"CEMENT REDUCTION IN CONCRETE"

PAPER by ENG. ROBIN W.A. OSBORNE, Ph.D., R.E. (T&T) at the:
I.Struct.E. (Caribbean Division)/CCEO/APETT/TTIA Conference on Environmentally Sustainable Construction, Queen's Park Oval, Port of Spain, Trinidad, 15-16 September, 2011.

KEYWORDS:
Cement reduction; cement resources; tropical construction; concrete performance;

ACKNOWLEDGEMENTS:
The support of the TCL Group of Companies, for sponsoring the Author's attendance at this Conference, is gratefully acknowledged. The particular support of Mr. Wayne Benjamin (Works Chemist, TCL), for his unhesitating assistance with relevant supporting information, and Mr. Rodney Cowan (Marketing Manager, TCL), for making initial arrangements and obtaining the approval of the Company management to support this initiative, are also gratefully acknowledged. Engineer Hannah Wei-Mudeen, Group Health, Safety and Environment Manager, TCL Group (also past President, APETT), was also both helpful to, and supportive of, this exercise.

INTRODUCTION

The construction sector has often been among those with the lowest investment in R&D per dollar of business done; within construction, the area of construction chemicals is a notable exception. Substantial expenditures in product R&D are typical of this sub-sector.

Many specifiers are reluctant to move away from "tried and true" precedents; this is understandable, since experimentation on the construction site is a risky, potentially irresponsible, and un-recommended affair. Over-caution (sometimes laziness?) has often extended into stagnation, and even an unwillingness to invest in "offline" investigations that can reduce project cost, improve efficiency, and enhance environmental responsibility.

In civil engineering, specifications tend to change slowly; some specifiers still think little beyond 20.7 MPa or "3000 psi concrete" for "routine" or "run-of-the-mill concrete" (whatever that is). The considerable sophistication necessary to cost-effectively match concrete performance to project (and societal) requirements is probably not adequately reflected in the curricula of many engineering schools. Concrete is often seen as a low-technology, high-mass material of relatively little value which does not require much beyond some basic technical literacy and common sense to use to the best advantage. Nothing could be further from the truth.

In addition, the continuing pressure to build more, build better, and build more quickly for less, coupled with the unrelenting (and understandable) scrutiny of environmentalists, demands that the use of concrete is competently and diligently managed in construction projects; this should begin at the planning and design phase, and should also include consideration of the intended operation and maintenance of the proposed facilities.

THE MANUFACTURE OF PORTLAND CEMENT

This will be very briefly reviewed.

The manufacture of Portland cement is energy-intensive; depending on the process and the raw materials, plants may vary in their energy efficiency. The energy is consumed in the following operations:

Mining/quarrying of raw materials;
Processing (sieving, grinding, blending) of raw materials ;
Transportation of raw materials to the cement plant;
The firing process, which requires the most energy per amount of cement produced. This stage changes the powdered raw materials to the lumps of **clinker** so familiar to cement producers. The major differences in process energy requirements are between:
(a) wet processes, in which kilns are fed with raw materials containing significant amounts of water (these processes consume more energy), and
(b) dry processes, which can consume considerably less energy per tonne of cement produced.

Grinding of the clinker with the other materials (gypsum, additives for general or special cements, pozzolans, etc.) to produce the powder familiarly known as 'cement'. This process also consumes a significant amount of energy, particularly with the present trends towards finer cements;
Materials handling. This includes movement, storage, packaging, bulk dispatch, etc.

ADVANTAGES OF REDUCED CEMENT IN CONCRETE

In addition to the obvious environmental and cost arguments for cement reduction, it is not always remembered that higher cement contents in concrete are associated with the following technical issues:
(i) Greater heat generation (a potential problem in members of large and bulky dimensions; major cracking can occur due to temperature differences between the hot core and the external outer layers of the concrete; advice varies as to the magnitude of the temperature differential at which the risk begins to become significant)
(ii) An increased risk of internal cracking from shrinkage resulting from drying and/or hydration of the cement paste, particularly around the relatively volume-stable and incompressible aggregate particles.

TYPICAL REQUIREMENTS FOR THE PERFORMANCE OF CONCRETE

A brief reminder of the main groups of performance requirements which concrete is typically required to satisfy (a) during construction, and (b) in service, may be appropriate here:
1. Construction requirements. The **wet, fresh,** or un-formed concrete should be able to be successfully transported into place, consolidated (compacted), and finished (if appropriate; this is largely related to flatwork such as floors and slabs). It should therefore be sufficiently workable (and should retain such workability for long enough) to suit the equipment, manpower, and other features (e.g. amount and spacing of reinforcement) of the particular project.
In addition, the concrete should remain homogeneous, i.e. it should be resistant to **segregation** during handling, consolidation, and finishing.

