UNDERSTRENGTH CONCRETE :

DESIGN CONSIDERATIONS AND SERVICE LIFE

By

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ABSTRACT

Concrete is the primary construction material in use in Malaysia today. In the 90's the industry moved rapidly to supporting mega projects and supplying grades of concrete well above 60 Mpa cube strength. The industry also saw the shift from small on site batching to large centrally located sophisticated and computer controlled facilities. The rapid modernization of concrete supply was necessary to meet the demands of the construction industry. While the industry has demonstrated that it can deliver high performance high strength concrete, problems however do exist particularly for concrete Grades in the range 20 Mpa to 50 Mpa most commonly used on construction sites. The problems are related primarily to strength non-compliance and there has been a need to assess affected structures beyond mere code requirements. In situ concrete strength assessment provides a key tool for the owner, designer and concrete supplier to decide when such transgression of concrete design strength is acceptable.

The paper considers in situ strength assessment in accordance with the concrete society report TR11. It also summarises the latest research in the United Kingdom which is currently on going to update TR11. By way of a case study a rigorous investigative approach to resolving the problems of concrete strength non-compliance resulting in a significant reduction in remedial costs is discussed.

INTRODUCTION

Understrength concrete continues to be a much debated issue and increasingly a subject of litigation in Malaysia. Often the Ready Mixed Industry is blamed for not being up to mark but the problem is much more complex than just poor performance at the batching plant. Today concrete is a complex material consisting not only of cement, aggregates and water but also Admixtures and cement replacement materials. Concrete problems can arise from a myriad of causes:

- Inadequate specification
- Batching Problems
- Site Logistics and Long transport times
- Poor placement
- Lack of attention to finishing and curing

Inadequately prepared specifications are the first problem to contend with. The author has been involved in investigating problem structures where on occasion the specifications refer to CP110 a code which has not been in use for over two decades. In other cases the cutting and sticking of specifications from one project to another has meant that some of the suggested approaches are not totally relevant to the projects at hand. Problems at the batching plants do exist but increasingly the larger companies are much better organised, with internal training and many are ISO 9000 accredited. Site logistics and long transport times can be overcome by good planning and concrete designed for long setting times. Construction problems such as poor placement, finishing and curing are a function of poor training and lack of supervision. The issue of training and skills development in the construction industry clearly needs urgent attention..

During the design process it is normal to select a concrete strength requirement on the basis of a 28 day strength of a cube (or in some countries a cylinder) tested in compression. The justification for this is the wealth of information that relates such an arbitrary test to observed structural performance. Even at this stage it is appreciated that the compressive strength as measured is only valid for the cube and in absolute terms shows only the potential for the concrete when used elsewhere in a structure itself.

So we have a convenient assessment with which designers can work – a 28 day compressive strength requirement.

At this stage it should be remembered that in arriving at the quality (strength) of concrete, designers will have already incorporated some safeguards for uncertainty into the design process. Partial safety factors are used to increase material strength requirements to allow for some variability in the materials in a structure and in test specimens. Design loading is also increased using partial safety factors to take into account variations that may exceed the expected loading and to allow for inaccuracies in loading assessment and some loss of dimensional accuracy during construction. In the determination of required material properties therefore a built in element of safety already exists.

In selecting concrete type and mix, the need to provide concrete to a reliable standard involves an appreciation of the variability of the constituents that make up a concrete mix as well as its inherent non-uniformity. A statistical approach is taken to allow for variability. In this way the minimum strength requirement is increased so that a characteristic strength is selected and used as a target that within the scale of variability will mean that only some 5% of the test results will fall below the minimum specified level. While this provides a working platform for concrete production it should also mean that the majority of concrete used will be above or well above the limit.

In general this means that compared to the designer's initial requirement well designed and well produced concrete mixes should be more than adequate.

So why do we have non-compliance and how does one deal with this on site.

IN SITU STRENGTH ASSESSMENT

General

Experience has shown that good concrete control can best be developed in plants producing large quantities of concrete so that operators have sufficient time to use their experience to refine and improve performance. This situation applies within the ready-mixed concrete industry and can also be achieved on larger scale projects where large batching and mixing plant are in use for a long period.

