

**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	C85MK	C85NF	C37N	C37P	C37F	C37PG
		Microsilica	Metakaolin	Fiber	Normal	Plasticised	Flowing	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 Gravel	1170	1146	1173	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

starting date. In this case, however, bearing in mind the number of mixes involved, the short time-scale for preparatory work, the BRE intention to set up a laboratory on site, and the need to avoid duplication of effort, correlation specimens were cast on-site during concreting of the structure. In each case these comprised four 200mm timber moulded cubes (Lok-tests), four 200mm timber moulded cubes (CAPO-tests) and one 150mm cube containing a temperature probe connected to a data logger (maturity). Results from these specimens were compared with cube results provided by BRE. Records of ambient temperature and humidity were also made.

RESULTS AND DISCUSSION.

The objective of an in-place test is to obtain an estimate of the properties of concrete in the structure. Very often the desired property is the cube compressive strength. To make a strength estimation it is necessary to have a known relationship between the result of the in-place test and the strength of the concrete for the particular concrete mix concerned. Correlation specimens, air-, water- and temperature matched cured cubes, cast on site by BRE during concreting of the main structure, were tested by STATS Ltd.

Strength Correlations.

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. 2, with results from this project. The Y intercepts and the slopes of the strength correlations vary considerably for each individual concrete mix, but the combined correlation for all mixes is surprisingly very close to the

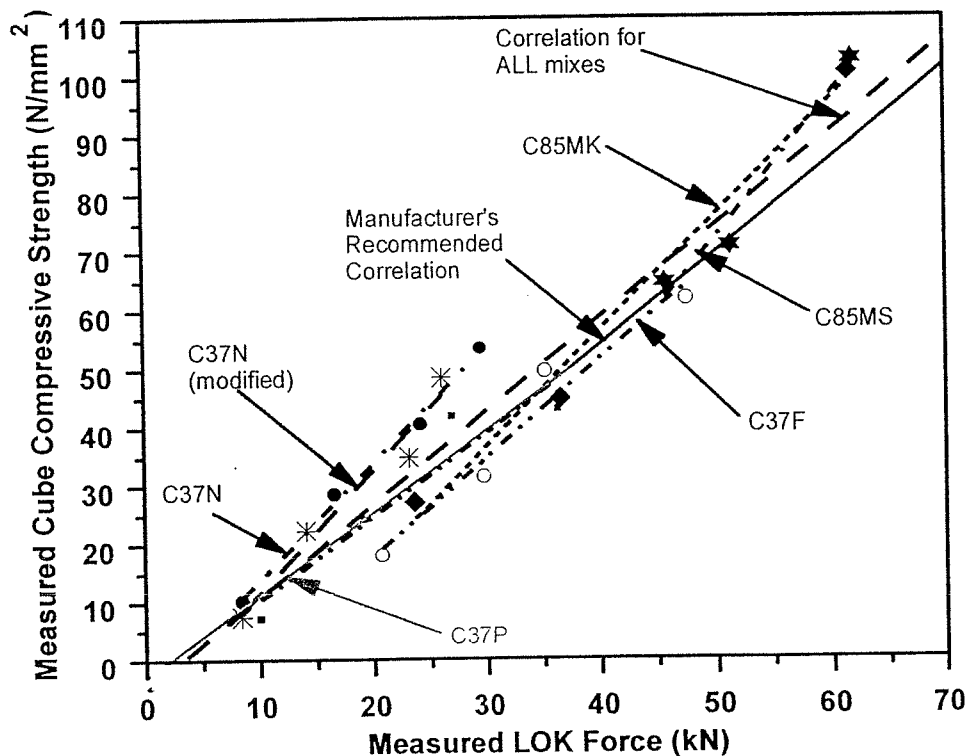


Fig. 2: Lok test strength correlations.

