IN-SITU STRENGTH ASSESSMENT OF CONCRETE
- THE EUROPEAN CONCRETE FRAME BUILDING PROJECT -

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ABSTRACT.

A full scale seven-storey insitu advanced reinforced concrete building frame designed to Eurocode 2 by Buro Happold was constructed in the Building Research Establishment's Cardington laboratory encompassing a range of different concrete mixes and construction techniques. This provided an opportunity to use in-situ non-destructive test methods, namely the Lok and CAPO tests, on a systematic basis during the construction of the building. They were used in conjunction with both standard and temperature-matched cube specimens to assess their practicality and their individual capabilities under field conditions. Results have been analysed and presented to enable comparisons of the performance of the individual test methods employed.

KEYWORDS

In-situ non-destructive tests, strength development, temperature matched curing, maturity, temperature, pull-out test, Lok and CAPO tests.

INTRODUCTION.

In most countries in the world the quality of the concrete in a structure is assessed indirectly by measuring the strength of cubes or cylinders which are made from the concrete supplied to the site. Whilst this is well accepted by industry, it has its limitations in that problems are not detected until it may be too late for economical remedial action as testing is generally carried out at 7 and 28 days. In addition, these procedures can be the subject of abuse - either by making cubes prior to the addition of water to the mix or, in extreme cases, by the contractor supplying cubes from a specially prepared mix, which will meet the specifications. Fortunately, the latter practices seldom if ever arise in the United Kingdom, but all these shortcomings could be eliminated by measuring the strength properties of the concrete in-situ and at an early age. This also permits the effectiveness of compaction and curing processes to be incorporated in providing a reliable indication of the condition of the finished product.

Fig. 1 : The in-situ concrete frame building project at Cardington.

Another advantage to be gained from in-situ testing is that the speed of the overall construction programme can be increased if an accurate assessment of the early-age in-situ strength is made because this allows a much faster 'turn-around' for formwork and back-propping.

This report describes work undertaken as part of the insitu concrete frame building project at Cardington. The objective of that project was to re-engineer the business process of such buildings in order to reduce costs, increase speed and improve quality. The need, established through industry-based studies, was addressed by a thorough re-appraisal of the supply chains and construction processes. A full scale seven-storey insitu advanced reinforced concrete building frame, see Fig. 1, designed to Eurocode 2 by Buro Happold was constructed in the BRE Cardington laboratory encompassing a range of different concrete mixes and construction techniques. This provided a focus for a number of construction-phase research investigations, including that reported here, which was concerned with the practicality on site and individual capabilities of non-destructive test methods.

The in-situ concrete test building at Cardington provided an ideal opportunity to establish a benchmark for alternative systems of concrete strength assessment to cube testing for early age strength monitoring.

EXPERIMENTAL PROGRAMME.

An important feature of the Project was the need to balance the 'research' requirements of the Academic Institutions involved, with the practical and commercial requirements of the

Contractor (Byrne Bros.) to complete the work with a minimum of delay and disruption. Compromises were necessary on both sides, and one consequence was the limitations that were necessary upon the number of tests performed. These numbers were relatively small in comparison with those typically associated with laboratory based studies, and in some instances were further curtailed as a result of operational circumstances. Some conflict of requirements between the five Universities involved was also inevitable.

Test Methods.

Previous studies by Bungey [1] have established that surface hardness testing is unreliable at early ages, and that whilst Ultrasonic Pulse Velocity measurements can yield good early age strength estimates usage is usually precluded by the need for access to two opposite faces. Where testing is required on one face, penetration resistance testing is quick and suitable for large members such as slabs, but this again has been shown to be unreliable at low strength values. Internal fracture tests are generally recognised as having high variability and are thus similarly considered unsuitable for early age work. The previous studies concluded that pull-out testing, maturity testing and temperature-matched curing were the most reliable and practicable techniques at low strength levels. It is on this basis that these three techniques were selected for use in this programme of work.

Pull-out testing involving preplanned inserts cast into the pour is particularly suitable for direct insitu measurements of early age strength utilising cut-out panels in shutters where appropriate. The Danish Lok-Test system was selected for this project since this is the version, which has gained greatest commercial acceptance worldwide. A companion CAPO-Test system is also available in which tests may be conducted on hardened concrete without preplanning, except to avoid reinforcement, utilising drilling and under-reaming with specialist equipment. This was also used in the project to provide supplementary information and to permit a controlled comparison of the two techniques under 'field' conditions. One key feature of these pull-out methods is the good sensitivity to compressive strength and the relative insensitivity of correlations to mix variables such as aggregate type.

Maturity and Temperature Matched Curing techniques are both well established and are based upon measurements of within-pour temperatures. Both can provide reliable results but suffer from potential practical disadvantages [1]. They were adopted for this project to permit overall comparison with the two partially-destructive techniques, and to assist interpretation of results as well as further examination of the benefits of test combinations.

Scope Of Variables.

The flat slab insitu concrete frame was designed to encompass a range of different concrete types and construction procedures. The seven different mixes are detailed in Table 1. It must be noted that the ready-mixed concrete supplier reserved the right to make adjustments to these mix proportions during construction, e.g., to make savings when the target mean strength was proving to be higher than what was needed. It is understood that these adjustments are a norm during the construction of a project. Five out of the Seven mixes have been covered in this study with the principal variables being concrete grade (C37 and C85), admixtures (plasticiser and superplasticiser) and aggregate type (gravel and limestone).

Table 1: Concrete mixes originally submitted for approval to be used for the construction of the in-situ concrete frame building project.

	CONCRETE TYPES AND DRY BATCH WEIGHTS.						
	C85MS Microsilica	C85MK Metakaolin	C85NF Fiber	C37N Normal	C37P Plasticised	C37F Flowing	C37PG GGBS
Location							
Column	2→3	1→2	G→1	3→6			6→7
Slab				1, 2, 5	3	4	6, 7
Portland Cement (kg)	400	400	400	360	330	335	210
Sand (kg)	732	717	690	780	815	810	790
20-5mm Coarse Aggregate (kg).							
Limestone	1170	1146	1173				
Gravel				1020	1010	1010	1015
Admixtures (ml)							
Plasticiser)	1232	1232	1232		990		1050
Superplasticiser	8800	8800	8800			5000	
CRMs (kg)							
Microsilica	40		40				
Metakaolin		40					
GGBS							140
Fibres (kg)			2.7				
Free W/C	0.25	0.32	0.32	0.52	0.52	0.52	0.49
Target Slump (mm)				100	100		100
Flow (mm)	550	600	480			550	

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 bottom). The selected test methods were each used at similar locations to further permit assessment of their practicality on site e.g. speed, relative cost, disruption and accuracy, and to assist determination of an optimum balance between insitu tests and cube testing.