Against such a background it should be rare for cube strengths to fall below specified levels and it is normal for material as supplied to be adequate for its purpose. However, there are occasions when cube strengths are not up to scratch or when construction problems may suggest that the potential of the concrete has not been realised in practice. In such cases there is a need to make an evaluation of the strength of the concrete that is 'in place'.

Some form of non-destructive scanning system that could be used to directly relate its readings with concrete strength would be ideal. Unfortunately, at present, no such system exists. Although much development work is being done on scanning systems they are currently aimed at identifying and locating reinforcement, the presence of corrosion activity, etc.

So for the time being the use of cores remains the best and only practical system for determining the strength of concrete as and where it was placed. By using this system the core itself also provides an opportunity for a visual assessment of the concrete, the presence of voids, density tests, and a source of samples for material analysis.

Characteristic Strength

The basis for selecting design strength is well defined in BS 5328, BS 6089, CSTR11 and BRE report Design of Normal Concrete Mixes (1988). A summary of the main considerations are as follows :

It is common practice to specify concrete quality based on a 'characteristic strength' below which a specified proportion of the test results, often call 'defectives' may be expected to fall. The characteristic strength maybe defined to have any proportion of defectives, BS 5328 and BS 8110 adopt the 5% defective level in line with the CEB/FIP International recommendations for the design and construction of concrete structures.

As a result of the variability of the concrete in production, it is necessary to design a mix to have a mean strength greater that the specified characteristics strength by an amount termed the margin.

Thus:

$$f_m = f_c + ks$$

where	f_m	=	the target mean strength
	f_c	=	the specified characteristics strength
	ks	=	the margin, which is the product of
	s	=	the standard deviation
	k	=	a constant

The constant k is derived from the mathematics of the normal distribution and increases as the proportion of defectives is decreased, thus :

k	for	10% defectives	=	1.28
k	for	5% defectives	=	1.64
k	for	2.5% defectives	=	1.96
k	for	1% defectives	=	2.33

For the 5% defective level specified in BS 5328 k = 1.64 and thus $f_m = f_c + 1.64s$.

In the UK it is normal to have standard deviations of 4 to 6 Mpa compared to 2 to 3 Mpa for normal strength concrete in Australia. This means strengths are typically 10 Mpa above specified strength in UK and only 5 Mpa higher in Australia. Results in Malaysia are typically not collated but the Author's experience suggests that 4 to 6 Mpa standard deviation is not uncommon. A standard deviation of s = 8 can be considered a worst case value and is often applied in the absence of historical data.

The standard deviation used to calculate the margin should be based either on results obtained using the same plant, materials and supervision, as for example in ready-mixed concrete plants or precast concrete works, or, in the absence of such information on a value which is specified. MS532: Part 4 specifies a 3MPa margin.

Concrete Society Technical Report 11 (TR11)

The Concrete Society published TR11, entitled Concrete Core Testing for Strength, in May 1976, with an addendum update in 1987. This document has been extensively used in insitu assessment of concrete strength. When in situ strengths, estimated from cores are used as a means of assessing the quality of concrete in a structure they are usually compared with specified or anticipated strengths relating to moulded cubes made sorted and tested in a standard way. TR11 demonstrated that even well compacted typically cured concrete would be expected only to have about 80% of the strength at 28 days of standard cubes for the same batch. When allowing for other factors such as typical sedimentation and site compaction and for the effects of poor curing lower values could occur in parts of such common elements as columns, walls and slabs. BS 6089 accepts the realism of this order of values which has been reported in TR11.

Concrete complying with BS 5328 or BS 8110 is permitted to have moulded cube strengths down to 90% of the specified characteristic strength (c) so that estimated strengths of cores from concrete just in compliance could be 0.9 x 0.80 x c = 0.72c.

Thus, when judging an estimate of in situ strength, it is important to consider the possibility of values as low as 0.72c being associated with compliant concrete, compacted and cured to currently accepted standards. If a lower value is obtained it may be indicative of non-compliant concrete or it may be indicative of an adverse construction situation.