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 $\pm 63 \text{ N/mm}^2$ 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 $\pm 15 \text{ N/mm}^2$ for mixes C37N, C37F and C37P respectively. The strength correlation for all mixes combined had a 95% confidence interval of $\pm 4 \text{ N/mm}^2$. 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

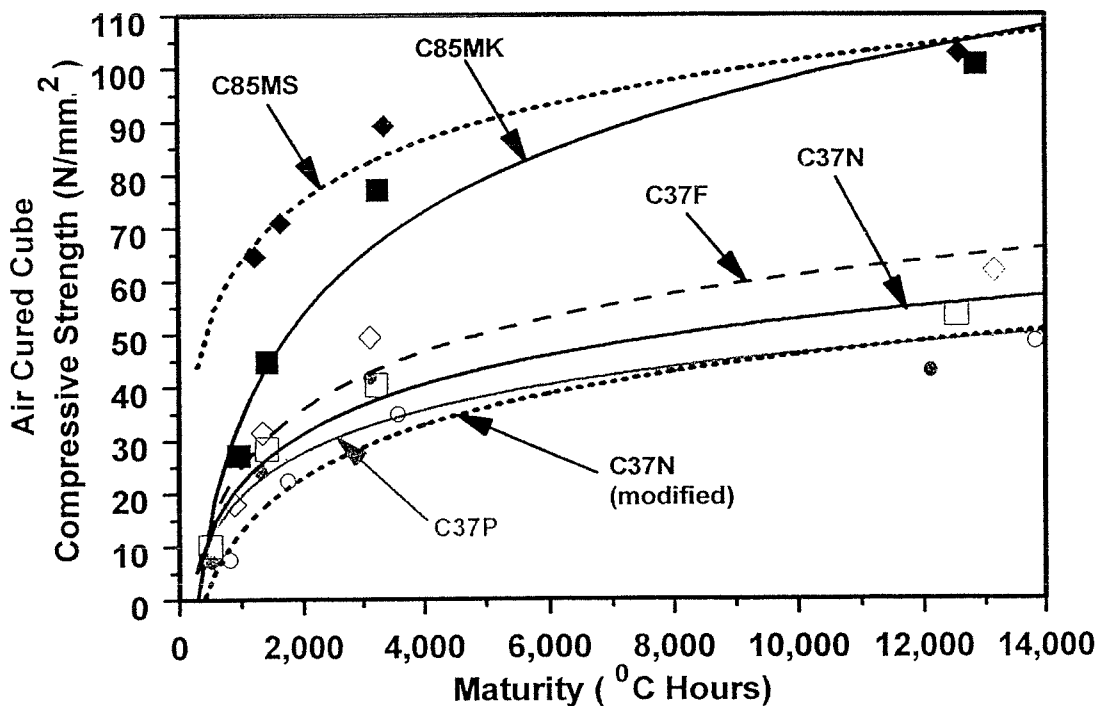


Fig. 3: Maturity strength correlations.

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 interpret 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°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 °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 °C Hours, corresponds to 47 and 104 N/mm² 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°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°C and 14°C in the column and in the air-cured cube, respectively. The ambient temperature was approximately 8°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