Insitu tests using the Lok and CAPO, were undertaken at 1 day (or as soon as practicable), 3 days, 7 days and 28 days. Temperature measurements were made (by BRE) from the time of casting at several locations on columns at a depth of 25 mm below the surface and on slabs at 25 mm above soffits and 50 mm below top surfaces. Results for corresponding temperature-matched cured cubes (based on sensors at a depth of 50 mm below the tops of slabs midway between columns), air cured and water cured cubes were also made available. These were designed to enable comparisons of insitu strength with cubes experiencing differing curing regimes.

Data Collection.

During the development of the work programme, extensive discussion and pre-planning was undertaken with the staff of BRE, leading to the programme outlined above. Preparation of correlations between measured property and strength is a key issue for insitu testing, and it is recommended that for normal practice these should be prepared in advance of the construction

Manufacturer's Correlation [2].

This line crosses the Manufacturer's recommended correlation at a Lok force of 10.5 kN but because of its different slope it starts deviating resulting in an estimated in-situ strength which is higher by 4.8 N/mm^2 at a Lok force of 37 kN. Beyond this Lok force the Manufacturer's recommended correlation has the same slope as the Cardington correlation but the Y intercept is lower by 4.8 N/mm^2.

It was decided, because of the limited number of test points for each mix, that grouping mixes might offer better strength predictions from in-situ test results. The ordinary least square method was used to study what effect the grouping of mixes would have on the 95% confidence band for the whole strength correlations. If only three testing ages are used to establish the strength relationship, then the 95% confidence interval width is unacceptably high; ±85 and ±63 N/mm^2 for mixes C85MK and C85MS at the average of X values, i.e. 40 and 53 N/mm^2, respectively. Increasing the number of results to four decreases the width of the 95% confidence interval considerably; ±5, ±15, and ±15 N/mm^2, for mixes C37N, C37F and C37P respectively. The strength correlation for all mixes combined had a 95% confidence interval of ±4 N/mm^2. It must be noted that the confidence statement applies to the line as a whole, and therefore the confidence interval for y corresponding to all the chosen x values will simultaneously be correct a proportion (1 - 0.05) of the time. A confidence interval for a point on the line, i.e. a confidence interval for y' (the true value of y and the mean value of Y) corresponding to a single value of x = x', will be smaller. The wider interval is the "price" paid for making joint statements about y for any number of or all of the x values, rather than the y for a single x [3]. Another caution is in order. The estimated line may be very close to the true line, in which case nearly all of the interval predictions may be correct; or the line may be considerably different from the true line, in which case very few may be correct. In practice, provided the situation is under control, the estimate of the line should always be

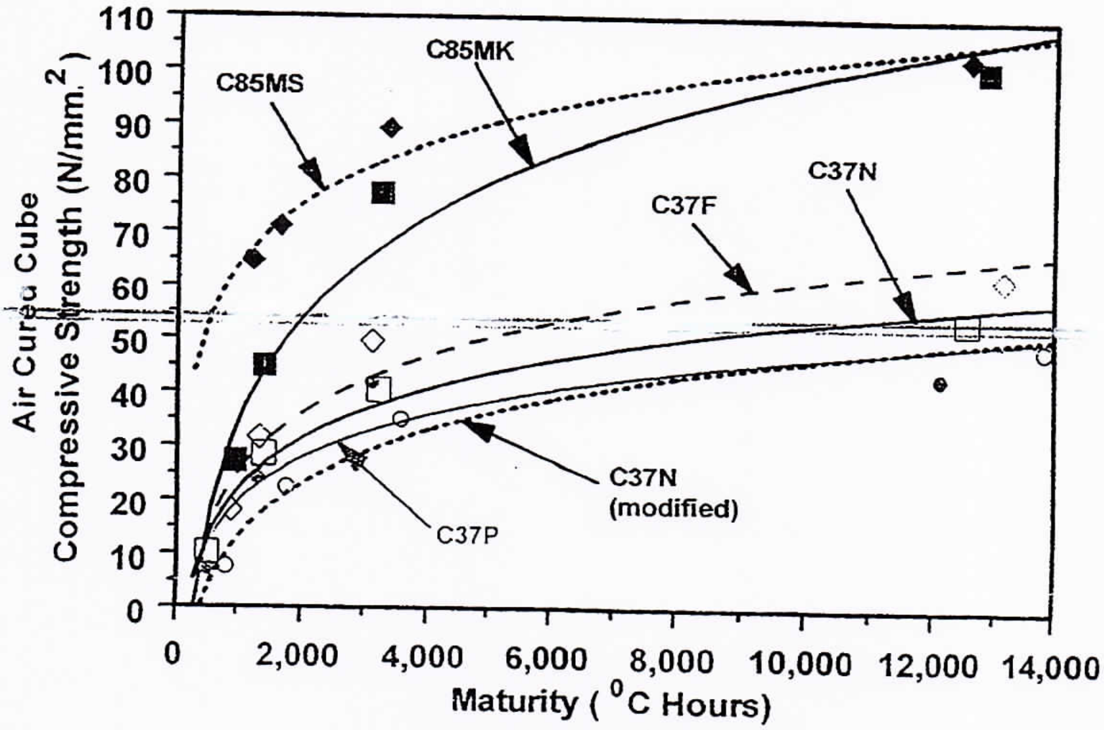

Fig. 3: Maturity strength correlations.

revised to include additional information in the way of new points. Whether or not considering all the data obtained from different mixes as belonging to one group of results, yields an estimated strength relationship which is close to the true one, will be examined when considering the in-situ strength estimates.

CAPO-Test Strength Correlations. The possibility of using the Lok-test correlation to interprete the CAPO-Test results has been investigated. It was found that because of the similarity of the best-fit line, for all normal strength concretes, with that obtained for the Lok-test, one strength correlation can be used for both the Lok and CAPO-tests

Maturity Strength Correlations. The ambient temperature inside the Cardington hangar varied between 5 and 10^{0}C during the construction period. The air-cured cube temperatures dropped to the ambient temperature within 2-days after casting. This resulted in almost linear relationships between the maturity, expressed in ^{0}C Hours, and time after casting in days. The compressive strength was plotted against the natural logarithm of the maturity to determine equations relating the two. These equations have been plotted on normal axes as shown in Fig. 3. It is clear that, as expected, one strength correlation *cannot* be used for all concrete mixes. The same maturity, say 12000 ^{0}C Hours, corresponds to 47 and 104 N/mm^2 for mixes C37N(modified) and C85MS respectively. Fig. 3 also shows that modifications to the concrete mix proportions of the C37N concrete affected the maturity strength correlation. Individual strength correlations for each mix were therefore used to predict the in-situ strengths, described in the next section.

