Chapter 5

Measuring, Mixing, Transporting, Placing and Testing

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CHAPTER 5

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5.0 Measuring, Mixing and Transporting

The fundamental principles of ASTM C 94 and ACI 304 apply to lightweight concrete as they do to normalweight concrete. Aggregates need to be handled according to the procedures that have been established by the aggregate supplier or the ready-mixed concrete producer. The absorptive nature of the lightweight aggregate requires prewetting to as uniform moisture content as possible before adding the other ingredients of the concrete (ACI 213, 302, 304).

Section 5.1.2 of the materials section of ASTM C 94 requires normalweight aggregates to conform to specification C 33 and lightweight aggregates to conform to C 330. Therefore C 94 permits the use of any combination of these aggregates providing they meet their appropriate specification.

Lightweight concrete can be transported by the same means used for normalweight concrete. This includes ready-mix trucks, pumping, or conveyor belts. The method of transportation used should effectively deliver the lightweight concrete to the point of placement without significantly altering its desired properties with regard to water-cementitious materials ratio, slump, air-content, density, and homogeneity. The method of transportation needs to be determined at preconstruction meetings with consideration given to mixture ingredients and proportions, type and accessibility of placement, required delivery capacity, location of the batch plant, and weather conditions. These various conditions should be carefully reviewed in selecting the type of transportation best suited for economically obtaining quality concrete in place. ACI 304R provides descriptions of the various concrete transportation systems.

5.1 Placing

There is little difference in the techniques required for placing lightweight concrete from those used in properly placing normalweight concrete. ACI 304.5R discusses in detail the proper and improper methods of placing concrete. The most important consideration in handling and placing concrete is to avoid segregation of the coarse aggregate from the mortar matrix. The basic principles required for a good lightweight concrete placement are:

- A workable mixture that meets both quality and placement requirements;
- Equipment capable of expeditiously handling and placing the concrete;
- Proper consolidation; and
- Good workmanship.

Because of its lower density well-proportioned lightweight concrete mixture can generally be placed, screeded, and floated with less effort than that required for normalweight concrete. Over-vibration or overworking of lightweight concrete should be avoided. Delamination issues have been reported on air-entrained normalweight and lightweight concrete floors when riding trowels with float pans have been used prematurely. Over-manipulation can bring excessive mortar to the surface. Upward movement of coarse lightweight aggregate may also occur in mixtures where the slump exceeds the recommendations provided in this chapter.

Pumping Lightweight Concrete (also see ESCSI Information Sheet 4770.1)

General considerations – Unless the lightweight aggregates are satisfactorily prewetted, they may absorb mixing water and subsequently cause difficulty in pumping the concrete. For this reason, it is important to adequately condition the aggregate by fully prewetting before batching the concrete. The conditioning of the lightweight aggregate can be accomplished by any of the following:

- Atmospheric – Using a soaker hose or sprinkler system. The length of time required to adequately prewet a lightweight aggregate is dependent on the absorption characteristics of the aggregate. The lightweight aggregate supplier may be able to supply useful information. Uniform prewetting can be accomplished by several methods, including sprinkling, using a soaker hose, and by applying water to aggregate piles at either or both the aggregate plant or batch plants.
- Thermal – By immersion of partially cooled aggregate in water. It should be carefully controlled and is feasible only at the aggregate plant.
- Vacuum – By introducing dry aggregate into a vessel from which the air can be evacuated. The vessel is then filled with water and returned to atmospheric pressure. This is normally performed only at the aggregate plant.

Prewetting minimizes the mixing water being absorbed by the aggregate, therefore minimizing the slump loss during pumping. This additional moisture also increases the density of the lightweight aggregate. This increased density due to prewetting will contribute to cement hydration with the remainder eventually being lost to the atmosphere (see section 6.2).

Proportioning pump mixtures – When considering pumping lightweight concrete, some adjustments may be necessary to achieve the desired characteristics. The architect/engineer and contractor should be familiar with any mixture adjustments required before the decision is made as to the method of placement. The ready-mixed concrete producer and aggregate supplier should be consulted so that the best possible pump mixture can be produced.

When the project requirements call for pumping, the following “Team approach” rules apply. These are based on the use of lightweight coarse aggregate and normalweight fine aggregate.

“The Team Approach”

Design Engineer

1. Mixes that are regularly used in a market area will be the most economical. Consult the lightweight aggregate suppliers for detailed mixture design information and material capabilities (i.e., unit weight, strength, etc.)
2. Specify 4 to 7 percent air entrainment for pumpability, workability, finishability, and durability.
3. Specify the maximum size aggregate rather than specifying individual sizes.
4. Allow higher slump into the pump to accommodate possible slump loss (slump control at discharge of pump).
5. Have the testing lab run design curves based on the maximum specified slump and air per ACI 301.
6. Specify a pre-pump meeting with the following present: engineer, architect, contractor, ready-mix supplier, lightweight aggregate supplier, testing agency, admixture supplier, and pumping contractor.
7. On large jobs, these same people should be present at the first concrete pump placement.
8. Specify exactly where concrete should be tested, preferably at the end of the discharge line as per ACI 304.2R.
9. Realize that absorbed water does not affect the water/cement ratio, as defined in ASTM C 125.

General Contractor

1. Keep everyone communicating; this is a team effort!
2. Use an experienced pumping contractor.
3. Make arrangements so that two ready-mix trucks can unload simultaneously.
4. Designate a laborer to help the testing lab inspector.
5. Provide a washout area for ready-mix trucks.
6. Make use of the ready-mix truck radio when placement delays occur.
7. Specify to the ready-mix supplier the number of yards needed per hour, not how many truckloads.
8. Make an agreement with the ready-mix supplier as to how the quantity of concrete delivered will be determined.

9. It is necessary to properly lubricate the pump line before placing concrete.

Pumping Contractor

1. Know the concrete unit weight being pumped.
2. Order concrete to coincide with actual pumping time, not when the pump arrives at the job site.
3. Maintain continuous placement.
4. Operator should know the maximum slump allowed.
5. Use 5" minimum clean steel lines; minimize rubber at the end of line; avoid reducers if possible.
6. Keep the same pump and operator throughout the duration of the job.
7. Use a pump whose piston size is as close as possible to the line size to maintain the best performance and least slump loss.

Ready-Mix Producers

1. The lightweight aggregate must be prewetted prior to batching using procedures recommended by the lightweight aggregate supplier.
2. Check with the lightweight aggregate supplier for the recommended pump mix design and field correction procedures.
3. The aggregate moisture content or unit weight should be checked frequently. This is necessary for concrete yield control.
4. Make drivers aware of what admixtures are being used for slump control.
5. Maintain a minimum 3" slump before the addition of “super-plasticizer”.

Testing Labs

1. The field inspector shall be ACI Field Technician Grade 1 (or equivalent) per ASTM C 94.
2. Make sure the inspector has the proper tools including a roll-a-meter for volumetric air tests and a proper strike-off plate for unit weight determination.
3. On large jobs use the same inspector for all concrete placements.
4. The inspector should know fresh unit weight limitations (min and max).
5. Place test cylinders immediately upon casting in a curing box protected from the ambient temperature and vibration per ASTM C 31.
6. Sample for density, slump and air early.

