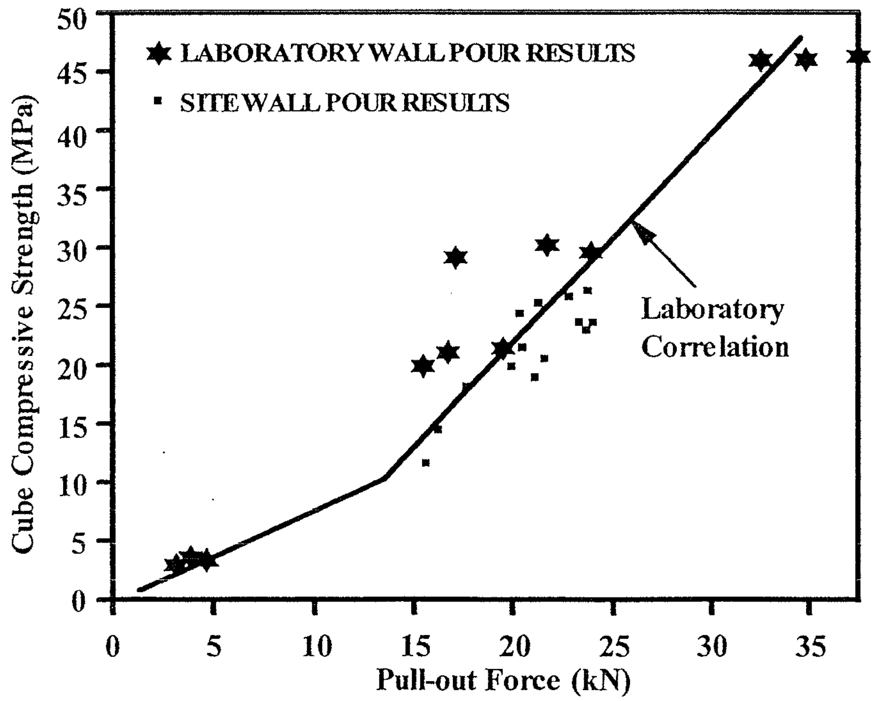


Figure 6b: Site and Laboratory Wall Pour Pull-out Results.