In-Situ Strength Estimates.

The strength correlations determined in the previous section have been used to estimate the in-situ strengths based on measurements on the structure. These are compared to strengths obtained from air-, water- and temperature matched cured cubes.

Lok-test strength estimates. Fig. 4 shows the estimated strengths for columns and slabs, versus the measured compressive strengths obtained from air-cured companion cubes. The average coefficients of variation from the equality line are: (a) 27.9 % for the concrete mixes used in the columns and 22.2 % for the strength of the mixes used in the slabs. It must be noted that some deviation from the equality line is expected from the in-situ strength results. This is because of the difference in the compaction and temperature curing regime of the concretes in a structural element and in air-cured cube moulds. The peak temperatures in the column and in the air-cured cube for the C85MS concrete were 41 and 16^{0}C respectively. Similar trends were obtained for the other mixes but the temperature difference was smaller, e.g., for the C37N-10 the peak temperatures were 24^{0}C and 14^{0}C in the column and in the air-cured cube, respectively. The ambient temperature was approximately 8^{0}C.

The in-situ strengths should ideally be related to strengths obtained from temperature matched cured cubes. The average coefficient of variation from the equality line was found to be 13.9%. Unfortunately, this was only possible to do for the C37 mixes, as no temperature matched cured cubes for the C85 concretes were available for testing.

In-situ strength estimates quoted above included different locations on structural elements; top middle and bottom for columns and top and soffit for slabs. In the columns with the C85MK and the C85MS mixes the highest strength was obtained at mid-height. The average strength for all ages at the top of columns was 3.3 % lower than at mid-height, while the strength for

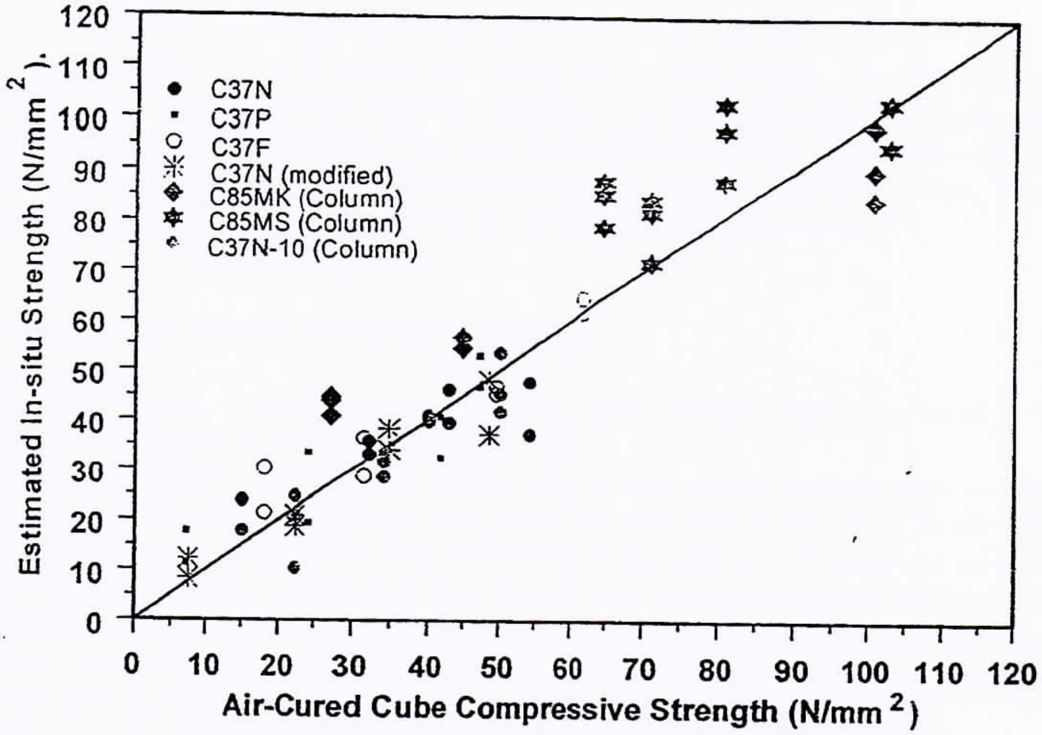

Fig. 4: Estimated in-situ compressive strengths using one Lok-test strength correlation for all the mixes tested.

the bottom of columns was considerably lower at 5.0 %. Only one column cast with the C37N-10 concrete mix was tested and the highest strength was obtained at the top. The average strength differences, for all ages, were 4.6% and 8.0% lower from the top, for mid-height and bottom respectively. These differences appear to be due to different insertion times of the poker vibrator.

The average difference between the top and soffit strengths of slabs at mid-bays was 13.6 %, the highest compressive strength being at the soffit. This difference is however affected by the location; the strength difference increases to 34.8% for concrete placed adjacent to columns.

Capo-Test strength estimates. The similarity of the strength correlations for the Lok and Capo tests was discussed in the previous section. The estimated in-situ strengths showed similar average coefficients of variation about the equality line with air-cured cube compressive strengths as those of the Lok test; 16.0 % and 22.2 % for the Capo and Lok test respectively. It may therefore be concluded that the Capo test may be used to complement data obtained by the Lok test since the same correlation can be used.

Maturity strength estimates. Individual strength correlations only have been used to convert maturities into in-situ strengths. Fig. 6 shows the estimated in-situ strengths plotted against the compressive strengths obtained by testing air-cured companion cubes. Coefficients of variation from the equality line are 16.3% and 21.9% for columns and slabs respectively. Similar trends as with the Lok-test results were found, i.e. (a) early-age in-situ strengths are higher than compressive strengths of air-cured cubes but are similar to water-cured cube compressive strengths, (b) the 28-day in-situ strengths are lower if compared to the water-cured cube compressive strengths, and (c) the in-situ strengths should ideally be related to strengths obtained from temperature matched cured cubes. Unfortunately, as mentioned