7. Communicate test results promptly to designated parties (superintendent, engineer, Q/C representative, architect, etc.)

Consolidation

During vibration of lightweight concrete, the entrapped air bubbles are brought to the surface through buoyancy and are dissipated in a similar fashion to normalweight concrete. However, the lower density of the mixture results in somewhat less buoyancy for the air bubble. Vibration should continue until entrapped air is removed and stopped before mixture segregation.

Segregation of the concrete mixture ingredients during vibration is caused by differences in material densities. In normalweight concrete, the coarse aggregate is heavier than the mortar and therefore tends to sink during vibration. In lightweight, the reverse is true, although the tendency for the coarse aggregate to float is less when the mortar contains lightweight fine aggregate. Dry mixtures will not segregate as rapidly under vibratory action as wet mixtures.

A thorough discussion of consolidation is given in ACI 309R. The equipment and procedures recommended for consolidating normalweight concrete are also suitable for lightweight concrete, with some additional considerations as described in the following paragraphs.

As with normalweight concrete, lightweight concrete should be placed as closely to its final position as practicable to avoid segregation. Vibrators should not be used to move the concrete laterally. Shovels are frequently helpful in depositing or moving the concrete.

Finishing Floors

Air-entrained structural lightweight concrete has a long history of successful use on suspended floor slabs. This was achieved with properly proportioned quality materials, skilled supervision, and good workmanship. The quality of the finishing will be in direct proportion to the efforts expended to ensure that proper principles are observed throughout the finishing process. Finishing techniques for lightweight concrete floors are described in ACI 302.1R.

Building codes mandate the requirements for fire rated floor assemblies and are explicit with regard to the use of structural lightweight concrete. The concrete used in Fire Rated Underwriter Laboratory floor assemblies, and tested in accordance with ASTM E 119, are assembly specific as regards to density (unit weight) and air content.

By definition, lightweight concrete is lighter than normalweight concrete. This is made possible by replacing heavy, ordinary aggregate with expanded shale, clay or slate lightweight aggregate, and by maintaining air content at approximately 6%. Air entrainment in concrete improves durability and workability, reduces bleeding, and is recommended for lightweight concrete by both ACI 211.2 and ACI 302. For workability and weight reduction, ESCSI recommends 4 to 6 percent air entrainment.

The typical lightweight suspended floor slab is used with floor coverings for foot traffic in office, commercial, multi-unit residential and institutional buildings. ACI 302 calls this type of floor a Class 2 Floor with a flat and level slab suitable for applied coverings, and having a "light" steel-troweled finish. The floor flatness/levelness tolerances for this floor are F_F25/F_L20. On some occasions, flatness/levelness tolerances are higher to meet specific design requirements. The "light" steel-troweled finish is not the same as "normal" or "hard" steel-troweled finish recommended by ACI 302 for commercial or industrial floors subject to vehicular traffic.

The increasing call for faster construction and flatter tolerances has increased the use and development of ride-on power trowels with float pans. This equipment is capable of providing flat floors with a minimal amount of labor, and has been used extensively on non-air entrained slab-on-grade concrete. It is now being used successfully on many elevated floors which are usually constructed with lightweight concrete. The user of this equipment needs to be aware that lightweight concrete is normally air entrained at about 5-6%, and has a different timing sequence during finishing.

Ride-on power trowels with pan floats impart more energy to the concrete surface at an earlier age than walk-behind power trowels. Power trowels with pan floats exert much lower surface pressures, thereby allowing the contractor to commence finishing sooner with this equipment. This can contribute to delamination issues.

Concrete Construction, March 1998, pp. 277-283, reported surface pressures of 0.36 to 0.98 psi for walk-behinds and ride-on power trowels equipped with blades, 0.16 to 0.42 psi for pan floats, and 3.3 to 6.0 psi surface pressure for a person walking on the concrete. ACI 302 recommends that machine floating be started when the concrete will support a finisher on foot without more than a 1/8 to a 1/4 inch indentation. As a general rule, ACI 302 also recommends that when flatness tolerances are not high, power floating should be started as late as possible. This is indicated when a foot print is barely perceptible.

Problems may develop when the floor is power floated prematurely or over worked. This is not a new development. For many decades, delamination has been known to apply to inappropriately timed troweling.

Manny Mattos of D&M Concrete Floor Company, Fall River, MA, has reported that success of time-tested rules of thumb for finishing concrete and knowing when to start power floating: (1) When the top surface allows a footprint indentation no deeper than 1/8". or in some cases 1/4 "; (2) When no bleed water sheen is visible on the surface. "We finished a lot of lightweight air entrained concrete floors without blistering or delamination problems. We always start our power floating operation on a lightweight floor using a 36" walk-behind machine with a float pan. This ensures we are not on the floor too soon, because the heel (footprint) test is fool-proof. After the first power float, we then use a ride-on power trowel with float pans".

Awareness of surrounding weather conditions must also be taken into consideration. Sun, wind and broad changes in temperature and humidity during the placing and finishing operation will play a big part in crusting, blistering and delamination issues. These conditions need to be part of the discussion at a pre-slab construction meeting.

Slump - Slump is an important factor in achieving a good floor surface with lightweight concrete and generally should be limited to a maximum of 5 in. (125 mm). A lower slump of about 3 in. (75 mm) imparts sufficient workability and also maintains cohesiveness and body, thereby preventing the lower-density lightweight coarse particles from working to the surface. This is the reverse of normalweight concrete where segregation results in an excess of mortar at the surface. In addition to surface segregation, a slump in excess of 5 in. (125 mm) may cause unnecessary finishing delays.

Good practice - A satisfactory finish on lightweight concrete floors can be obtained as follows:

a. Prevent segregation by:
    1. Using a well-proportioned and cohesive mixture;
    2. Requiring a slump as low as possible;
    3. Avoiding over-vibration;

c. Time the placement operations properly;
d. Use magnesium, aluminum, or other satisfactory finishing tools;
e. Perform all finishing operations after free surface bleeding water has disappeared; and
f. Cure the concrete properly.

Curing

Upon completion of the finishing operation, curing of the concrete should begin as soon as possible. Ultimate performance of the concrete will be influenced by the extent of curing provided. ACI 302.1R and ACI 308.1 contain information on proper curing of concrete floor slabs.

Unlike traditional curing where moisture is applied to the surface of the concrete, internal curing occurs by the release of water absorbed within the pores of lightweight aggregate. Absorbed water does not enter the w/cm ratio that is established at the time of set. As the pore system of the hydrating cement becomes increasingly smaller, water contained within the relatively larger pores of the lightweight aggregate particle is wicked into the matrix, thus providing an extended period of curing. The benefits of internal curing have been known for several decades where ordinary concrete incorporating the lightweight aggregate with a high degree of absorbed water has performed extremely well in bridges, parking structures, and other exposed structures. Internal curing is beneficial for high-performance concrete mixtures containing supplementary cementitious materials, especially where the w/cm is less than 0.45. These low w/cm mixtures are relatively impervious and vulnerable to self-desiccation because external surface curing moisture is unable to penetrate.