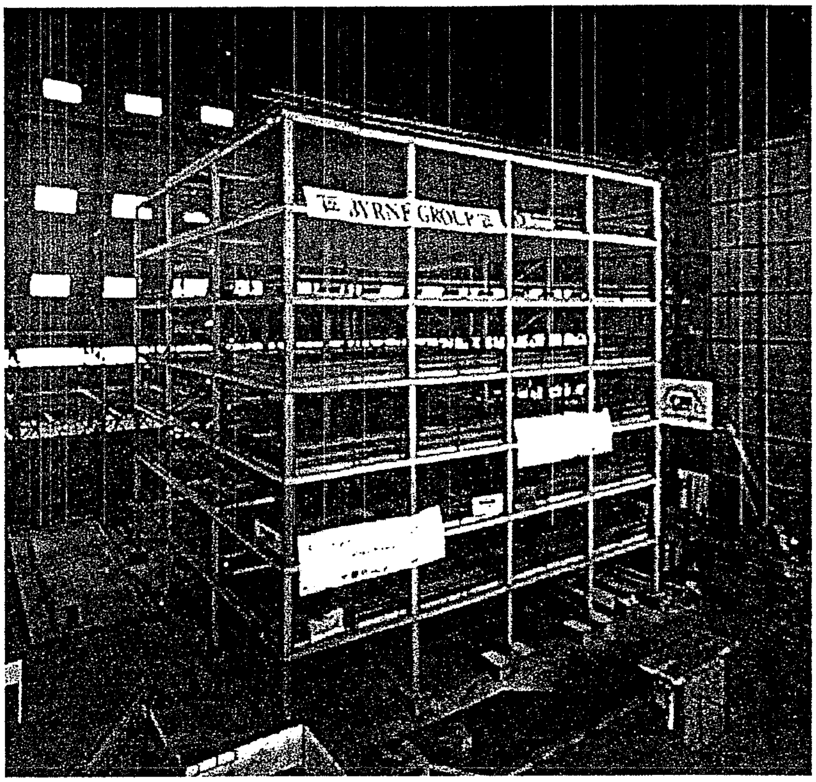
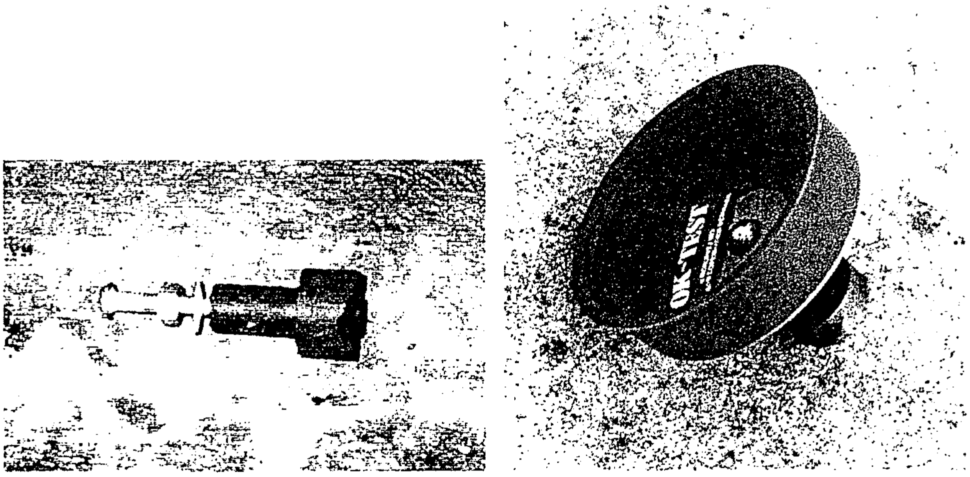


Figure 7: Cardington Insitu Concrete Building.



(a) High strength Lok-Test Insert. **(b) Flotation cup.**

Figure 8:Lok-Test Inserts.

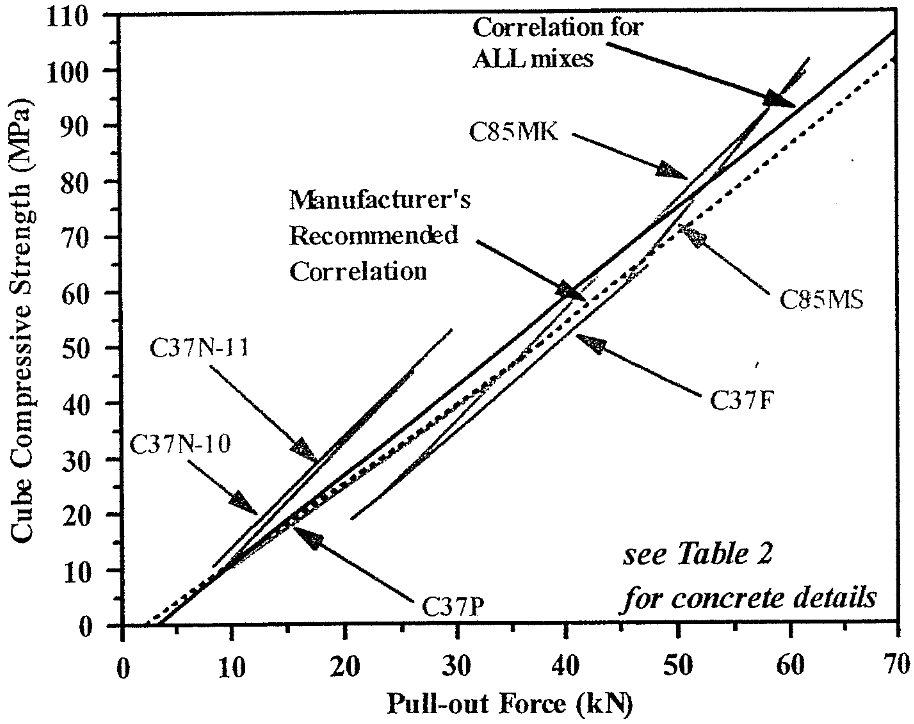


Figure 9: Lok-test strength correlations.