TR11 effectively advises in clause A/3.6.2.1 that concrete in an element may be deemed safe if an estimate of in situ cube strength exceeds.

$$\frac{c}{1.5} \times \left(1 + \frac{0.12}{\sqrt{n}}\right) \text{ e.g. } 0.75c \text{ when } n = 1,\ 0.71c \text{ when } n = 3 \text{ etc.} \qquad (1)$$

where n is the number of cores used to assess the in situ cube strength.

Clause 6.5.3 of 6089 advises the use of

$$\frac{c}{1.5} \times 1.2 = 0.80c \qquad (2)$$

as the criterion, irrespective of the number of cores tested.

The TR11 formula takes account of specified characteristic cube strength, partial safety factor y_m number of cores and variability of sampling and testing.

The BS 6089 formula takes account of specified characteristic cube strength, partial safety factor y_m and an extra factor of 1.2.

Concrete Society - Present Research in Updating TR11 (Ref 8)

Introduction

A Concrete Society Working Party is undertaking a revision and update of TR11 with the objective of incorporating cements and combinations which contain pfa and ggbs that have been in common use for a number of years. This report is to be published later this year but the following is a summary of the work so far.

Test Elements

Three types of test elements were manufactured, blocks, slabs and walls.

The blocks are cubic with side length of 1.5m. The formwork for each block consisted of plywood, which was clad internally on five sides with 100mm polystyrene.

Slabs were cast directly on the ground which was topped with a Type 1 sub-base of crushed rock and crushed concrete waste. Slab thickness was set to a minimum of 200mm but probably varied up to 240mm in places.

Walls were cast at least one week after the slabs, and in some cases, two weeks later, to allow sufficient strength gain to accommodate the wall loadings. The formwork was struck after 2 days and a sprayed proprietary curing membrane applied to both faces.

Materials and Concrete Mixes

Cements

The project used the following cements and cement combinations.

Mixes 1-4, Portland cement (BS 12:1996)

Mixes 4 - 8, combination of 70% Portland cement (BS 12) and 30% pfa (BS 3892:Part 1:1997)

Mixes 9-12, combination of 50% Portland cement (BS 12) and 50% ggbs (BS 6699:1992

Mixes 13 - 16, Portland limestone cement (BS 7583:1996)

Aggregates

All the aggregate was supplied with the concrete from Tarmac Quarry Products Ltd., as their standard production run of materials available at the time.

Admixtures

No admixtures were used in the concretes simply to reduce the number of variables.

Mix design

The Project Specification required inclusion of:

- two cements, two combinations, making a total of four cement types
- two strength levels
- two aggregate types; natural rounded aggregate and crushed rock.

Mix designs were set such that for each mix two strength levels providing a low strength (30 N/mm^2) and a medium strength (50 N/mm^2) were developed. All relevant details are given in Table 1 below.

Concrete Grades	**30N/mm^2 and 50N/mm^2 Target Mean Strength**

<table>
<tr><td rowspan="4">Mix Code and Cement Type</td><td>PC</td><td colspan="2">- Portland cement conforming to BS 12</td></tr>
<tr><td>P/FA-B</td><td colspan="2">- A combination of 70% Portland Cement to BS 12 and 30% pfa to BS 3892:Part 1</td></tr>
<tr><td>P/B</td><td colspan="2">- A combination of 50% Portland cement to BS 12 and 50% ground granulated blastfurnace slag conforming to BS 6699</td></tr>
<tr><td>PLC</td><td colspan="2">- Portland limestone cement conforming to BS 7583</td></tr>
<tr><td>Aggregates</td><td colspan="3">Uncrushed quartzite and pit sand
Crushed limestone with limestone fines and pit sand</td></tr>
<tr><td rowspan="3">Structures</td><td>Walls</td><td colspan="2">- 3m high, 2 metres long and 0.3 metres thick</td></tr>
<tr><td>Slabs</td><td colspan="2">- 2m square and 0.2 metres thick</td></tr>
<tr><td>Blocks</td><td colspan="2">- 1.5m cube (insulated on all but one exposed vertical face)</td></tr>
<tr><td>Casting phases</td><td colspan="3">Winter (Feb 24 to March 12) and Summer (June 16 to July 2) 1997.</td></tr>
<tr><td>Cores</td><td colspan="3">100mm diameter, nominally 110mm long cores taken and tested at four ages: 28, 42, 84 days and 1 year. Four cores at each age for each structure, except the blocks which were cored at two locations, near to and distant from the insulated end.</td></tr>
<tr><td>Cubes</td><td colspan="3">100mm cubes tested at 7, 28, 42, 84 days and 1 year. Two cubes at each age, except three at 28 days.</td></tr>
<tr><td colspan="4">Note:
Concrete for the blocks and slabs was supplied in one truckload and the walls cast one week later, along one edge of the corresponding slab and strutted to the slab, thus avoiding the need for wall foundations.