5.2 Laboratory and Field Control

Changes in absorbed moisture or relative density of lightweight aggregates, which result from variations in initial moisture content or grading, and variations in entrained-air content suggest that frequent checks of the fresh concrete should be made at the job site to ensure consistent quality (ACI 211.1). Sampling should be in accordance with ASTM C 172. Tests normally required are: density of the fresh concrete (ASTM C 138); standard slump test (ASTM C 143); air content (ASTM C 173); and Standard Practice for Making and Curing Concrete Test Specimens in the Field (ASTM C 31).

At the job start, the fresh properties, density, air content, and slump should be determined promptly to verify that the concrete conforms to the laboratory mixture. Small adjustments may then be made necessary. In general, when variations in fresh density exceed 3 lb/ft^3 (48 kg/m^3), an adjustment in batch weights may be required to meet specifications. The air content of lightweight concrete should not vary more than ± 1-1/2 percentage points from the specified value to avoid adverse effects on concrete density, compressive strength, workability, and durability.

5.3 Laboratory Testing Programs

Systematic laboratory investigations into the physical and engineering properties of high strength lightweight concrete are too numerous to be elaborated here. Most early programs extending strength/density relationships were conducted by lightweight aggregate manufacturers and innovative precast concrete producers striving for high early-release strengths, longer span flexural members, or taller one-piece precast columns (Holm 1980a). These in-house programs developed functional data directly focused on specific members supplied to projects. In general, project lead-times were short, the practical considerations of shipping and erection were immediate, and mixtures were targeted toward satisfying specific job requirements. This type of research brought about immediate incremental progress but, in general, was not sufficiently comprehensive.

Unfortunately, some investigations did not take advantage of the advanced admixture formulations or pozzolans and slag (i.e., HRWRA, silica fume, fly ash, ground granulated blast-furnace slag) that significantly improve matrix quality, and as such provide data of no commercial value. These investigations, as well as others incorporating unrealistic mixtures, inappropriate lightweight aggregate, or impractical density combinations, are not reported.

Special requirements of offshore concrete structures have now brought about an explosion of practical research into the physical and engineering properties of high strength lightweight concrete. Several large, initially confidential joint-industry projects have become publicly available as the sponsors release data according to an agreed-upon timetable. These monumental studies, one of which was summarized by Hoff (1992), in addition to providing comprehensive physical property data on high strength lightweight concrete and high strength specified density concrete developed innovative testing methods such as, revolving disc tumbler and sliding contact ice-abrasion wear tests, freeze/thaw resistance to spectral cycles, and freeze bond testing techniques, which measured properties unique to offshore applications in the Arctic.

Major North American laboratory studies into properties of high strength lightweight concrete include those conducted at or sponsored by Expanded Shale, Clay, and Slate Institute (1960); Malhotra (1981, 1987); Seabrook and Wilson (1988); Ramakrishnan, Bremner, and Malhotra (1991); Berner (1992); and Luther (1992). Because of their special structural needs, much work has been conducted by Norwegian sources, with additional important contributions from other Russian, German, and UK sources. some of which have been referenced by Holm and Bremner (1994).

It has been estimated that the cost for these commercially supported research programs investigating the physical and structural properties of high strength lightweight concrete has exceeded several million dollars (Hoff 1992). While much research has been already effectively transferred into actual practice on current projects, there remains a formidable task of analyzing, digesting, and especially codifying this immense body of data into design recommendations and code standards.

5A

“Evaluation of Non-Destructive Strength Testing in Lightweight Concrete”

Evaluation of non-destructive strength testing of lightweight concrete

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An extensive laboratory experimental study has been undertaken to assess the reliability of a range of non-destructive strength testing techniques applied to lightweight concretes. These tests have included the most widely used non-destructive and partially-destructive methods as well as small diameter cores. The range of concretes examined encompasses lightweight aggregate types used in the United Kingdom, and includes the use of both natural sand and lightweight fine materials to provide cube compressive strengths up to 50 N/mm². It has been demonstrated that, with one exception, all the tests considered may be applied satisfactorily to all the concrete types examined. Correlations between measured values and compressive strength are shown to differ according to aggregate type and the nature of fine materials used. In many cases, the variability of results is less than might be expected for normal dense aggregate concrete, and accuracy of strength estimation is generally comparable or better than for dense aggregate concretes, provided that appropriate specific correlations are used.

Introduction

Interest in the determination of in-situ concrete quality and strength has increased steadily in many countries for over 30 years. In recognition of the growing need for in-situ testing, a great deal of research has been carried out to assess the reliability of a range of techniques applied to concretes made from natural dense aggregates.

2. Despite a steady growth in usage of concrete made from lightweight aggregates over a similar period of time, the appraisal of such structures has received only limited attention. Research based on these materials as used in the UK has recently been reviewed by Mays and Barnes,[1] together with a consideration of durability performance of a selection of structures built before 1977. It is reported that there is no evidence to suggest durability which is inferior to dense aggregate concrete, although increased sensitivity to poor workmanship is noted. It is nevertheless likely that the need for in-situ testing will increase, and present information related to lightweight concrete is scattered and sparse.

3. In recognition of this situation, an extensive and systematic laboratory experimental study has recently been undertaken in the Department of Civil Engineering at Liverpool University. This programme has encompassed the most widely used non-destructive and partially-destructive test methods as well as small diameter cores. Their application to three different types of lightweight aggregate used in the UK, together with the use of either lightweight or natural sand fines, has been considered for cube compressive strengths up to 50 N/mm². The principal findings of the study are summarized in this Paper, which also provides guidance for site investigations to determine in-place concrete strength.

Experimental programme

Materials

4. Three types of lightweight coarse aggregate were used:

(*a*) Lytag: sintered pulverized fuel ash (12 mm)
(*b*) Leca: pelletized sintered clay (12 mm)
(*c*) Pellite: pelletized foamed slag (10 mm)

5. Leca and Pellite were both known to be of limited application for structural purposes when used in conjunction with lightweight fines; only low strength levels are possible with Leca used in this way, while potential mixing difficulties with Pellite were confirmed by preliminary trials. These two materials were therefore only considered for mixes incorporating a North Notts Zone M quartzitic sand fine aggregate. Lytag, however, was used in combination with lightweight fine material of similar origin, as well as with natural sand. The mixes containing Lytag fines will be identified subsequently as 'All-Lytag', while those containing sand will be referred to as 'Lytag'.

6. Four different mixes were designed for each material to provide a range of cube strengths up to 50 N/mm² at 28 days using Castle ordinary Portland cement. Lightweight coarse aggregates were used in an air-dry condition, while lightweight fine material was oven-dried to minimize mix variability resulting from variations in moisture content of the material as supplied. The cement was supplied in bags, and material from a single batch was used throughout.

7. Four normal weight mixes with similar strength levels were also made with North

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Notts 20 mm and 10 mm crushed gravel coarse aggregate for comparison.

Specimens

8. A range of specimens was made for each mix to suit the particular test methods. Wherever possible, use was made of standard laboratory specimens; but where larger specimens were necessary, these were made using plywood moulds as detailed below. Compressive strengths were measured on 100 mm and 150 mm cubes, while both static and dynamic elastic modulus as well as tensile splitting strength measurements were made on 500 mm × 100 mm × 100 mm prisms and 300 mm long × 150 mm dia. cylinders. Tests were performed at seven and 28 days after casting in each case, with specimens subjected to both wet and dry curing regimes. For non-destructive methods, additional tests were taken at other ages up to 28 days, while a limited range of tests was made with all methods at later ages up to 360 days. All specimens were compacted on a vibrating table. Wet-cured specimens were kept under water in a 20°C curing room, with dry-cured specimens stored in a dry laboratory atmosphere after 24 hours of initial moist curing under damp hessian and polythene sheeting.