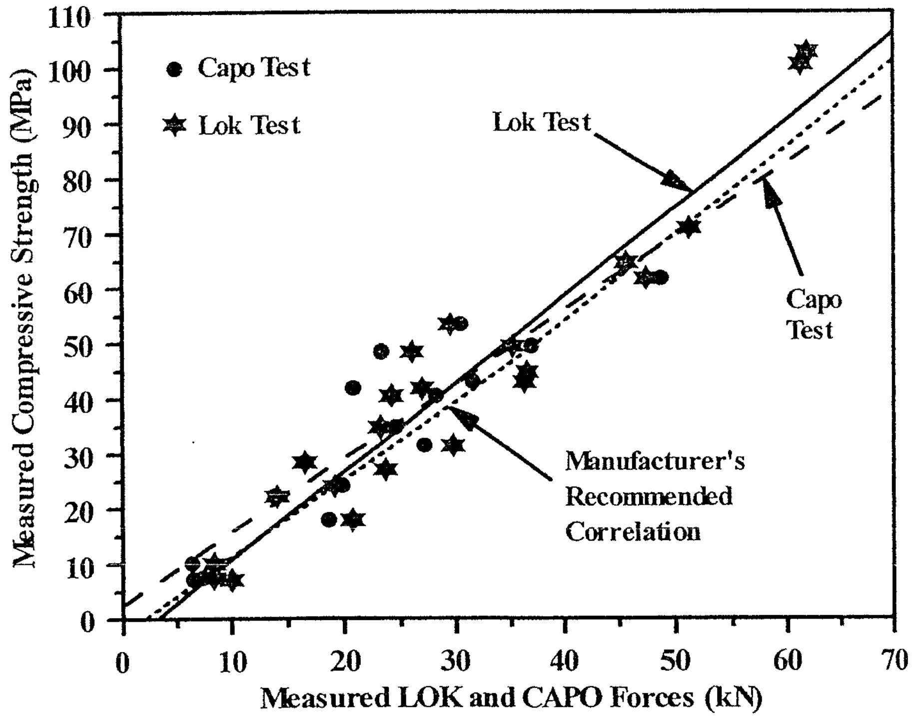


Figure 10: Lok and Capo-test strength correlations.