Cores were prepared by cutting and grinding to provide a test length of around 110mm. By choosing finished core sample of 110mm length, correction factors are obtained of 0.954 and 1.037 for vertically and horizontally cut cores relative to the casting direction and reduces the correction to a minimum.

P/B and P/FA-B are nomenclature defined by the Quality Scheme for Ready-Mixed Concrete which are in use throughout the ready-mixed concrete and construction industry in UK.</td></tr>
</table>

Table 1 Concrete strength, cement combinations, aggregate types, structure sizes, casting periods and details of the cube and core sampling. (Reproduced from Reference 8)

Results and Discussion

General

While the core strengths described herein **have** been corrected for the fact that their lengths are not quite equal to their diameters they **have not** been corrected for any density difference from their companion cube or adjusted to take account of any variation in strength, that might be due to the direction of coring relative to the casting direction.

In the analysis of the strength data, where more than two results were available, outliers (results deemed to be spurious) were identified and excluded using Cochran's Test (see BS 5497:Part 1:Precision of test methods). Error bands on strengths and strength ratios, are for a 95% confidence level.

Fresh and hardened concrete density

As far as the test elements are concerned, the results show that the blocks have lower densities than either the slabs or walls. This could reasonably be attributed to a poorer degree of compaction in the blocks. This raises the interesting point of whether, in general, larger elements tend to be less fully compacted than smaller ones, using poker vibrators in a conventional way.

Cube and core strengths

In order to appreciate the complex interrelationships affecting in situ strength development, viz cement type, element size, ambient temperature and continued hydration, it is instructive to examine the changes with age of the ratio of core strength to 28 day cube strength. These are plotted in Figures 1 and 2 below.

Inspection of *these graphs* shows that the strength development of the cores in the test elements may, or may not, follow that of the companion cubes. In general, the similarity is nearest for the lower strength mixes and widest apart for the stronger mixes. There is clearly a complex influence of cement type and concrete strength level, combined with element type, on the in situ strength development. This includes effects due to:

The temperature generated by the concrete mix due to cement hydration and its effect on early and later strength.

The size of the test element and the influence of this both on the temperature rise due to cement hydration and heat losses to ambient.

For the mixes containing PC, ratios are lowest for the cores from the blocks and, usually, the ratios for cores from slabs are the highest. The ratios for blocks tend to be lower when the concrete strength is higher, for example from graphs 69 and 70 for the PC, the values are 0.85 compared with 1.00 at 365.

This has important implications for investigation of existing structures when due to restricted access and/or critical structural elements cores may not be taken at the element of concern but at an adjacent area where similar concrete is used.

SERVICE LIFE

While the need to deal with concrete strength non-compliance to design load requirements is well established, durability and therefore service life issues is seldom considered during remedial works. Understrength concrete and low cover provide the ideal conditions for the ingress of the environment to the level of reinforcement and possible initiation of corrosion mechanisms.

For instance in buildings away from the marine environment the primary corrosion mechanism is likely to be carbonation damage. Here a low strength cover concrete could reduce time to penetration considerably. However if design strength considerations are within allowable requirements a coating of anti-carbonation paint could restore life cycle requirements to their original intent without any further remedial measures. Such considerations may be achieved at relatively low cost and should therefore be carefully considered.

CASE STUDY : NON-COMPLIANCE CONCRETE ASSESSMENT - A 19 STOREY LOW COST FLAT DEVELOPMENT

Background

Taywood Engineering Sdn. Bhd. (TEL) were engaged to conduct a technical assessment and recommendation for the concrete strength used at low cost flats being constructed in the state of Selangor.