9. In addition to the specimens outlined above, one 2·2 m × 0·3 m × 0·5 m reinforced beam was made for each of the five concrete types, using mixes designed to give 28 day cube compressive strengths of about 30–40 N/mm^2. These required five batches in each case, and were used to assess in-place strength variability in elements of a size that might be encountered in practice. The beams were all subjected to seven days curing under damp hessian before storage in the laboratory atmosphere.

Test methods

10. All the methods used are well established and are described in detail in textbooks[2] and elsewhere. Available apparatus has also recently been described by the first Author.[3] In each case, testing was performed in accordance with the procedures defined in the relevant British Standards.

11. *Non-destructive methods.* Although these are not recommended for quantitative strength estimation, on account of the large number of factors that influence correlations, they may play a valuable comparative role.

(*a*) Surface hardness: BS 1881, Part 202.[4] A type N rebound hammer was used for tests on 100 mm cubes clamped in a compression testing machine. Each result comprised the average of 45 tests. Fifteen measurements were made on the moulded faces of each of three separate specimens, which were later crushed to provide a compressive strength value.

(*b*) Ultrasonic pulse velocity: BS 1881, Part 203.[5] Pundit apparatus with 54 kHz transducers was used on 100 mm and 150 mm cubes, each result representing two tests between side faces on each of three specimens, which were later crushed to provide a compressive strength value.

12. *Partially-destructive methods.* These all cause a limited amount of localized surface damage, but correlations with compressive strength for normal-weight concretes are affected by a smaller range of variables than the non-destructive methods. All are included in BS 1881, Part 207.[6]

(*a*) *Penetration resistance.* Windsor Probe equipment was used in conjunction with 1000 mm × 150 mm × 250 mm unreinforced concrete beam specimens to achieve adequate edge distances and spacings between test points. These were all located in the mid-height region of the side faces of the beams to minimize the effects of within-specimen variability. Each result represented the average of three 'gold' probes, which are intended for testing lightweight concrete, used at 'low' power setting of the instrument. Attention was concentrated on 'All-Lytag' concrete for comparison with published results on other concrete types, and compressive strengths were based on the mean of three 100 mm cubes.

(*b*) *Internal fracture.* Two versions of this test were undertaken involving different load application techniques. These comprised the commonly used torquemeter method developed by the Building Research Establishment (BRE), and a direct pull approach using apparatus developed by Bungey.[7] In both cases, tests were performed on side and bottom faces of 150 mm cubes, each result being the average of three tests on each of two cubes, which were later crushed. Correction factors for compressive strength of such specimens were established by comparison with a limited number of undamaged cubes of the same size.

(*c*) *Pull-out.* Lok-Test apparatus (model L12.3) was used to test standard 25 mm dia. inserts cast 25 mm deep in each of the six faces of 200 mm cubes, which were necessary to achieve adequate edge distances. Compressive strengths were based on the mean of three 100 mm cubes.

(*d*) *Pull-off.* Limpet apparatus was used in conjunction with aluminium disks which were 20 mm thick and 50 mm in diameter. These were fixed to the prepared concrete surfaces of two opposite side faces of 150 mm cubes, using Devcon '5-minute' Epoxy adhesive. Each result represented the average value obtained for three such specimens, which were subsequently crushed to provide a compressive strength value. A limited number of tests on companion undamaged cubes established that the damage caused by surface pull-off tests did not affect the compressive strength measured across undamaged faces.[8] Tests were also undertaken on specimens with partial coring to a depth of 20 mm, in which case, compressive strengths were based on the mean of three companion 150 mm cubes.

It should be noted that the tests with this method were extended considerably beyond the range of variables described in this Paper, and detailed results have been reported elsewhere.[9]

(*e*) *Cores*. Experimental limitations restricted tests on cores to the use of 50 mm nominal diameter. While smaller than the preferred diameter recommended by BS 1881, Part 120,[10] cores of this size are not uncommon in practice owing to physical constraints, and these specimens were tested in accordance with the procedures given in the Standard. The cores were cut from 650 mm × 225 mm × 120 mm unreinforced beam specimens, both horizontally and vertically relative to the direction of casting. They were capped with a sand/sulphur mixture, with a range of length/diameter ratios between 1·0 and 2·0. Each result represented the average of three cores and was related to the compressive strength obtained by crushing three 100 mm cubes.

Discussion of test results

13. Key features of the results obtained are summarized here and are illustrated by Figs 1–11 and Tables 1–4. More extensive details of both test and analytical procedures, and detailed results, have been provided by Madandoust.[8] It is important to recognize that the results which are presented relate only to laboratory specimens at ages of less than one year, and in each case, are relevant only for the particular combination of variable parameters used. Strength correlations are known to be affected in practice by many factors, including mix constituents, curing, environment and age.

14. Emphasis in this study has been placed on comparisons between the effects of different aggregate types in each case and, except where indicated, the correlations which are given in Figs 1–8 and Table 1 should not be applied directly to either laboratory or in-situ testing without experimental verification.

Surface hardness

15. Initial tests confirmed that, as expected, higher rebound numbers were obtained on bottom faces of cubes than on side faces. Leca concretes were especially susceptible to this effect, while 'All-Lytag' concrete, with only a 5% differential, performed better in this respect than both Lytag and normal concrete at 11%. Comparisons of strength correlations based on values from side faces of cubes indicated clearly that, as for normal-weight concretes, different correlations were obtained for different aggregate types, as illustrated in Fig. 1. Individual data points have been omitted to assist comparisons, but there was considerable scatter about each of the lines shown. These results were obtained by varying the age for dry-cured specimens of one mix only for each aggregate type, with a 28 day cube strength of approximately 35 N/mm^2 (25 N/mm^2 for Leca). Further cases were not considered because of the known susceptibility of the test method to a wide range of variables including curing conditions and mix proportions. 'All -Lytag' concrete yielded the highest rebound number at a given strength level; but with the exception of Leca, all correlations tended to merge at cube strengths below 15N/mm^2. Leca concrete gave substantially higher strengths corresponding to low rebound numbers than did other materials.

16. With the exception of Leca, where high within-specimen variability was known to be present, all lightweight concretes yielded averaged test coefficients of variation between 6% and 8% compared with 10% obtained on the normal-weight concrete.