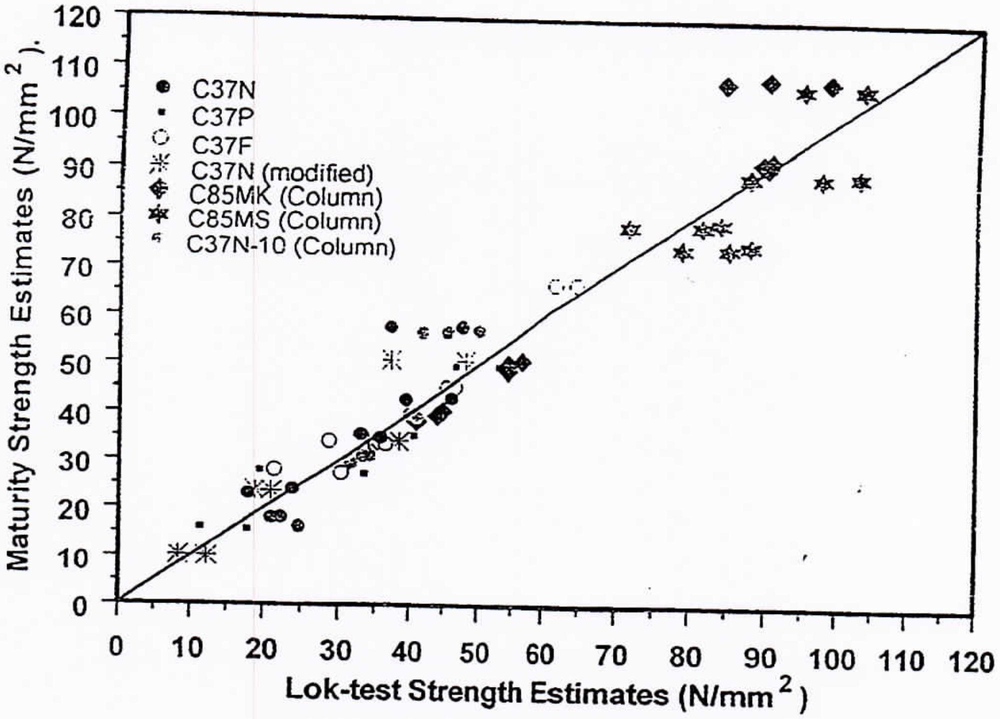

Fig. 6: The strength estimates from the maturity measurements are plotted against the Lok-test estimates.

- Relating maturity to Lok-test strength estimates offers a way of validating the values and thus increases the confidence of the strength estimates obtained from each test. The values estimated should be within ±5 N/mm^2. If any results fall outside this equality line band width then further tests may be performed using the CAPO test apparatus. If maturity measurements consistently overestimate the in-situ strength as determined by the Lok or CAPO tests then it is likely that the concrete mix proportions have changed.

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STRENGTH DEVELOPMENT MONITORING

CASE STUDIES

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

1. 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 faces 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 even at 'low power' settings. Internal fracture tests are similarly unsuitable at early ages because of their high variability. It was concluded [1] 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. 1a 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. 1b 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. This must influence the location of test points. The peak temperature was found to occur at approximately mid-height of the 1.5m high lift at about 12-15 hours after casting as shown in figure 2. 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. The influence of shutter materials is compared in figure 3 and it was noted that companion 150mm cubes stored alongside the pour closely followed air temperature but that 225mm cubes (for correlation specimens) experienced higher temperatures.

It was also noted that whilst an approximately linear strength/maturity relationship was found to exist for the mix in use, variations were encountered between batches: This reinforced the view that reliable insitu strength estimates cannot be obtained from maturities alone at such early ages. Maturity is however a useful preliminary to pull-out tests.

Temperature-matched curing was also trialled on this project with considerable success despite the physical obstructions caused by the presence of the curing tank on the cramped working platform and the need to carry specimens to ground-level for testing. Results confirmed the major differences between within-pour strengths and those of air-cured cubes located adjacent to the pour at 15-24 hours.

Shortly after completion of this project, a new cooling tower was constructed at Fidlers Ferry in Cheshire to replace one that had collapsed in high winds. Speed of construction was vital in this working power station environment, and on this occasion CEGB decided to use temperature matched curing alone. It was claimed that construction was speeded-up by over 1 month, but a degree of suspicion and hostility was encountered from some of the workforce. On a number of occasions the system was rendered inoperative by power failures and acts of vandalism. This highlights the risks of reliance upon one method alone.

2. 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, 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 [3]. 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 1. 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 were used for the High Strength mixtures, whilst standard flotation cups were used to locate inserts on the top surfaces of slabs.

Lok-Test Strength Correlations

Historically, most strength relationships have been assumed to be straight lines, and ordinary least-squares analysis has been used to estimate the corresponding slopes and intercepts, as shown in Fig. 4. Each point represents the average of 4 No. pull-out tests on the side faces of 200mm cubes and 3 No. 100mm cube compressive strength values. Results for individual groups of similar mixtures show small scatter about their respective correlation lines but the intercepts and slopes vary considerably for each individual concrete mixture. The combined correlation for all mixtures is however surprisingly very close to the Manufacturer's correlation [4]. This is consistent with previous assertions that a generalised correlation can be used, but that confidence limits can be improved by specific correlation for the mixture concerned [5]. The Manufacturer does recommend that, in order to improve the accuracy of the strength correlation, the range of concrete strengths considered should be as wide as possible. This, for commercial buildings which are unlikely to use so many different concretes, can be achieved by testing at various ages.

The combined strength correlation crosses the Manufacturer's recommended correlation at a force of 10.5kN but because of its different slope results in an estimated in-situ strength which is higher by 4.8MPa at a force of 37kN. Beyond this force the Manufacturer's recommended bi-linear correlation has the same slope as the Cardington correlation but the compressive strength intercept is lower by 4.8MPa. It was found that grouping all the results together to obtain one strength correlation for all the mixtures that were tested improved the confidence in the strength prediction; the 95% confidence interval was ±4MPa for a concrete strength of 43MPa. This single strength correlation, based on all the results, was therefore used for estimating the in-situ strength from measured Lok test values.

Capo-Test Strength Correlations

The possibility of using the Lok-test correlation to interpret the Capo-test results has been investigated. Correlations were developed in the same manner as for the Lok-tests and results have confirmed that one strength correlation can be used for both the Lok and Capo-tests, Fig. 5, even for ages as low as 1 day. The slight deviations of the two individual correlations appear to be due to the inclusion of high strength concrete mixes for determining the strength correlation for the Lok-test. Only normal strength concretes were tested with the Capo-test because of the limitations of the equipment mentioned below.

Pull-Off Strength Correlations

The ordinary least-squares method has again been used to determine the strength correlations which were obtained from 6 No. side face measurements on 150mm cubes. These are shown graphically in Fig. 6. It is apparent that the accuracy of these strength correlations has been affected by the limited number of sets of data, three for each mix, which was due to the difficulties encountered when testing concrete at one day. It was found that the epoxy bonding compound did not harden quickly enough to allow one day testing.