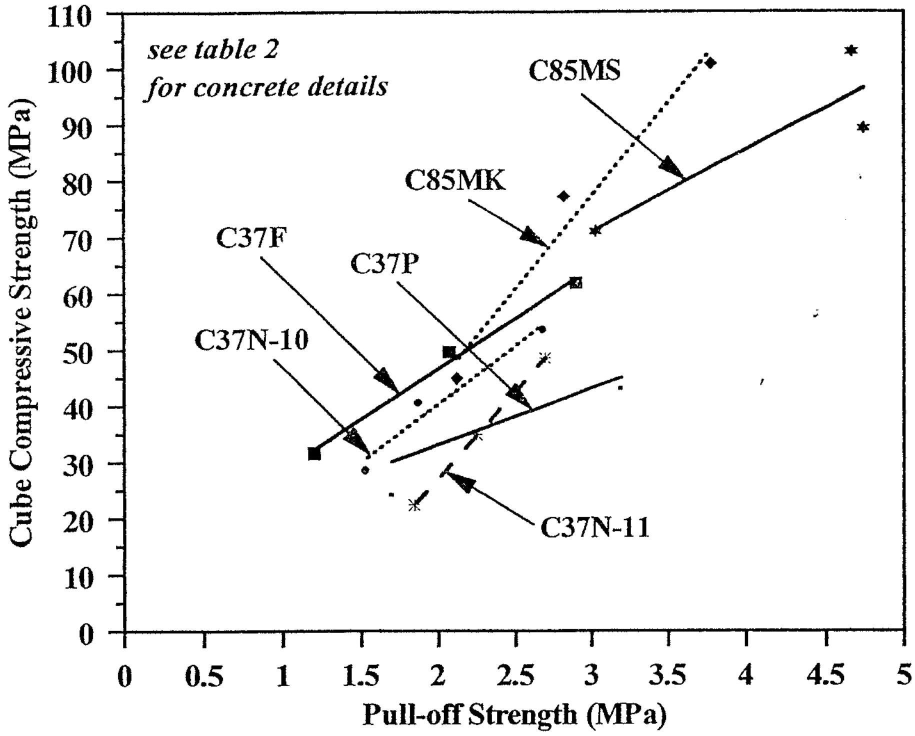


Figure 11: Pull-Off Test Strength Correlations.

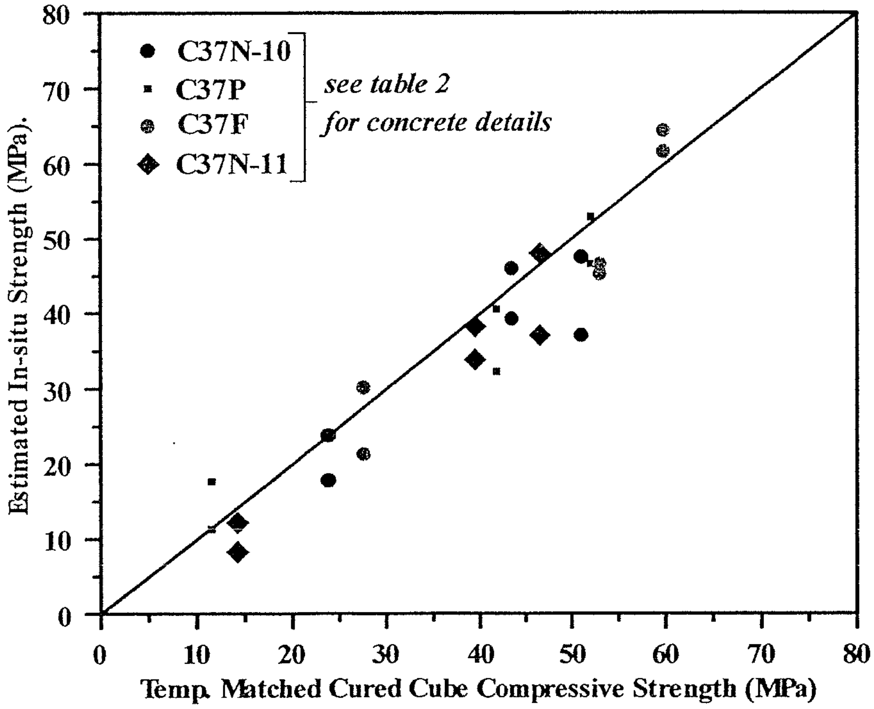


Figure 12: Insitu strength (Lok-test) versus Temperature Matched Cube results.