Ultrasonic pulse velocity

17. Ultrasonic pulse velocities in normal-weight concrete are known to be affected similarly by a wide range of variables. This feature was confirmed for the lightweight aggregates used, and attention was concentrated on the influence of aggregate type on strength correlations developed by varying age for low and high strength mixes subjected to both dry and wet curing conditions in each case. For every lightweight aggregate type, it was found that separate curves relating pulse velocity and strength were obtained for each of the mixes

Fig. 1. Comparisons of rebound hammer correlations

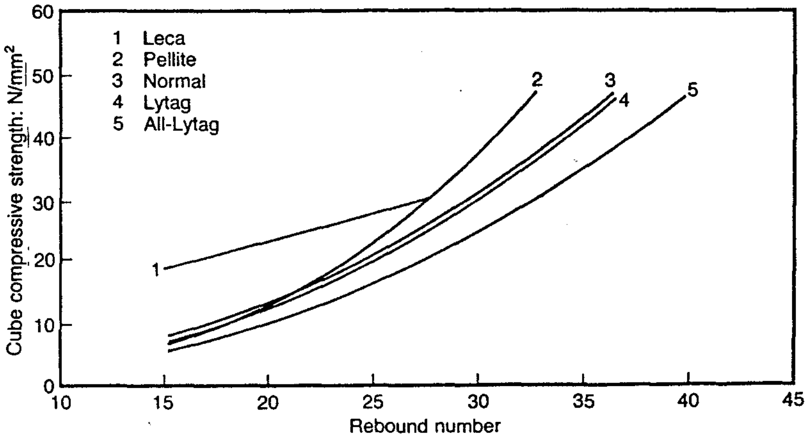


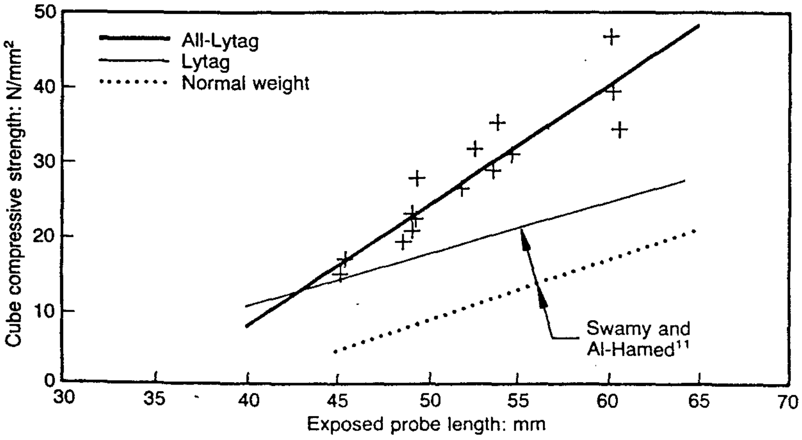
Table 1. Illustrative comparison of effect of aggregate type on Ultrasonic Pulse Velocity for wet-cured specimens at various strength levels (km/s)

Concrete type	Cube compressive strength: N/mm^2				
	20	25	30	40	50
Pellite	4·10	4·17	4·25	4·35	4·45
Lytag	3·67	3·77	3·85	3·97	4·10
All-Lytag	3·45	3·50	3·60	3·70	3·75
Leca	3·40	3·50	3·62	—	—
Normal[2]	4·25	4·35	4·45	4·60	4·70

and both curing regimes. It was noted that in all cases the correlation differences were greatest for dry-cured specimens, possibly on account of the dominant influence of the large amount of water present in the wet-cured lightweight concretes at the time of test. A limited number of longer term tests at up to 360 days of storage in the laboratory atmosphere suggested that this effect may lead to significant errors if short-term correlations are used for longer term strength assessments.

18. Table 1 compares pulse velocities at different strength levels for the strongest mix for each of the lightweight aggregate types when subjected to wet curing at ages up to 28 days. It must be emphasized that the numerical values relate only to the specific mixes and curing conditions used, and that these comparisons are purely for illustrative purposes, but the effects of aggregate type can be clearly identified. The use of natural sand increases the pulse velocity at a given strength level for Lytag concrete, as would be expected from the resulting increase in elastic modulus, but all pulse velocities are significantly below those to be expected on normal concretes at comparable strength levels.[2] With the exception of Leca, coefficients of variation were found to be below the value of 1·5% suggested for normal-weight concrete.[2]

Fig. 2. Comparisons of Windsor Probe correlations (Low Power)



Penetration resistance

19. Initial attempts to use 'standard' power settings caused splitting of specimens. 'Low' power was therefore used throughout, despite strength levels which would suggest the need for 'standard' power. Variability between groups of three individual measurements were always within the allowable range of 5 mm specified by the manufacturer. It was found that age of test (seven or 28 days) and curing conditions had little effect on strength correlation for the 'All-Lytag' concrete tested, but this cannot necessarily be assumed to apply for older concretes. The overall relationship obtained is compared with published results[11] for Lytag and normal gravel concretes in Fig. 2. The scatter of results can readily be seen, as well as the marked differences between concrete types. It must be noted that the normal-weight concrete results here relate to the use of 'silver' probes.

20. Attempts were also made to estimate cube strengths from a procedure suggested by the equipment manufacturer for lightweight aggregates. These were found to differ substantially from measured values except for strengths in the region of 20 N/mm^2, confirming the findings of Swamy and Al-Hamed[11] concerning the unreliability of manufacturers' relationships for lightweight concrete. The typical coefficient of variation of test results of 2·5% obtained here was found to be within the range reported for Lytag concrete by the same authors, and is less than the value of 4% to be expected on normal-weight concrete.[2] Ninety-five percent confidence limits for strength estimations for the 'All-Lytag' concrete tested here were found to be ±26% at the 30 N/mm^2 cube strength level, compared with ±20% expected for normal-weight concrete.

Internal fracture

21. An average reduction in compressive strength between 'damaged' and sound cubes was found to be 4·3%, which is similar to that reported for comparable normal-weight concrete specimens.[7] This factor has been applied to all such compressive strength values reported here.

22. Figures 3 and 4 present overall strength correlations for each aggregate type for the two different load application methods. Individual data points are provided for only one case in Fig. 3 to illustrate the typical scatter obtained. These have been omitted for other cases in Figs 3 and 4 to permit easier comparisons of correlation curves. The major differences between concrete types for the torquemeter method can be clearly seen in Fig. 3, while the closer agreement achieved by the direct pull method is apparent in Fig. 4. It is nevertheless recommended that a specific correlation is necessary for each particular aggregate type, whichever

method is used. Results for Leca concrete were mostly unsatisfactory, as a result of the particularly soft nature of this aggregate. This resulted in little resistance to the expansion clip on the anchor bolt, which allowed the bolt to pull completely through the clip. For the other materials, curing condition and mix proportions were found to have little effect on strength correlations, although applicability of the short-term relationships shown in Fig. 3 for the BRE method to older concrete is questionable.

23. It is clear that for both loading methods, pull-out resistance is less for lightweight concretes than for normal-weight concretes at a given strength level. This is accentuated when a twisting action is applied to the bolt as in the BRE method, and the use of lightweight fines in the 'All-Lytag' concrete gives a particularly reduced torque resistance. With the exception of Leca concrete, the measured coefficients of variation of the lightweight concretes are less than those for normal-weight concrete of comparable strength, as illustrated in Table 2, with the direct pull values being generally less variable than the torquemeter method. Strength estimation accuracies are also better for the direct pull method (Table 3) except for Leca, but are generally similar or worse than those for normal-weight concrete despite the lower variabilities of measured values.