The site consisted of four blocks of 19 storey flats upto. At the time of the investigation, the construction had stopped at about floor twelve in all four blocks. The non-compliant concrete has been a major concern particularly in terms of the concrete strength. Therefore, all the problematic areas had to be identified and further tested to determine whether remedial actions were necessary.

Two main Ready-Mix Concrete Suppliers (A and B) supplied Grade 25 concrete for the project between late 1996 and early 1998.

Due to the perceived problems of concrete non-compliance, the Structural Consultant had instructed some testing to be undertaken to determine the in-situ strength of the structural elements. In this context, Laboratory A was engaged to undertake core and Ultrasonic Pulse Velocity (UPV) testing. In addition, Laboratory B was also engaged to carry out coring at various locations.

TEL were invited to act as an Independent Consultants to assess and review the issues involved with concrete non-compliance.

Concrete Cube Results

As part of the quality control for fresh concrete deliveries to site, cube samples were taken and tested for compressive strength.

For the concrete strength compliance, the BS 5328 Part 4 : 1990 (Clause 3.16.2) and the local standard, MS 523 Part 4 : 1993 (Clause 3.16.2) state that all test results shall satisfy both the following requirements:

a) The mean strength determined from the first two, three or four consecutive test results or from any group of four consecutive test results complies with the appropriate limits in Column A of the following table.

b) Any individual test result complies with the appropriate limits in Column B of the following table.

Specified Grade	**Group of Test Results**	**A**	**B**
		The mean of the group of test results exceeds the specified characteristic compressive strength by at least:	**Any individual test result is not less than the characteristic compressive strength less:**
C20 and above	first 2 first 3 any consecutive 4	1 N/mm^2 2 N/mm^2 3 N/mm^2	3 N/mm^2 3 N/mm^2 3 N/mm^2

In applying the above criteria, it is normal practice to consider the running average of 4 results as the first requirement, (i.e.) compliance at 28 MPa for Grade 25.

If non-compliance is noted then the running average of 2 and 3 results can also be checked. If non-compliance is confirmed, in-situ testing is then undertaken to confirm if remedial measures are necessary.

Grade 25 Concrete a 28 Days Strength

Taking the rolling mean of 4 as the initial non-compliance criteria (i.e.) concrete strength > 28 MPa as being compliant and that any individual test result is not below 22 MPa. For the period between 3 February 1997 and 2 September 1998, Grade 25 concrete supplied by both Companies A and B at the following dates required further investigation:

	Dates	Concrete Supplier
1.	10 May to 12 May 1997	A
2.	6 June to 10 June 1997	A
3.	20 June 1997	A
4.	27 June to 1 July 1997	A
5.	10 July 1997	A
6.	15 July 1997	A
7.	28 July to 30 July 1997	A
8.	15 August to 23 August 1997	A
9.	8 September to 15 September 1997	B
10.	2 December 1997	B
11.	30 June 1998	A

Following that, a further analysis using the rolling mean of 2 and 3 criteria (ie.) to meet the 26 MPa or 27 MPa strength requirement respectively was undertaken. This resulted in more periods being of concern. It follows that further in-situ testing would be required in these areas to confirm if in fact strength non-compliance was a problem. The locations of concern analysed based on BS5328 are summarised in Table 2.

Overview of Testing on Hardened Concrete

General

A series of in-situ testing (i.e. coring and NDT testing) was carried out on the structural building elements to examine / assess the concrete strength.

In-Situ Testing by Extraction of Cores

29 nos of cores were randomly taken on the slabs among the four blocks by Laboratory B. In addition, 10 nos and 27 nos of cores were also randomly taken on the slabs and beams respectively by Laboratory A. The 27 nos of cores taken from the beams were used for the purpose of correlating the core results and the in-situ UPV results, which will be discussed in the following section.

All core test results were assessed in accordance with BS 6089:1981 (Guide to Assessment of Concrete Strength in Existing Structures).