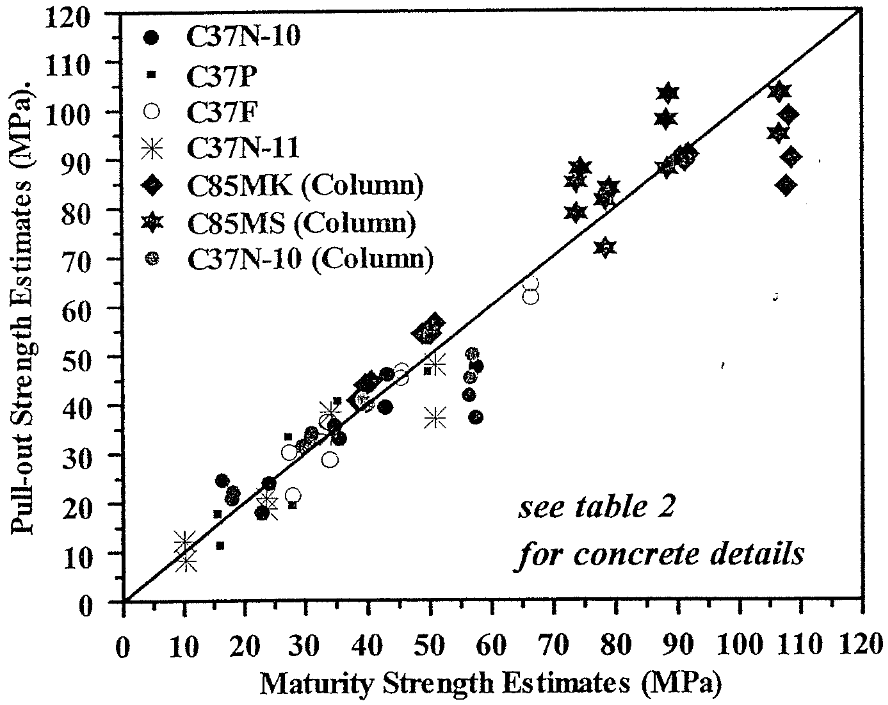


Figure 13: **Insitu strength (Lok-test) versus insitu strength (Maturity).**

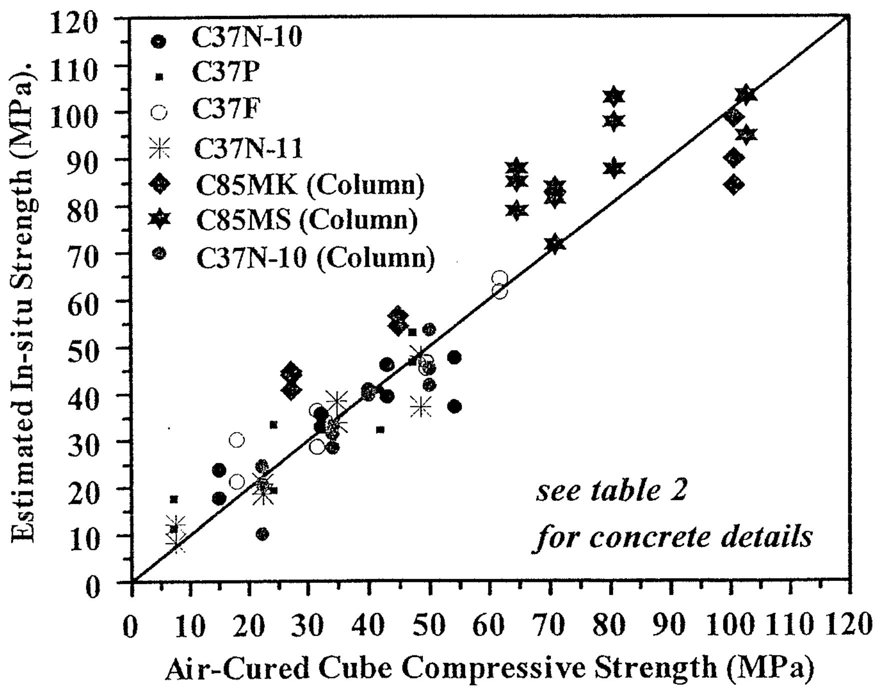


Figure 14: **Insitu strength (Lok-test) versus Air-Cured Cube Strength.**