Pull-out

24. Tests on bottom faces of specimens made with Leca were found to yield results approximately 70% higher than those on side faces, owing to the lack of uniformity of aggregate distribution. Bottom face values were therefore discarded in this case, but for other concretes only minimal differences of this type were found. Curing conditions and age of test were found to have only minor influence on strength correlations, and it was confirmed that short-term correlations could confidently be used for tests at later ages, as is the established case for normal-weight concretes.

25. Figure 5 shows that strength correlations for all types of lightweight concrete are very close together over the whole strength range, but are significantly different from that for normal-weight concrete. Individual data points have generally been omitted for clarity, but the three points shown for normal-weight concrete obtained here correspond well to previously reported correlations,[12] which are widely regarded as applicable to all natural aggregate concretes irrespective of age. This important feature of the pull-out test is a function of the test mechanism involved,[2] and it is suggested that a generalized correlation may also be acceptable for lightweight aggregates if specific correlation for the aggregate type is

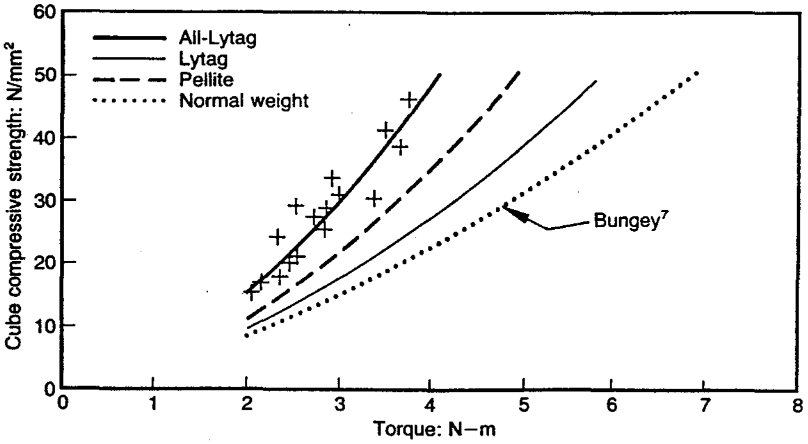


Fig. 3. Comparisons of internal fracture correlations (BRE method)

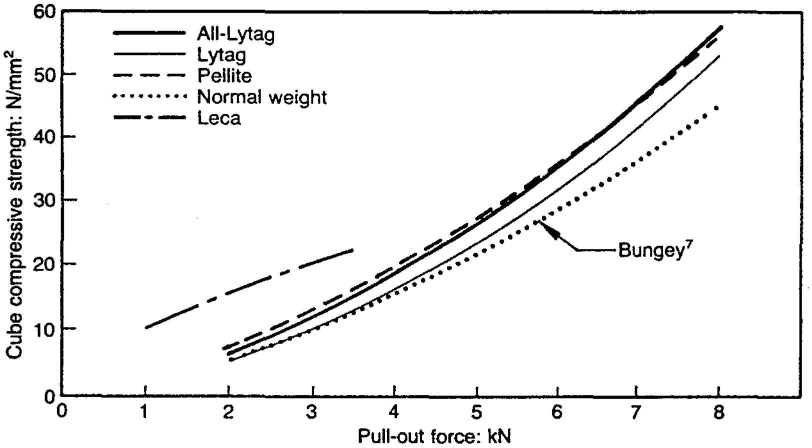


Fig. 4. Comparisons of internal fracture correlations (direct pull method)

Table 2. Summary of coefficients of variation (%)

Concrete type	Approx. cube strength: N/mm²	Test method			
		Internal fracture: BRE	Internal fracture: direct-pull	Pull-out	Pull-off (surface)
Pellite	35	13·6	8·7	7·4	9·0
Lytag	35	13·4	8·3	7·0	8·6
All-Lytag	35	9·0	9·8	5·6	5·7
Leca	25	—	34·0	12·0	23·8
Normal	35	15·9	15·6	7·0	8·0

Table 3. Summary of estimated strength prediction accuracies (95% confidence limits)

Concrete type	Test method			
	Internal fracture: BRE	Internal fracture: direct-pull	Pull-out	Pull-off (surface)
Pellite	±26%	±18%	±18%	±24%
Lytag	±39%	±32%	±13%	±19%
All-Lytag	±34%	±16%	±17%	±24%
Leca	—	±77%	±23%	±15%
Normal	±28%[2]	±20%[2]	±20%[2]	±25%

unavailable. The reduced pull-out capacity of lightweight concrete at a given strength level is attributed to the absence of aggregate interlock contributions to the failure mechanism. With the exception of Leca, variability (Table 2) and strength estimation accuracy (Table 3) with this method are again comparable to, or better than, those for normal-weight concrete.

Pull-off

26. Results for surface tests are compared in Fig. 6, from which the influence of aggregate type can be clearly seen. This emphasizes the need for specific correlation according to aggregate type. Pull-off strengths have been calculated on the basis of the nominal contact area between disk and concrete, in spite of 'overbreaking' ranging from 1 mm to 8 mm. Difficulties were encountered in achieving reliable bonding for the wet cured specimens without a considerable drying period necessitated by the high water absorption of the lightweight aggregate. The results presented here are therefore confined to the dry curing regime, but cover a range of mixes and test ages. Good agreement was found between long-term tests up to 360 days and those correlations based on tests up to 28 days,[8] as illustrated by the typical case shown in Fig. 7. Variability of results (Table 2) and accuracies of strength prediction (Table 3) were found to be generally comparable to, or better than, those for normal-weight concrete, with the exception of Leca.