It is clear that a specific correlation is needed for each mix but if this is available then a reasonable level of strength prediction can be achieved.

Insitu Measurements

Insitu Lok-test strength predictions for slabs are compared with temperature matched cube results in Fig. 7 based on the average of 4 No. Lok-tests at a particular location together with between 2 and 4 No. compressive strength cubes. It should be noted that Lok-test results are limited to those available from a location adjacent to the controlling sensor but include results for both top and soffit of the slab, thus significantly increasing variability. It was noted that insitu strengths, especially at the soffit, were generally found to be greater in the slab region adjacent to columns than at mid-bay.

A much closer relationship is seen in Fig. 8 between insitu predictions from Lok-test and Maturity results (using a similar function to that used in the cooling tower study) which serves to confirm the reliability of the Lok-test values. Comparisons of insitu and air cured cube strength results in Fig. 9 however clearly indicate the inadequacies of reliance on air cured cubes at early ages, at both low and high strength values.

Further details

Results of this project are discussed more fully in [6] which is attached and have led to the publication of the attached Best Practice Guide.

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Table 1 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

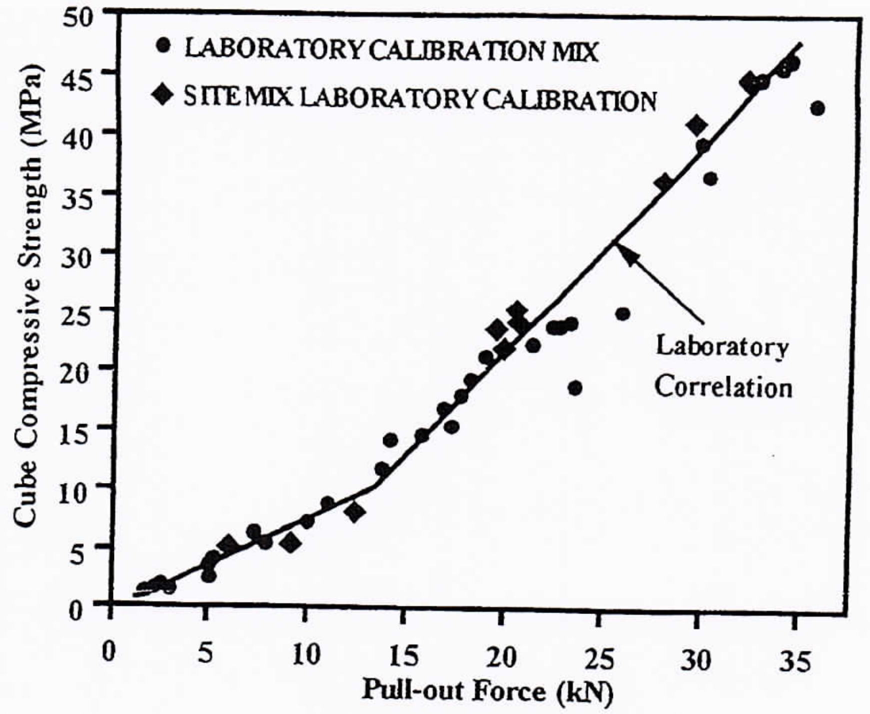

Figure 1a: Laboratory Pull-out Strength Correlation.

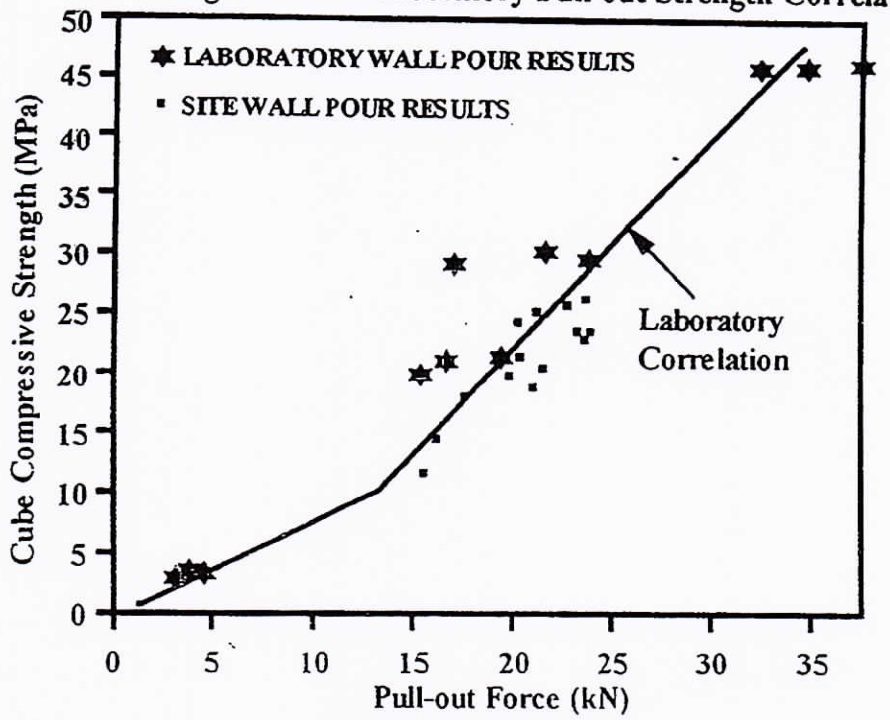

Figure 1b: Site and Laboratory Wall Pour Pull-out Results.