2. Structural performance requirements. The hardened concrete should be strong enough to satisfy the requirements of the design, and durable enough to satisfy intended life-cycle requirements without unacceptable deterioration or loss of intended function, including structural function. This is usually satisfied by a sufficiently low permeability, which in turn is usually enabled by a sufficiently low in-place w/c ratio.

The above requirements are largely satisfied by appropriate mix design using suitable materials, complemented by the use of sound construction practices. This is a large domain of study and practice, and except directly relevant to the objectives of this paper, will not be further addressed here.

Reducing the amount of cement in a concrete without compromising its suitability for its intended purpose may be achieved by one or more of the following methods:

THE REPLACEMENT OF SOME OF THE CEMENT BY ADDITIVES WHICH ARE 'WASTE' BY-PRODUCTS OF OTHER PROCESSES, SUCH AS: ggbs, pfa, microsilica, or metakaolin.

The successful use of these products is largely dependent on the following phenomena: The hydration of Portland cement produces substantial amounts of calcium hydroxide, $Ca(OH)_2$; this is able to react with the reactive amorphous reactive silica (SiO_2) present in these products to form secondary cementing compounds which add to the strength of the concrete, and reduce its permeability. In particular circumstances, these reactions also chemically 'bind' potentially reactive materials and reduce the risk of deleterious reactions, such as alkali-silica or alkali-carbonate reactivity. Because these are secondary reactions, they are generally slower, and in general contribute to later rather than earlier strength development (microsilica, due to its extreme fineness, can so rapidly respond to the availability of $Ca(OH)_2$, that it may be considered somewhat of an exception in this regard).

CEMENT REPLACEMENT BY OTHER SUPPLEMENTARY CEMENTING MATERIALS WHICH ARE NATURALLY AVAILABLE, SUCH AS:
Naturally-occurring pozzolans, such as volcanic ash from tested deposits, which reduce the actual % of manufactured OPC in a given amount of "cement" being added to concrete. In the Caribbean, there are known deposits of pozzolanic material in Martinique, Dominica, and St.Lucia, but not all are known to have been surveyed and tested for reactivity and uniformity.

In addition to reducing the energy required for the actual production of cement, a number of concrete-technology-based options are available to knowledgeable and environmentally-conscious concrete manufacturers, users, and specifiers; these include the following:

Reduction of water (and therefore of cement) requirements by the use of water-reducing admixtures**, while satisfying essential concrete-performance requirements for workability. This approach maintains the w/c ratio of the mix, and therefore its strength, and has long been known; cf. Malhotra (1980): "Superplasticizers can be used to produce concretes with reduced cement contents while the water to cement ratio is maintained constant".**

Reduction of cement-paste requirements **consistent with the requirements for both fresh (construction, handling) and hardened (structural, durability) behaviour of concrete (typically done by careful and consistent blending of size-controlled aggregates to reduce void ratios of the combined aggregate). Mixes intended for pumping require special attention to cement content and fine and coarse aggregate content and grading, because of the particular mechanics of concrete pumping (Neville, 4th edition, pp.219-223), and mixes for placing in slender members require special attention to adequate mortar content because of "wall effect" (Neville, 4th edition, pp. 609,610).**

The use of larger sizes of aggregate in larger members**, where their sizes will not interfere with (a) the integrity of the protective concrete cover to outermost reinforcement or (b) the internal monolithicity and composite structural behaviour assumed by structural designers (e.g. that the maximum particle-size of aggregate should not exceed $^{1}/_{5}$ to ¼ of the minimum thickness of a member, nor the minimum spacing between reinforcement, minus 5mm). The reduction of surface area which results from using larger aggregate reduces the amount of water needed to achieve a given workability; there is less surface area to be 'wet' by cement paste.**

The use of coarser gradings of fine aggregate where the need for fines is reduced by the reduction or absence of a need for surface-finishing operations. The principles at work here are similar to those of the preceding paragraph. Side-effect benefits include a reduced risk of, and severity of, plastic shrinkage cracking. Discussions with Readymix (West Indies) Ltd. have pointed to benefits derived from this well-established principle.

Reduction of the amount of cement needed to make a viable concrete, such as the use of roller-compacted concrete for pavements and the like, and zero-slump extruded concrete for highway barriers, kerbs, drains, golf-cart paths, pedestrian and bicycle paths, etc.