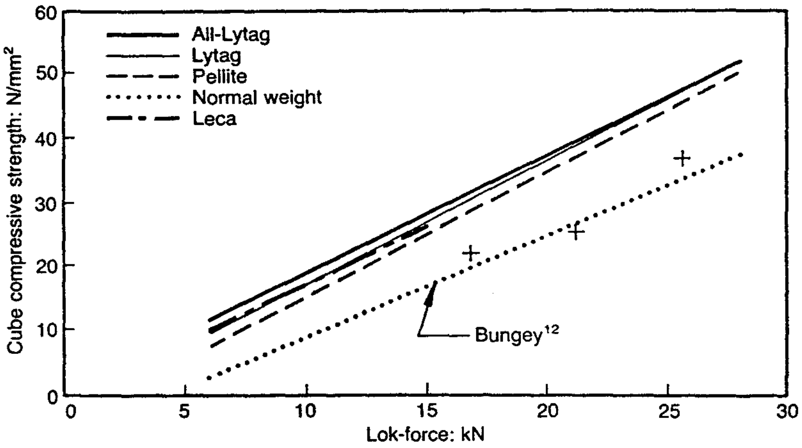


Fig. 5. Comparisons of Lok-Force correlations

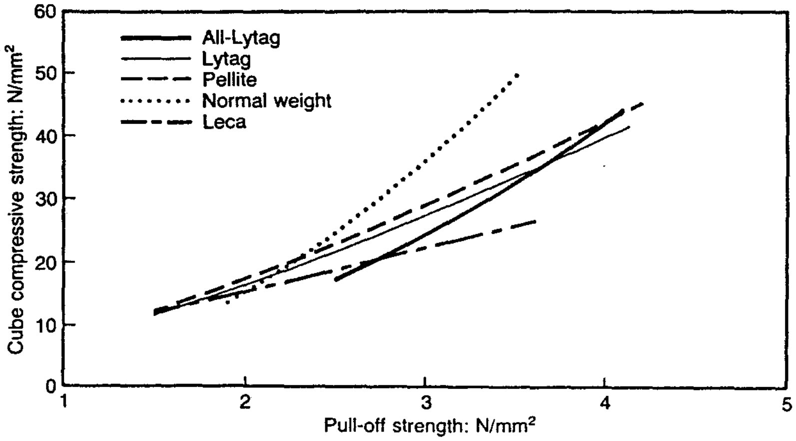


Fig. 6. Comparisons of surface pull-off correlations

27. The effects of partial coring are illustrated in Fig. 8, from which it can be seen that the pull-off strength is reduced significantly in every case, but to varying degrees. Individual data points have again been omitted for clarity. The general reduction in pull-off strength as a result of partial coring is consistent with established findings,[2] and is attributable to a combination of several factors. It was noted, however, that test variability was similar for surface and partially cored tests on 'All-Lytag' concrete, which differs from findings on normal-weight aggregate concretes. The need for a specific correlation for each aggregate type is clear, whichever test version is to be used.

Small cores

28. Features of strength assessment by small diameter cores are well established.[13] It was found in these tests that corrections necessary to allow for variations in length/diameter varied according to concrete type and curing conditions. These are summarized in Table 4. In all cases, the effects of this parameter were

Table 4. Summary of average length/diameter correction factors for small diameter cores

Concrete type	Curing regime	Length/diameter	
		1·0	2·0
Pellite	Wet	0·82	1·0
	Dry	0·85	1.0
Lytag	Wet	0·86	1·0
All-Lytag	Wet	0·86	1·0
	Dry	0·90	1·0
Leca	Wet	0·87	1·0
Normal (BS 1881, Part 120)	any	0·80	1·0

less than suggested by BS 1881, Part 120.[10] This confirms findings by Swamy and Al-Hamed.[14] but will increase uncertainty about estimated cube strength where core length/diameter ratios are significantly below 2·0. An effect of strength level on correction factors, as suggested by Munday and Dhir,[15] was also observed.

29. The direction of drilling relative to casting was found to have negligible influence for the lightweight concretes as illustrated in Fig. 9, which differs from accepted behaviour of normal-weight concrete. Curing conditions were found to have no detectable effect on core strength/cube strength relationships for the 'All-Lytag' and Pellite mixes, and 95% confidence limits of ±12% and ±11% respectively were found at the 30 N/mm² cube strength level for specimens with a length/diameter ratio of 2·0. Estimated cube strengths for such specimens calculated by application of a factor of 1·15 to measured core strengths, as recommended by BS 1881, Part 120 for vertically drilled cores, yields the results shown in Fig. 10. It can be seen that there is excellent agreement for all concretes except Leca, for which cube strengths are significantly underestimated. It was noted also that the Leca cores demonstrated an excess voidage estimated at 1·5%, while all other cases were estimated at less than 0·5%. On the basis of these results, it is clear that established procedures for estimating cube strengths for lightweight concrete from tests on small diameter cores should be treated with caution, and that particular problems may exist with Leca concrete.

Tests on reinforced beams

30. These results served to confirm many of the features observed on small specimens.

31. Tests included a range of the methods described here, and have been described in detail elsewhere.[16] Particular features emerging include the uniformity of strength distributions found across beam depths, although the magnitude of the difference between top and bottom varied according to material type as shown in Fig. 11. Lytag concrete was shown to exhibit similar features to normal-weight concrete, but 'All-Lytag' concrete was significantly less variable. Although the Leca concrete had the highest variability, it was found to be more uniform than that encountered in smaller specimens. It can also be seen that differences between in-situ strength and standard cube strength are not constant, but all lie within the allowances made in normal design procedures. A further point of interest was a 20% strength differential found between surface and interior of the 'All-Lytag' beam, which is significantly greater than expected for normal-weight concretes.

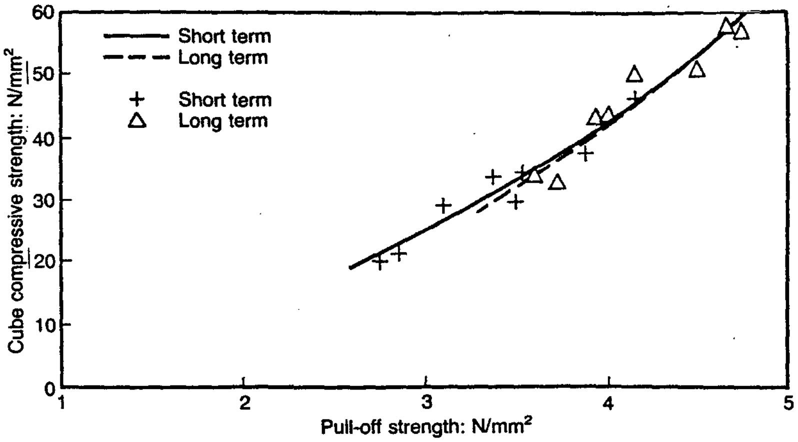


Fig. 7. Comparison of short-term and long-term surface pull-off correlations for 'All-Lytag' concrete

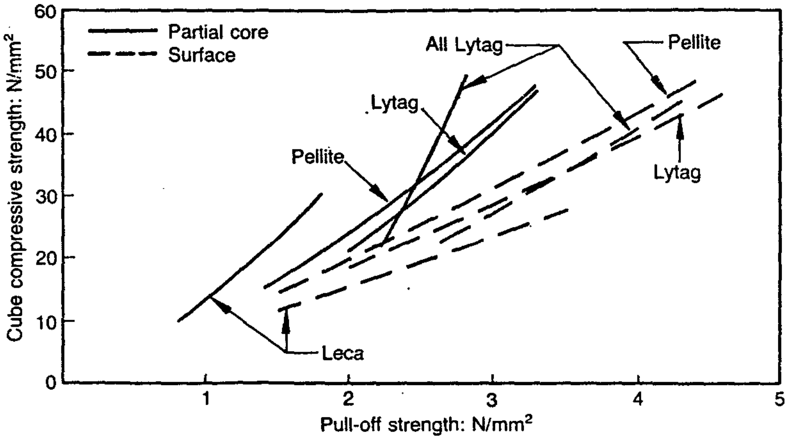


Fig. 8. Comparisons of surface and partially cored pull-off tests at 28 days

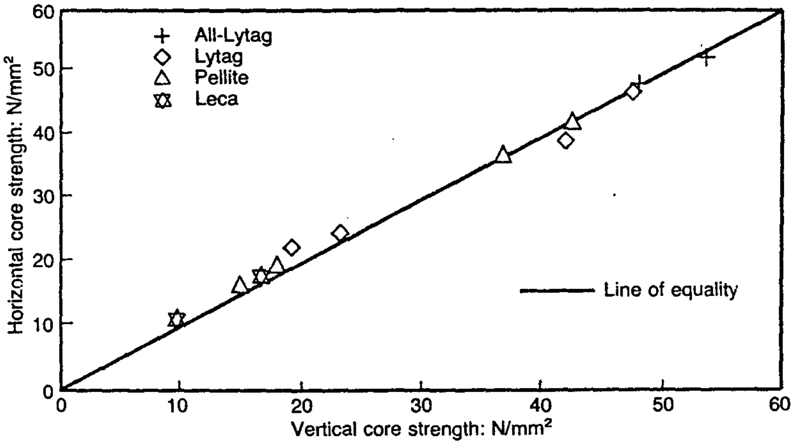


Fig. 9. Effect of core drilling orientation relative to casting direction

General observations

32. It was found during casting of the test specimens that Leca aggregate had a particular tendency to float, leading to significant lack of uniformity between the top and bottom regions of test specimens. The consequences of this have been evident from the test results described above. This effect was confined to