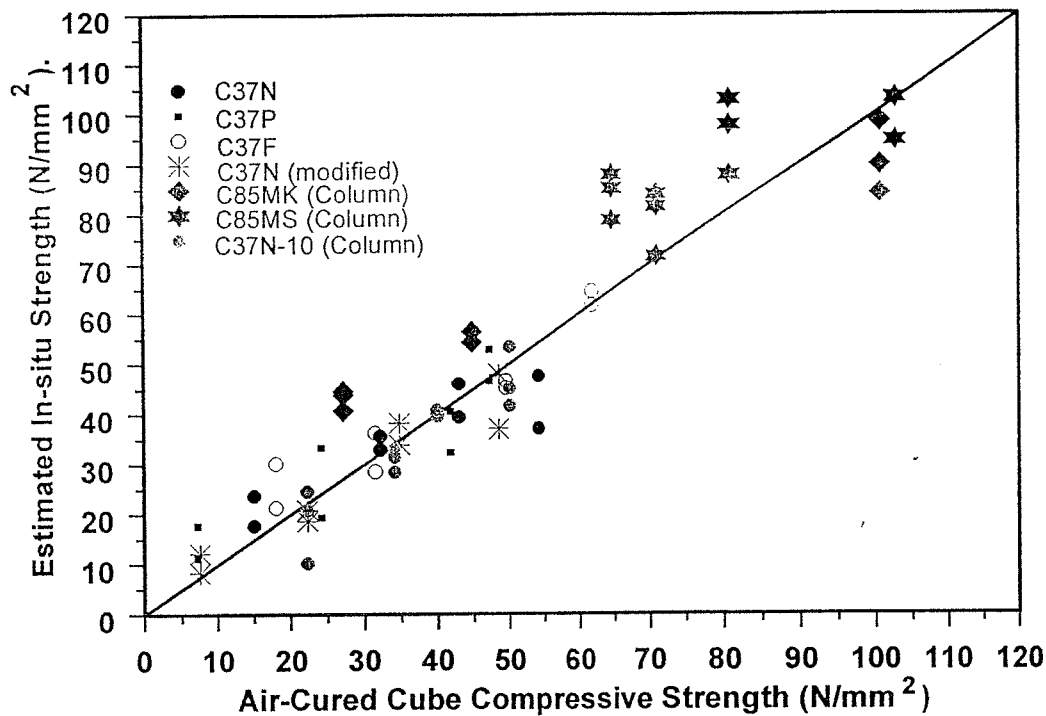


Fig. 4: Estimated in-situ compressive strengths using one Lok-test strength correlation for all the mixes tested.

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

earlier, temperature matched cured cubes were only available for the C37 concretes that were used in the slabs.

The above trends and their similarities with the Lok-test results implied that the strength estimates from the two tests might be similar. The strength estimates from the maturity measurements are plotted against the Lok-test estimates in *Fig. 7*. The strength predictions from the two tests show a very good correlation for the C35 concrete mixes. The scatter of results about the equality line appears to increase with higher strengths.

CONCLUSIONS AND RECOMMENDATIONS.

The project created a massive amount of data, some of which were presented in this paper. The main conclusions are:

- There are definite advantages in being able to rely on the manufacturer's recommended strength correlation, as was the case with the Lok and Capo tests, in the absence of a specific strength correlation. Concrete mixes to be used on site may not be finalised until just before the construction start date. In this case if the appropriate facilities exist on site, specific confirmatory strength correlations can thereby be developed if deemed necessary from companion cubes cast during concreting of the structure; thus minimising the cost of expensive pre-construction laboratory work.
- The norm for determining when to strike has been to use, on small sites, cubes that are air-cured alongside the structure, and only on bigger sites, temperature matched cured cubes. Air-cured cubes have been used on the assumption that their maturities do not differ significantly from those in the structure. In this project, however, the in-situ maturities at the early-age of one day were considerably higher (by a factor of 2.4 in some cases) from those of air-cured cubes.