Reduction of the amount of directly-produced Portland cement by the use of cements containing supplementary cementing materials, such as pozzolans (or by the direct addition of quality-assured pozzolans into the concrete mixing equipment);

Reduction of the variability of produced concrete.

To those acquainted with concrete quality control, the terms "target mean strength" and "operating margin" are familiar. The lower the variability of produced concrete, the lower can be the target mean strength, and therefore the lower can be the typical "headroom" or "cushion"of extra cement content required to reduce, to an acceptable level, the risk of the occurrence of a low-strength batch or delivery to a structure. There are direct implications for the quality of management of ready-mixed concrete and pre-cast concrete plants, where extra cement may be "insurance" to compensate for insufficient quality control. The particular implications include:

(i) Maintenance and calibration of batching equipment, particularly those dispensing water, cement, fine aggregate, and admixtures/additives;
(ii) Control of aggregate grading and cleanliness;
(iii) Training of batchers and ready-mix truckmixer drivers/operators
(iv) "Fail-safe" documentation of mixes and their delivery and sampling and testing;
(v) Maintenance and calibration of all sampling, handling, specimen end-preparation, measurement and testing equipment, particularly equipment for compressive strength testing;

In a single paper such as this, it is not possible to treat with all the factors that are involved in assuring produced concrete of low (strength) variability. These include:

Aggregates (particularly fine aggregates) of robustly consistent particle-size distribution (grading) and cleanliness;

Batching equipment that is in sound mechanical condition and a well-controlled state of calibration (the cement and water measuring systems are particularly important in this regard);

Similarly maintained admixture-dosage equipment;

Mixing equipment in sound mechanical condition;

Adherence to strictly-controlled procedures for batching and mixing;

Staff that are adequately trained, well informed, motivated towards diligence, and who are routinely checked for reliability of operation;

The corollary responsibilities for product dispatch and documentation, and for the processes of transportation, placing, compaction, finishing, curing, and de-moulding, of concrete.
The relaxation of the requirement of 28-day compressive strength as the criterion for the acceptance or rejection of concrete, particularly where full design loads will not be applied to the structure until considerably after this date (the corollary requirements regarding the maintenance of effective curing arrangements for appropriately extended periods will necessarily have to be addressed) If properly managed, this could lead to further reductions of cement required, particularly where 'extra' cement is not required for durability or other reasons.
Insisting on this traditional approval age for concrete strength forces the concrete to be approved while a significant amount of the cement present has not yet been hydrated.
Neville (1995), Fig. 2.2, p.68, reports work by Gonnerman and Lerch using concretes with a w/c ratio of 0.49 that have exhibited ratios of 1-year strength ÷ 28-day strength of approximately 1.35 for normal (i.e. not rapid-hardening) cements. Such a strength increase is substantial, and is often not considered in engineering calculations.

Improvement to the typical quality of testing services available in the Caribbean for the testing of concrete for compressive strength

What strength do we really want, and where in the structure do we really need this strength?
In the proceedings of the first conference on readymixed concrete in the UK (1975) there are reports of measured compressive-strength differences of up to 15% between the top and bottom zones of concrete columns. With wetter mixes, and particularly those which easily allow migration of finer particles and water when disturbed or 'worked' (i.e. mixes not exhibiting high resistance to segregation and bleeding), the upward migration of water under vibratory consolidation can lead to increased in-situ water/cement ratios
– and therefore lower strength and higher permeability – in the upper portions of vertical members.
R Osborne, PhD thesis UWI, 1990; over-vibration of cubes led to Schmidt-hammer values indicative of up to 17MPa (2465psi) differences in compressive strength between the top and bottom of a 150mm concrete cube. This finding has many implications for (a) systematic and repeatable compressive-specimen making, and (b) differences of strength in different parts of concrete members in the field, particularly when those of substantial vertical dimensions are placed in a single concrete pour.

A SELECTION OF CONCRETE CARIBBEAN ANECDOTES ILLUSTRATING SOME OF THE WEAKNESSES OF KNOWLEDGE WHICH EXIST

BARBADOS
"My client has ordered 3000 psi cube strength at 28 days; I am supplying them with 6000 psi" ("see what a good boy am I" is implied) !!!

GUYANA
The platen for the concrete compression-testing machine was used on a tree stump as a makeshift anvil to straighten by sledgehammer heavy-equipment steel parts which were being repaired in a readymix company's mechanical workshop!!