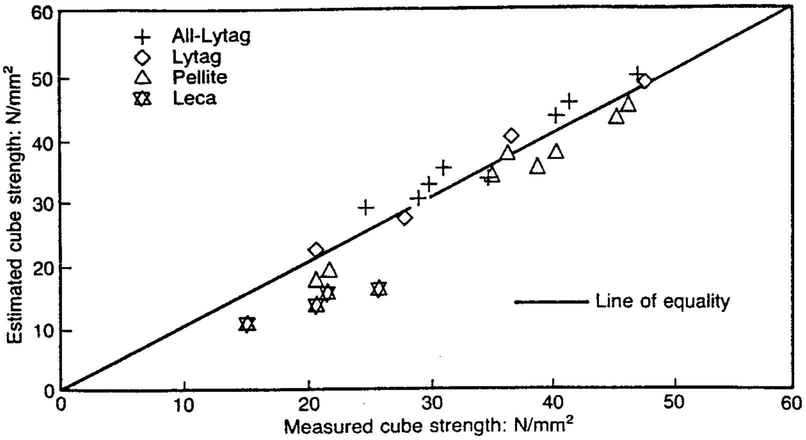


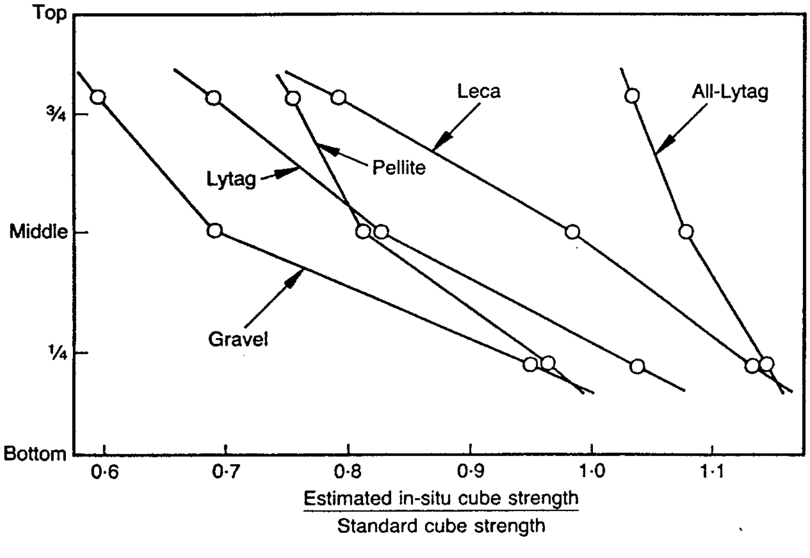
Fig. 10. Relationship between measured and estimated cube strengths for length/diameter ratio of 2·0

Leca concrete, and good aggregate distribution was found with other materials when vertically cast cylinders were examined after splitting in Brazilian tests.

33. It is beyond the scope of this Paper to attempt to explain all the observed differences in behaviour associated with the different aggregate types. It is nevertheless apparent that in many cases the failure mechanisms are influenced by the low strength of the lightweight aggregate particles and their effect on relationships between compressive strength, tensile strength and elastic modulus of the concrete. These factors have been considered in depth by Madandoust[8] and by the Authors elsewhere.[9]

34. The results clearly demonstrate the need for specific strength correlations according to aggregate type, although it has not been possible to account for all possible variables, including age and possible differences between site and laboratory, in the correlations presented. These specific correlations should therefore not be taken as being generally applicable. Many of the tests measure the surface zone, and particular care should be taken to account for possible long-term effects on the relationship between the interior and surface owing to factors such as moisture differentials and carbonation.

Fig. 11. Average relative strength distributions across beams of different concrete types



35. It must be noted when considering the values in Tables 2 and 3 that typical coefficients of variation are based on a series of tests at a strength level of approximately 35 N/mm² in each case (25 N/mm² for Leca). These represent nominally identical specimens and reflect the combined effects of test and material variability in each case. Strength estimation accuracies are, however, based on the overall correlation relationships developed for each method, as illustrated in the preceding figures. They incorporate a much wider range of variable parameters than are present in the assessment of coefficients of variation, and high initial moisture content of the lightweight aggregates may be a significant factor.

Conclusions

36. It has been demonstrated that a range of established test methods may be applied successfully to lightweight concrete to assess in-situ strength. In all cases, strength correlations will be different from those which apply to normal dense aggregate concrete, and in most cases different correlations will be required for different lightweight aggregate types. The effects of curing condition and age on correlations vary according to test method, and these, together with other possible variable factors, must be considered when correlations are being developed for use in particular circumstances. The nature of fine materials used may also influence these correlations, which reflects the effects of aggregate properties on test failure mechanisms. With the possible exception of the pull-out test, the illustrative short-term laboratory correlations given in Figs 1–8 should not be applied without validation for any particular case under investigation.

37. The non-destructive methods (rebound hammer and ultrasonic pulse velocity) have been shown to exhibit similar limitations to those experienced when they are applied to normal-weight concrete. The number of variables to be considered in the development of strength correlations is large, but the methods are nevertheless very useful for quick comparative surveys. Particular caution should be used when an attempt is being made to apply short-term ultrasonic pulse velocity correlations to older concrete.

38. Windsor Probe, internal fracture and pull-off methods were all found to be significantly affected by aggregate type but, within the confines of the programme, were affected to a lesser extent by other factors. Specific correlations are essential in all these cases.

39. As with normal-weight concretes, the pull-out test was shown to be that which is least affected by aggregate type, and, apart

from cores, offers the most reliable approach to strength estimation using a generalized correlation. Small diameter cores appear to be subject to greater uncertainties when lightweight aggregates are used, but nevertheless provide greater strength prediction accuracy than any of the non-destructive or partially-destructive approaches.

40. Particular problems of variability were encountered during the testing of Leca concrete, and the internal fracture method has been shown to be unsuitable for this type of concrete. Core results should also be treated with caution for this material. The high level of general uniformity associated with Lytag concrete incorporating lightweight fines has also been demonstrated, but an increased strength differential between surface and interior zones should be noted when the results of surface zone tests are being interpreted.

41. It is important to recognize that differences in test performance and material variability relative to normal dense aggregate concretes demonstrated in this work may have significant implications for the planning and interpretation of in-situ investigations of lightweight concrete structures.

Acknowledgements

42. Thanks are due to lightweight aggregate manufacturers (Boral Lytag Ltd, ARC Conblock Leca, and Tarmac Pellite Ltd) for their generous supply of materials for use in this investigation, and to the Government of Iran for their financial support of the work.

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