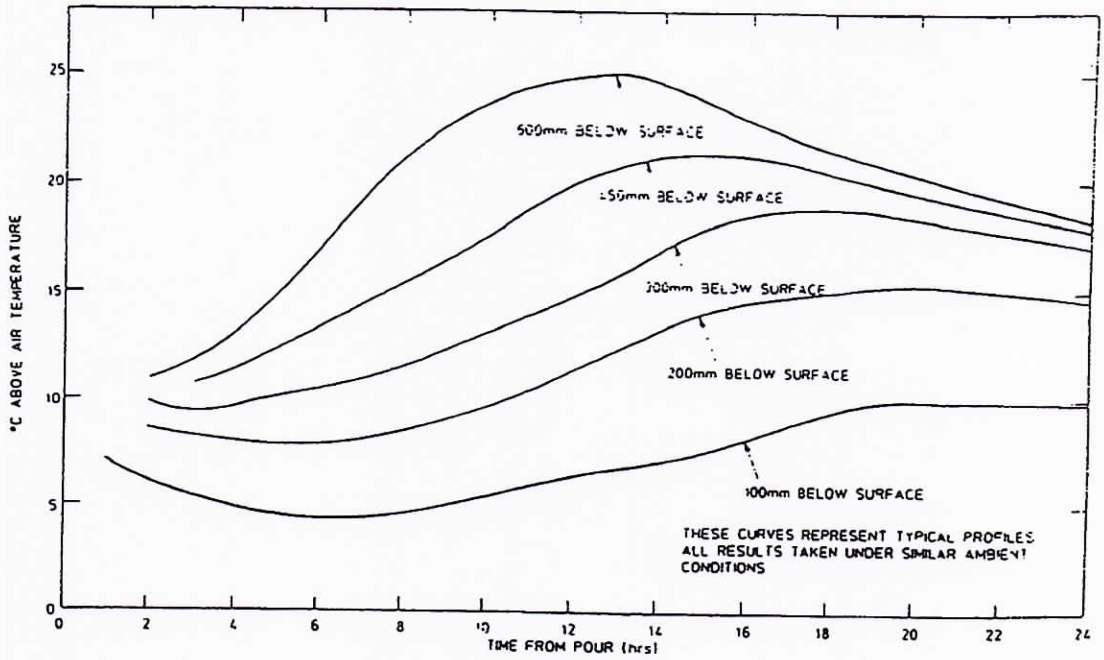

Figure 2. Typical Within-Pour Temperature Profiles

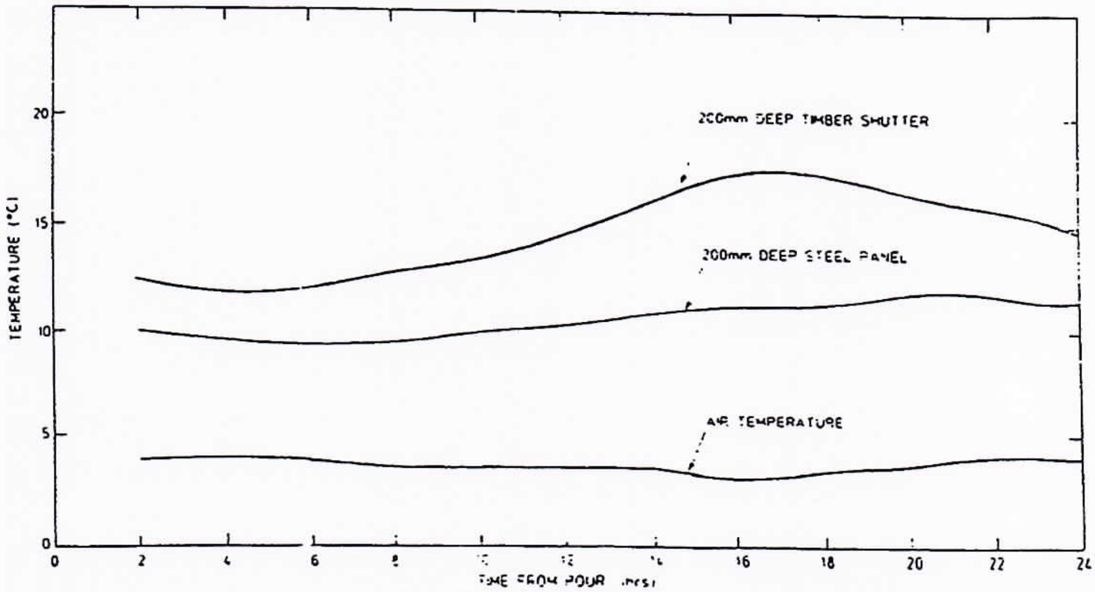

Figure 3 Within Pour Temperature Profiles – Steel vs Timber shutters

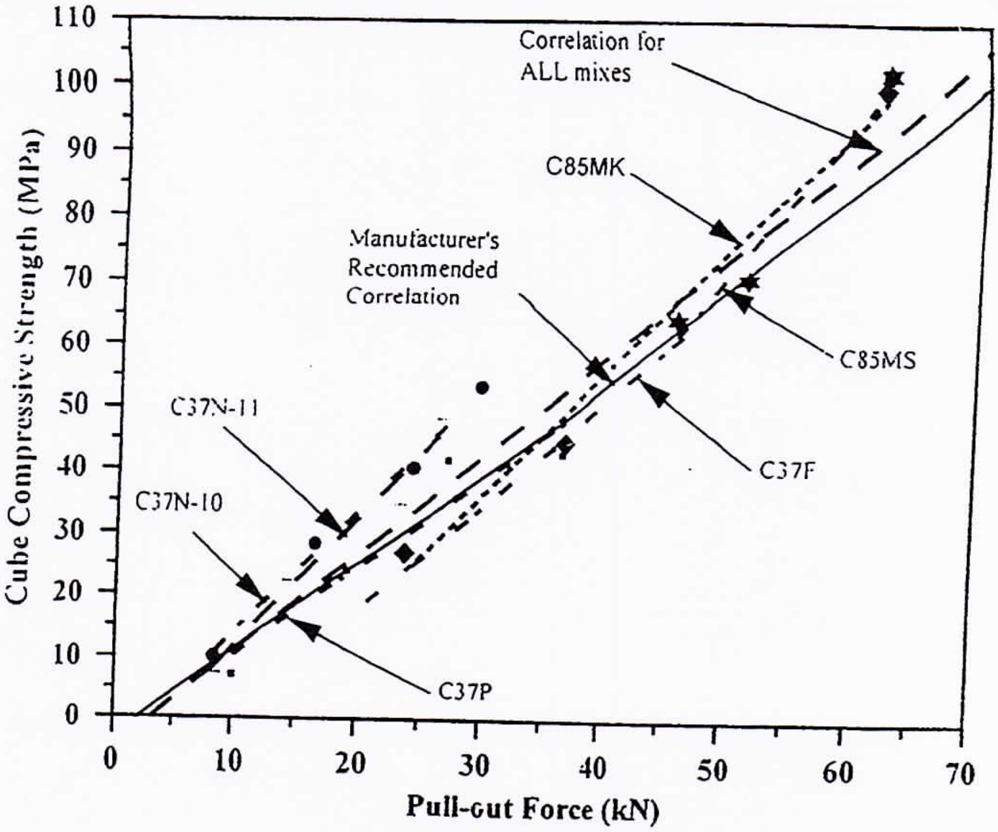