In-Situ Ultrasonic Pulse Velocity Test

A assessment using In-Situ Ultrasonic Pulse Velocity (UPV) Testing had been undertaken by Laboratory A at the request of the main consultant. A total of 1776 random sets of In-situ UPV tests were carried out on the beams of the four blocks. Further to that, 27 nos. of approximately 100mm diameter core samples were taken from the beams to establish the In-situ UPV and core strength relationship for the purpose of estimating the in-situ concrete strength of beams.

According to Laboratory A, the UPV testing was carried out in general accordance with BS 1881 : 1996; Part 2.3, Recommendations for Measurement of Velocity of Ultrasonic Pulses in Concrete. The ultrasonic tester measures the time of transmission (transit time) through the material (path length) to enable the velocity to be determined from :

$$\text{Pulse Velocity} = \frac{\text{Path Length}}{\text{Transit Time}}$$

UPV Correlation to In-Situ Strength

TEL analysed the results provided and obtained the correlation between pulse velocity and estimated cube strength (see Table 3). The correlation equation has been used to calculate the estimated in-situ cube strength at all beams tested.

The correlation curve is : $y = 1.2974\,e^{0.7781x}$

where y = the equivalent insitu cube strength in N/mm^2

x	=	the UPV transit time in km/sec
R^2	=	0.4061

The correlation between the UPV and the estimated cube strength was relatively poor with R^2 = 0.406. The results were therefore viewed with caution. In general, if more samples are used to produce the correlation curve, the better the reliability.

Based on the material engineering practice, the estimated equivalent in-situ cube strength is compared to the specified strength divided by 1.25. In this context, the cut off estimated equivalent in-situ cube strength would need to comply with 20MPa at the minimum.

Further Testing by TEL

A series of 36 nos. of cores were extracted by Laboratory A between 23 September 1999 and 28 September 1999 at locations selected and supervised by TEL. The cores were tested for UPV and compressive strength. TEL repeated the exercise with another 10 nos. of cores on 8 December 1999.

All cores were taken at locations that did not comply with the concrete cube strength assessment. The results obtained were therefore at a lower bound and could not be considered representative of the concrete as a whole.

Results and Discussion

Initial Test Results

Block A - Level 11 (Zone 1 & 4) and Level 12 (Zone 1)

At these two locations, the concrete did not meet the required strength based on the cube results. Coring was than undertaken to determine the in-situ strength. The core results at Levels 11 and 12 of the respective zones are less than 25MPa and remedial action is therefore required.

Block B - Level 5 (Zone 1), Level 6 (Zone 1) and Level 7 (Zone 1)

At these three locations of Block B, the concrete failed the cube strength requirements in accordance to the relevant codes and therefore, coring was deemed necessary to determine the in-situ strength. The f_{cu} was found to be within the strength requirements (as tested by Laboratory B) and therefore, no further action was needed at these areas.

Block C - Level 2 (Zone 1 & 4) and Level 6 (Zone 3)

The cube strength at these locations did not comply with the relevant code assessments. Following that, cores were taken to ascertain the characteristic strength, f_{cu}. Based on the assessment, the characteristic strength, f_{cu} at Level 2 (Zone 1 & 4) is much greater than the specified grade in accordance with BS6089 : 1981. The core results at Level 6 (Zone 3) however, fell below the specified grade value of 25MPa.

Block D - Level 6 (Zone 3), Level 7 (Zone 1 & 4) and Level 10 (Zone 2, 3 & 4)

8 nos of cores have been taken at the respective zones of this block following the failure of the cube strength. TEL noted that both Laboratories A and B had taken cores at Level 10 (Zone 2), the results however, show a variation of approximately 13MPa in strength. It is not clear why such a variation was obtained. However as all the available results from this block have complied, no further investigation was therefore deemed required.

<u>TEL Additional Testing</u>

The In-situ Compressive Strength Test results indicate that approximately 31% of the characteristic strength, f_{cu} are less than 25MPa (see Table 4). The average f_{cu} is calculated to be 29.6 MPa. The failure is concentrated at Block A, Level 10 Zone 1 and Block D, Level 7 Zone 4. It was therefore, recommended that strengthening of the beams be undertaken at this particular zone.