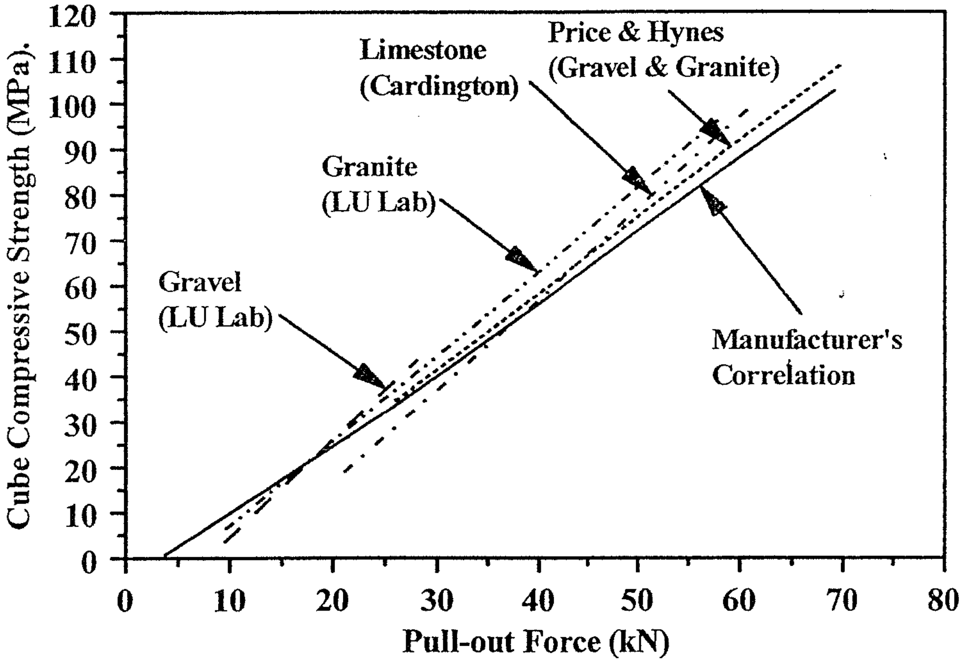


Figure 15: Lok-test strength correlations for high Strength Concretes

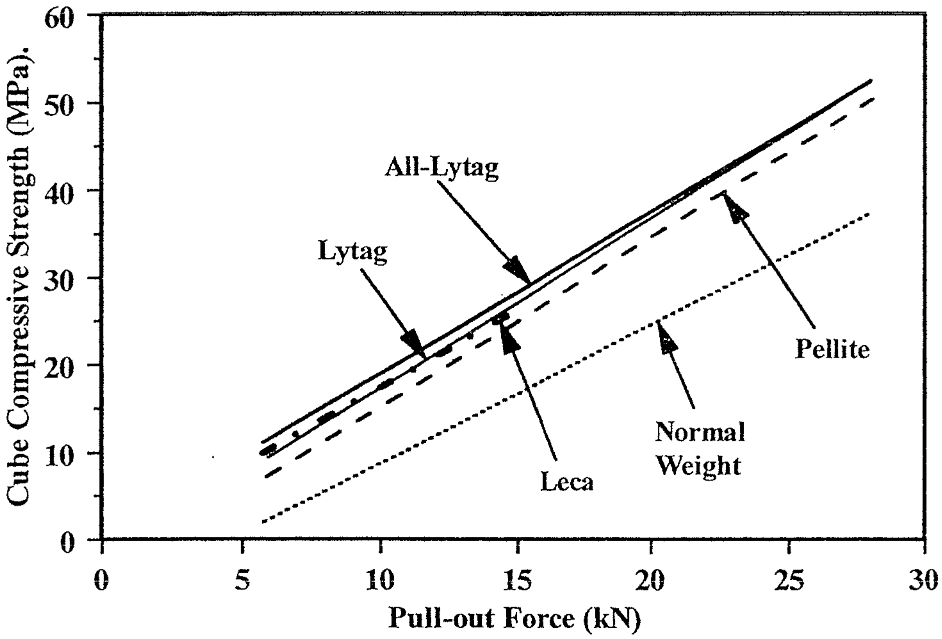


Figure 16: Pull-out test strength correlations for Lightweight Concretes [9].