Figure 4. Lok-test strength correlations

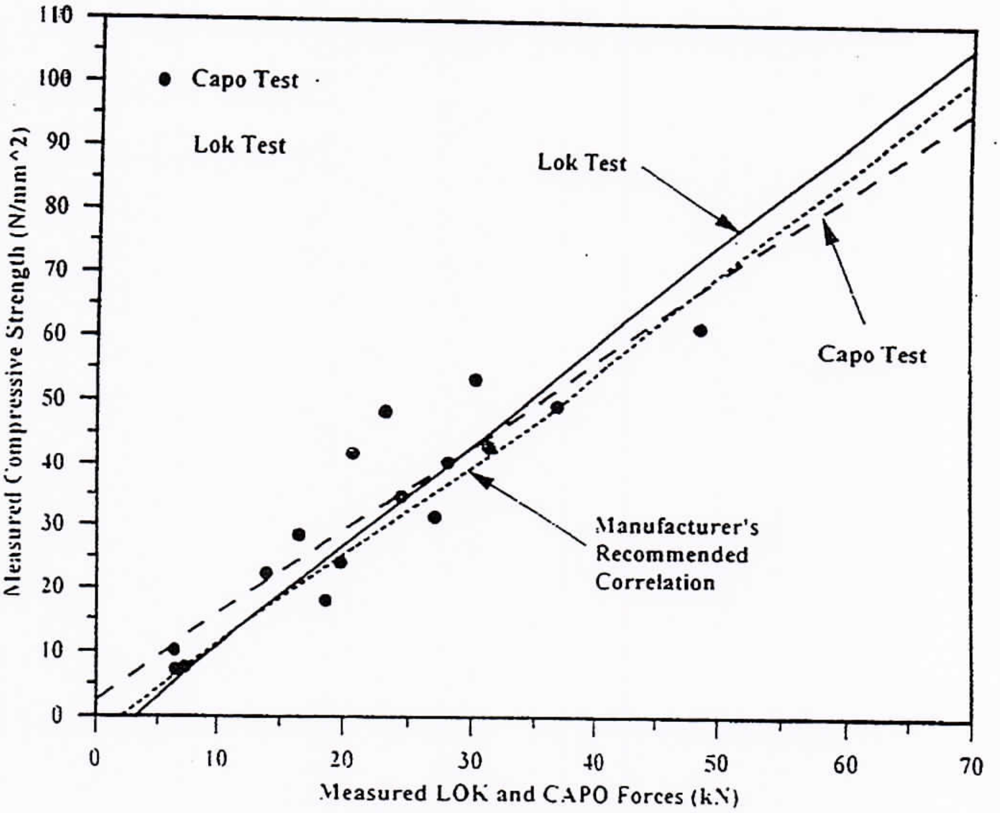

Figure 5. Lok and Capo test strength correlations

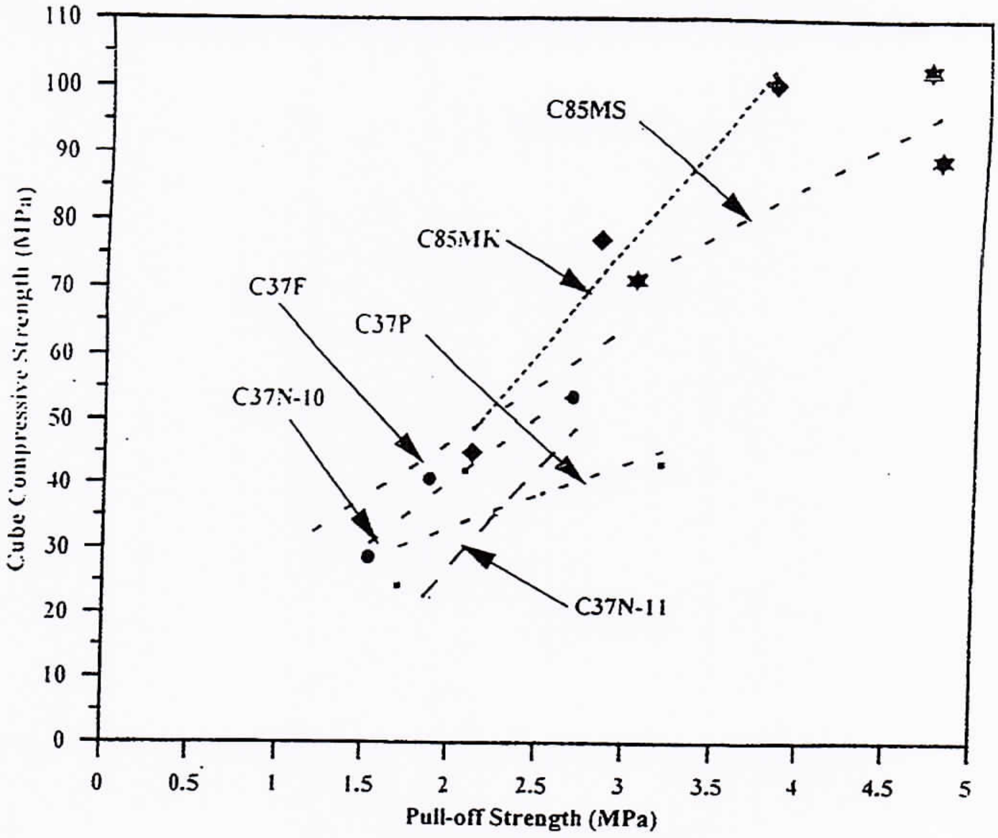

Figure 6. Pull-of test strength correlations

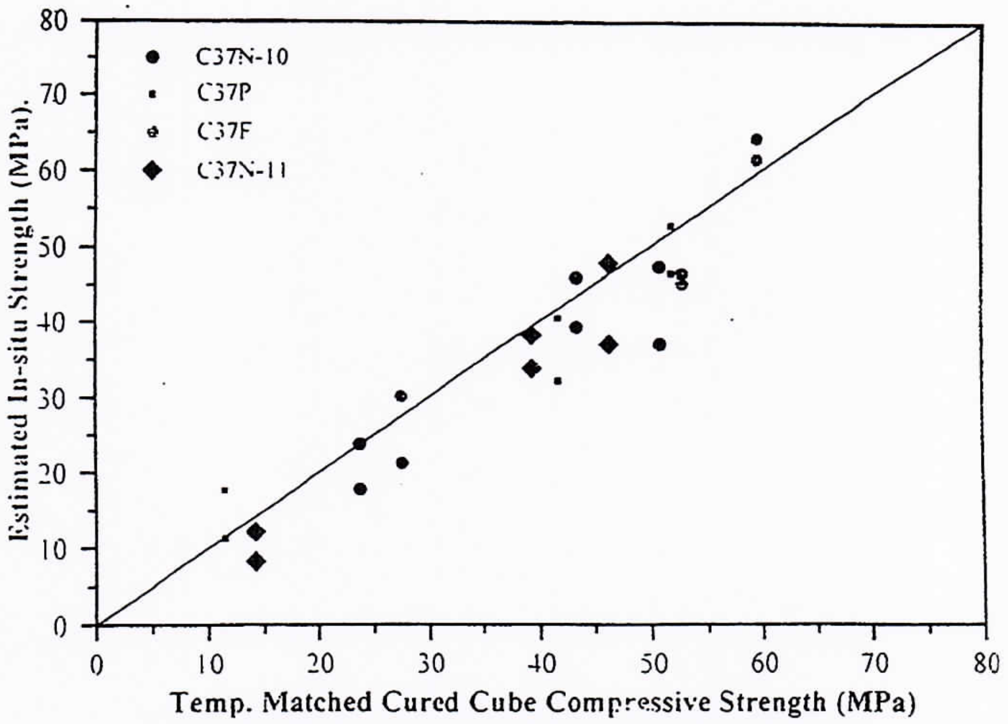