Ultrasonic Pulse Velocity Test was also carried out on the cores and the correlation curve between the estimated in-situ cube strength and UPV was also developed. The correlation between the UPV and the estimated in-situ cube strength is rather poor with $R^2 = 0.48$ (see Table 5). The results were therefore used with caution.

Site Practice

TEL did not study any records of the site controls. In-situ strength of concrete can be affected by site practices and this needs some consideration. Poor compaction, early formwork removal, poor curing of concrete and the addition of water to the concrete to increase slump are common site problems which can seriously affect in-situ strength and can only be avoided if strict supervision is implemented on an ongoing basis. Other factors which cannot be discounted are inexperienced workmen handling concrete and poor construction techniques and methods.

Conclusion

Following the systematic assessment undertaken by TEL as discussed above, the number of concerned elements, which needed to be strengthened was significantly reduced from what was originally intended.

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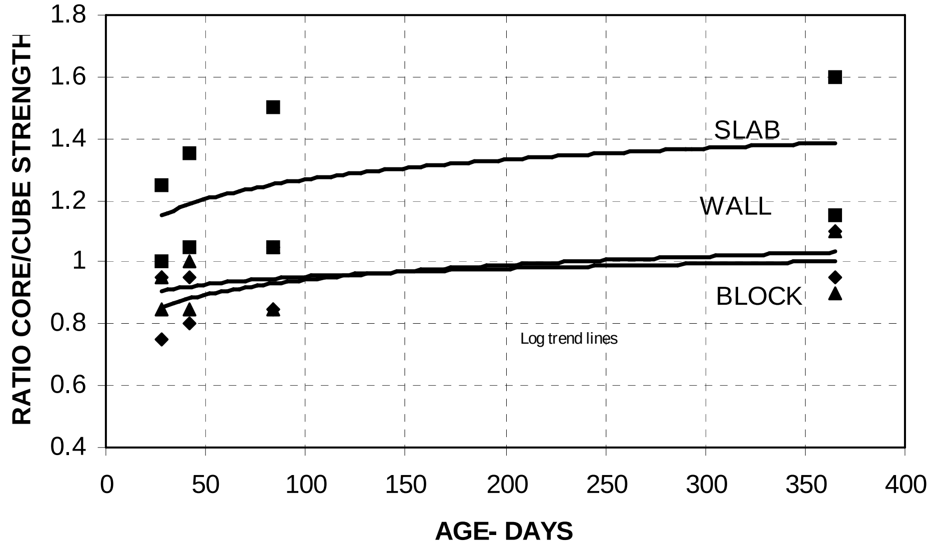
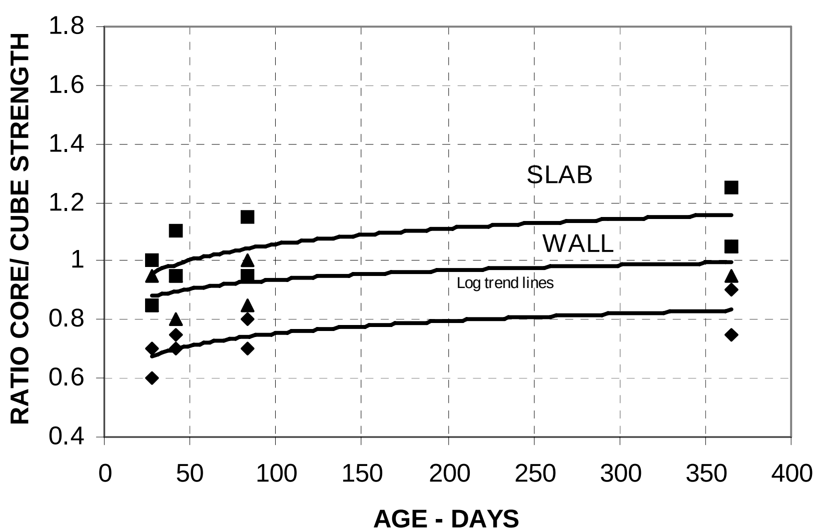


Graph 1 : Strength ratios for PC, C30 mixes 1 & 3



Graph 2 : Strength ratios for PC, C50 mixes 2 & 4

Note: The figures 1 and 2 are from the Concrete Society UK, Reference 8.