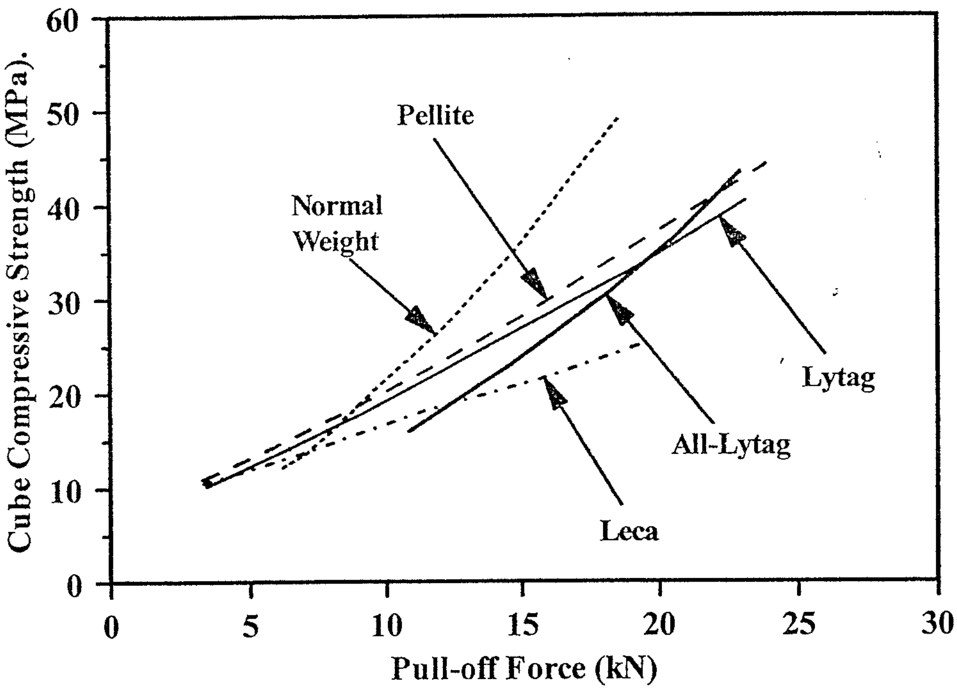


Figure 17: Pull-off test strength correlations for Lightweight Concretes [9].

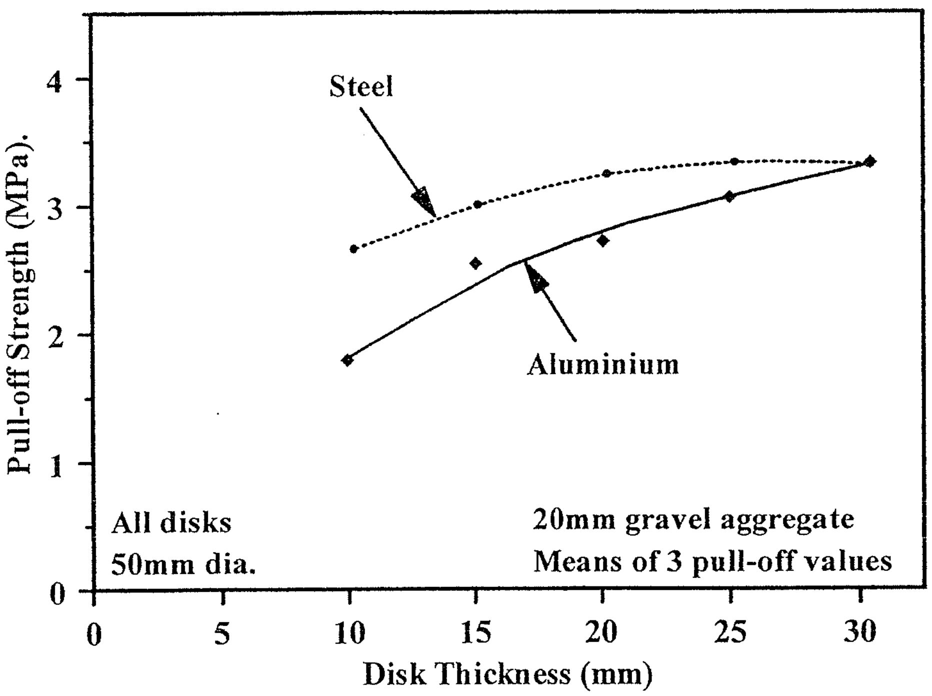


Figure 18: Effects of Pull-off disk characteristics [13].