Figure 7. Insitu strength (Lok) vs Temperature Matched Cube results

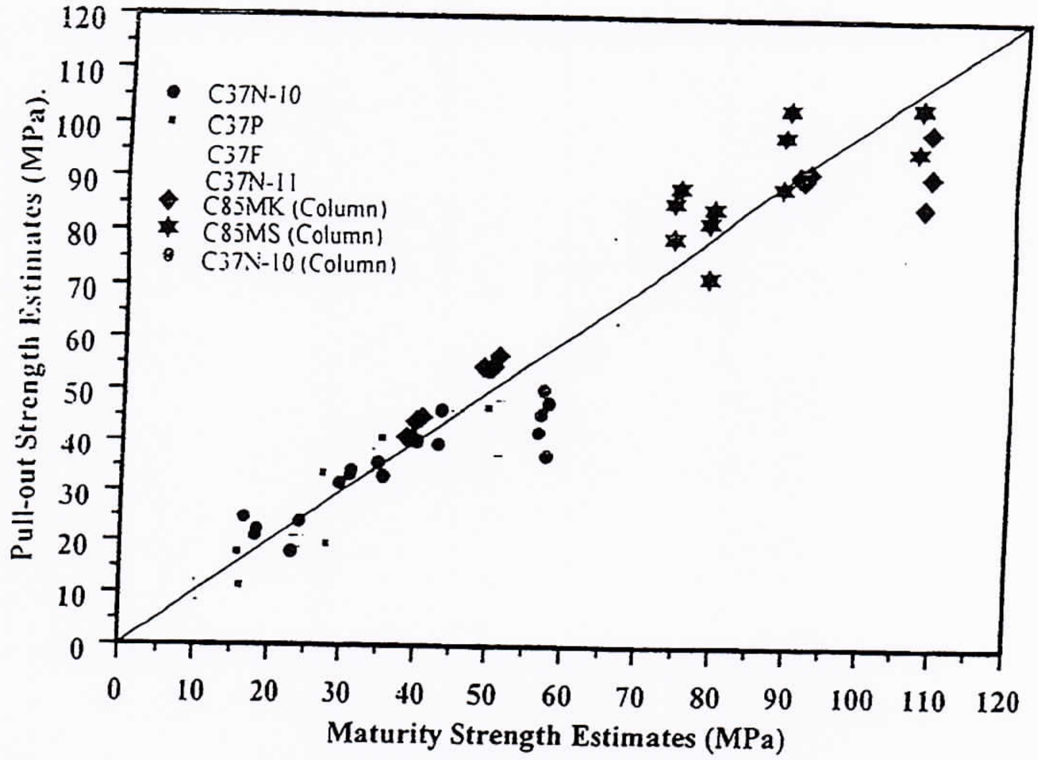

Figure 8. Insitu Strength (Lok) vs Insitu Strength (Maturity)

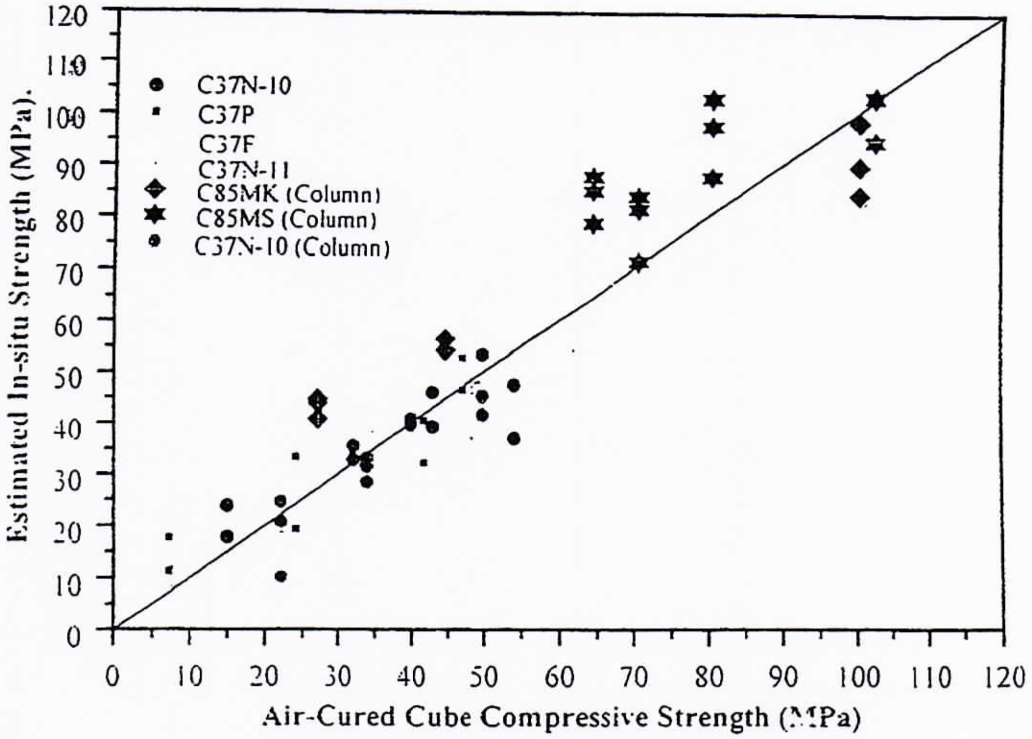

Figure 9. Insitu Strength (Lok) vs Air Cured Cube Strength