TRINIDAD
Request to one laboratory over which the Author had supervision: "Please finish testing these concrete specimens for us and provide us with a report; we started testing them, but our machine was not powerful enough to test them to failure" …!!!

TRINIDAD
"We cast these cubes in wood, because we did not have standard moulds; please test them for us" (submitted by an engineer). When the Author expressed unwillingness to test them because the results would be virtually meaningless (and certainly unreliable) the conversation almost descended into obscenities: "who the so-and-so do you think you are? Is my money not good?"

TRINIDAD
Side-by-side cores from the undamaged portion of a prestressed concrete pile sent "blind" to two different laboratories for compressive strength testing, as follows:
(i) One core was sent to a laboratory already referred to (to remain nameless – and also at the time the named testing laboratory for a TT$ 1.0 billion-plus project);
(ii) The other core was sent to CARIRI (the Caribbean Industrial Research Institute – multidepartment research institute including substantial concrete testing capability, funded by the government of Trinidad and Tobago, benchmarked to major international accrediting organizations, and locally highly respected for independence and reliability). The core tested at CARIRI came back satisfying the project specifications, the one tested at the other laboratory came back with a

strength value approximately 13.8MPa/2000psi lower, and, according to that laboratory, it failed to meet the project's requirements for concrete compressive strength.

TRINIDAD
A reputable readymixed concrete company's test cubes showed their delivered concrete to be satisfactory; the client, a reputable organization also possessing a concrete strength testing laboratory, produced strength test results about 30% lower for parallel specimens moulded by their staff from the same concrete; a dispute ensued. From the test records, the Author identified a concrete density approximately 5% lower in the "lower-performing" concrete. The specimens had apparently not been properly compacted, which could explain most of the discrepancy ; it is well known that concrete loses about 5% to 6% of its hardened compressive strength for every 1% reduction in density (or % of voids present) up to about 6% density loss (Neville 1995, Fig. 6.10, p,179); only about 5% **strength** difference remained unexplained once this effect had been taken into account.

BARBADOS
Ref. : An Assessment of the Concrete Technology Capability of the Barbados Construction Industry (1984).
Examination of the compression tester at a benchmarking national (governmental) testing laboratory revealed a machine with a load frame not particularly suitable for testing cubes. Further, examination of the stockpile of crushed cubes in the yard of the laboratory showed that almost all of them exhibited asymmetrical failure. (Research by Spooner, Foote and others of the former Cement and Concrete Association of the UK showed that cubes failing asymmetrically tended to produce 10% to 20% lower **indicated** test strengths when compared with parallel cubes from the same concrete, which had failed symmetrically). The laboratory staff at the institution in Barbados appeared completely unaware of the implications of the pattern of failure for the reliability of their results, let alone the use of excessive amounts of cement in local concrete, and the unnecessary costs to local construction.
The cost of unnecessary cement usage at the time was estimated to be sufficient to build, equip, and run a first-rate concrete-testing laboratory capable of serving the entire Barbados construction industry.

JAMAICA
Engineers in a local chapter were being addressed on concrete fundamentals during JIE Engineers' Week 2009. Many of those engineers were responsible at the time for major construction decisions on large jobs such as hotels and road infrastructure projects, but were unable to answer extremely basic questions regarding concrete variables and behaviour; the widespread deficiency of concrete knowledge among the engineers present was embarrassingly evident.

SOME CRITICAL REQUIREMENTS FOR IMPROVING EFFECTIVENESS IN THE USE OF CEMENT IN STRUCTURAL CONCRETE IN THE CARIBBEAN

1. **Better understanding of concrete** by designers, specifiers, and constructors. This may require in-career training of engineers; there have been a number of indicators over the years that many engineers and other construction professionals are insufficiently knowledgeable regarding the capabilities and limitations of concrete, and therefore often mis-direct its use. The problem is by no means confined to the Caribbean; Mehta (1999) raises the question as to whether universities provide adequate training to engineers and technologists for tackling issues of concrete durability and pollution-free disposal. He referred to a 1995 survey of civil engineering schools in North America which revealed that most undergraduates receive only insignificant exposure to cement concrete topics offered as part of a required course on all engineering materials.
2. **Team approaches** between designers, concrete producers, and constructors in the design, specification, manufacture, and use of concrete.
3. **Mix designs and laboratory and full-scale pilot testing**; **"R&D".**