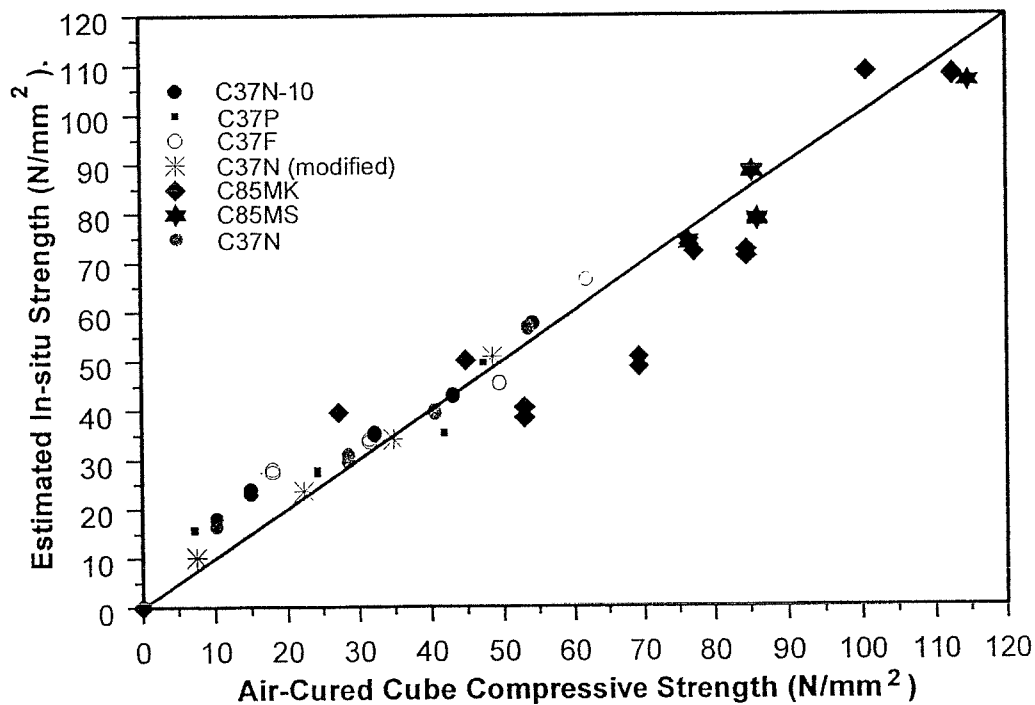


Fig. 5: Comparison between the estimated in-situ compressive strengths (using individual maturity strength correlation for each of the mixes tested) and the air-cured cube compressive strengths.

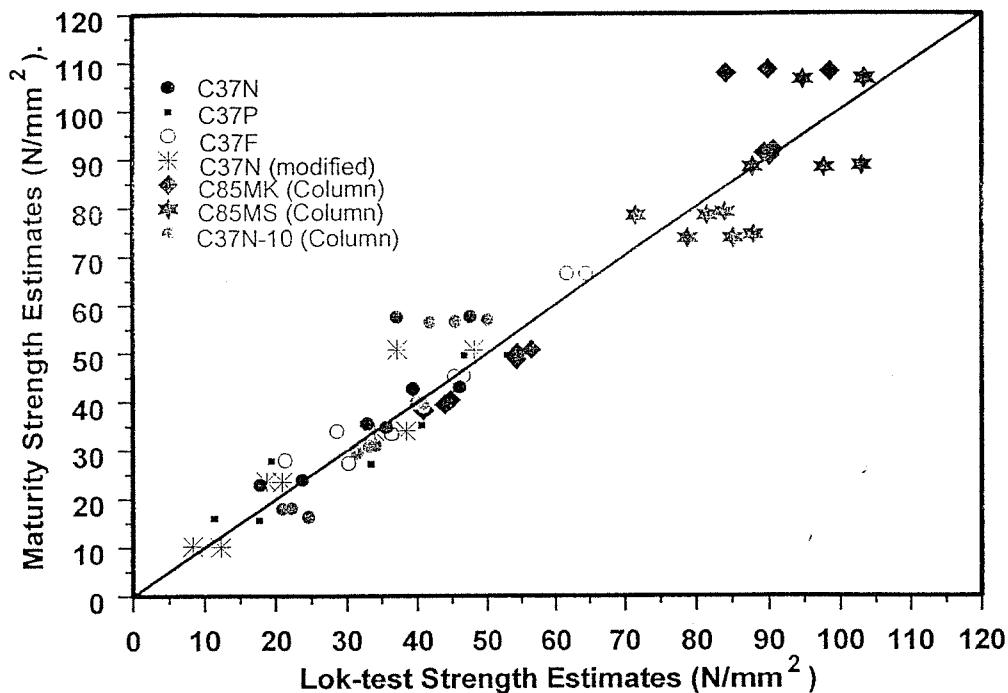


Fig. 6: The strength estimates from the maturity measurements are plotted against the Lok-test estimates.

- 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/mm². 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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