It cannot be over-emphasized that the construction site is **not** the place for experimentation; the consequences of such experimentation can be catastrophic. However, proper pre-construction trials can produce substantial advantages for site work, and greatly reduce the risk of rejectable or under-performing concrete in projects. This is particularly important when admixtures are being used for the first time, or for special concretes.
(i) The complex **chemical variations and interactions** between cement, supplementary cementitious materials, and admixtures,
(ii) the **physical effects** of temperature, the sizes of particles and particle interactions, and accidentally entrapped air, and
(iii) the **resulting effects** on (a) the timing, rate, and magnitude of shrinkage due to drying and hydration, on (b) porosity and permeability, and

(c) dimensional changes and hidden micro-cracking due to (i) internal stresses in the cement paste, and (ii) inter-facial paste-aggregate stresses,
together exert considerable influence on the eventual strength and durability characteristics of the concrete.
It is for this reason that the recommendations of a paper such as this must be made in general terms; specific performance must be verified for each combination of materials, tested under conditions that reliably reflect the particular construction circumstances of their intended use.

It should be noted that concrete used in full-scale trials need not be wasted; use can often be made of such concrete in non-critical areas, such as ground-replacement fill, or in ground-supported locations, or for encasement/protection of buried utilities.

CLOSING NOTE

The above observations should not be labelled: " Research notes, interesting but not of practicable value". As demands are increasingly placed on the concrete construction sub-sector, companies will come under increasing pressure to either (a) improve how efficiently they design and manage concrete, or (b) remain less profitable and less environmentally responsible – and possibly less likely to survive.

ROBIN W. A. OSBORNE
September, 2011

GLOSSARY OF TERMS
Ggbs; ground granulated blast-furnace slag, produced from the making of steel in blast furnaces, not in electric-arc furnaces.
Pfa , known as fly ash or pulverized fuel ash, is the ash precipitated from the exhaust gases of coal-burning power stations; it is probably the most common artificial pozzolan. Various types and finenesses are available; consistency of behaviour is important for predictable concrete performance.
Microsilica (condensed silica fume). This is a by-product of the manufacture of silicon and ferrosilicon alloys from high-purity quartz and coal in a submerged-arc electric furnace. The escaping gaseous SiO oxidizes and condenses in the form of extremely fine spherical particles of amorphous silica (SiO_2). Specific surface is about 20,000m^2/kg, about 13 to 20 times higher than other pozzolanic materials (and Portland cement), when measured by the same method. ASTM C1240 specifies the requirements for silica fume, but ASTM C 618 excludes it.
Metakaolin; pozzolanic material produced by the calcination of pure or refined kaolinitic clay at 650^{o}C to 850^{o}C, ground to a very high fineness (700-900m^2/kg)
Workability; the mouldability of fresh concrete, or the relative ease with which it can be successfully consolidated or compacted; usually measured by the slump test for normal concretes, and by the Flow Table test for self-compacting or flowing concretes; methods such as the Vebe Consistometer are more suitable for no-slump concretes, where the slump test cannot distinguish between concretes which may exhibit considerably different field properties.
Pozzolan/pozzolana; a naturally occurring or man-made material which possesses little or no cementitious value by itself, but will, in the presence of moisture, chemically react with calcium hydroxide (typically from hydrating Portland cement) to form substances having cementitious properties. The pozzolan must be in a finely divided state for satisfactory reaction to take place.

NOTE: 1.0MPa =1.0N/mm^2=1.0MN/m^2 ≈145psi

LIST OF REFERENCES
Neville, A. M. (1995). *Properties of Concrete*, 4th edition, 1995, Dorling Kindersley (India) Pvt. Ltd.(licensees of Pearson Education). ISBN: 978-81-7758-587-2.

Factors Affecting Selected Methods of Testing Concrete for Compressive Strength; Robin W.A. Osborne, Ph.D. Thesis, Civil Engineering, UWI St. Augustine, 1990 (unpublished).

An Assessment of Aspects of Concrete Technology Capability of the Barbados Construction Industry (1984, February; Robin W.A. Osborne, with CEP Barbados, funded by USAID), report submitted to the National Council for Science and Technology, Barbados, 57pp. incl. appendices.

Malhotra, V.M. (1980). *Superplasticizers: Their Effect on Fresh and Hardened Concrete;* V. M. Malhotra, in "Progress in Concrete Technology" (V. M. Malhotra editor), CANMET, 1980, p.373.

Mehta, P.Kumar (1999). *Concrete Technology for Sustainable Development;* P. Kumar Mehta, in "Concrete International", ACI, November 1999, p. 51.

BIBLIOGRAPHY

Design and Control of Concrete Mixes, 14th edition, by Kosmatka, Steven H. *et al,* PCA, Skokie, Illinois 60077-1083, USA, ISBN: 0-89312-217-3.