Concrete: From Mix Selection to the Finished Structure – Problems en Route

The majority of papers dealing with concrete concentrate on one property at a time, thus giving a somewhat distorted picture of the importance of the various parameters in achieving a good concrete structure. The theme of this paper is that this objective can be achieved only by a seamless process of a number of operations, which are briefly discussed. Among the topics presented are the composition of today’s cements, selection of concrete mixes, use of binders such as fly ash and silica fume, self-consolidating concrete and sustainable construction. The article concludes with a review of special aspects of precast concrete.

All studies of concrete have a single objective: achieving a satisfactory structure, i.e., one that is structurally sound and durable. Alas, despite thousands of research papers published every year, concrete in many structures is not as good as it could be. I will attempt to explain this situation.

This paper is a minor provocation in the hope that by pointing out the shortcomings in concrete construction (and not just the concrete as such) I would shock the readers into improving the various procedures or, at least, into reviewing the present shortcomings in concreting.

So, given my good intentions, I hope to be forgiven for any harsh words that follow. And, if the cap fits ...

There is one other aspect, in which this paper differs from most others, which discuss a single topic and point out its importance. This paper shows that all aspects of concrete-making matter.
NATURE OF THE PROBLEM

Why is concrete in many structures not as good as it should be?

First, a disproportionate amount of university research is confined to purely laboratory studies on artificial specimens under unrealistic conditions, and is performed by people with no experience of what happens in real life situations. In their experiments, the range of variables is very limited, deleterious conditions are unrealistically exaggerated so as to speed up their action, differential deformation within concrete, due to shrinkage or temperature, is avoided by the use of tiny specimens, and other limitations. Most academics are not renowned for investigations on an actual site or production facility, and prefer an air-conditioned laboratory to wearing gumboots and a hard hat.

Second, most civil engineering undergraduates have learnt almost nothing about concrete as a material. Consequently, when involved in design calculations in subsequent employment, usually almost exclusively in computerized form, they assign fixed values to the requisite properties of concrete: modulus of elasticity, shrinkage, creep coefficient, thermal expansion, and other properties. They rarely ask themselves whether the actual mix – as yet unknown and to be supplied by a producer still to be selected – will conform to the properties assumed in the design calculations. Indeed, it is rare that anybody looks into such conformance.

Third, overall, the labor force involved in the production of concrete, that is, batching, mixing, transporting, placing, compacting, finishing and curing the concrete is less well educated and less well trained than corresponding labor forces in many other trades, such as joinery, carpentry, electrical work, plumbing or even bricklaying. I do not mean that all concretors are incompetent: of course not; but rare is the construction site or plant where all the concretors are fully competent. And yet, any one step in the production of concrete can adversely affect the finished product. Thus, many concrete structures are imperfect with the consequence that, very soon after completion, they are in need of repair.

A small digression may be in order. The quality of workmanship depends not only on the competence of the work force but also on the quality and intensity of supervision. When I was young, there was a resident engineer, normally full-time, on every construction site, and his eagle eye prevented slipshod workmanship. Such supervision was expensive, but the designer’s fees were large enough to cover the cost. Acute competition for design projects, coupled with abolition of fixed fees, has resulted in low fees, and the first action to save money was to economize on supervision.

SEAMLESS PROCESS

The point of my catalogue of complaints is that achieving good concrete is a seamless project. Any one flaw will mar the end product. Sometimes the defect is visible, but at other times it is hidden, and no one knows about it until something happens so that an investigation and testing follow.

In the case of reinforced and prestressed concrete structures, it is difficult to ascertain what is inside a member, particularly after a period of time has elapsed. In the simplest case of a highway or runway pavement, the thickness of the concrete is rarely routinely checked, although recently some electronic methods have been developed. The old system of cores is destructive.

Verification of the degree of compaction and of the absence of honeycombing or of bugholes is not usual, if only because it is not easy, and is laborious and time-consuming. The position of reinforcing bars can be determined; provided we are certain that the correct size has been used. But even then, we do not necessarily know whether the right grade of steel was placed. I am aware of a case where color-coding of steel was misapplied in the steel shop so that using the right color resulted in using the wrong steel.

LOW-TECH CONCRETE

Concrete is peculiar in that it is both a low-tech material and a high-tech one. This sounds like a contradiction but concrete has evolved from a very simple material, which the man in the street can make without any technical knowledge, to a material expected to have very specific properties of various kinds and to be, in the engineering jargon, fit for the purpose. This development has occurred during my lifetime.

Such a development would not necessarily have adverse consequences as shown, for instance, by changes in the manufacture of cars. Less than a century ago, they were produced by skilled mechanics and assembled manually. Such cars are still obtainable today but they are worth their weight in gold! The hundreds of millions of cars available commercially every year are the product of sophisticated processes controlled by electronic means and largely executed by robots.

Of course, we are not yet at the situation in a modern power plant where the staff consists of a man and a dog. Why a dog? To make sure that the man does not interfere with the system. Then why a man? To feed the dog.

Let me elaborate the changes in concrete. I remember the days when concrete was batched by hand, that is by boxes, a cubic foot in size, filled with sand or coarse aggregate or cement. Indeed, the bag of 94 lb (42.6 kg) originates from the approximate weight of 1 cu ft (0.028 m³) of cement. On a small job, batching was done by shovels: so many of cement, so many of sand, so many of coarse aggregate. This is the origin of the so-called 1:2:4 or 1:1½:3 mixes.

The “specification” for these materials required the sand to be clean, and rounded, and the coarse aggregate was usually gravel found in the nearest riverbed. Alternatively, if available, continuously graded aggregate could be used.

Water was added as needed to produce a mix workable enough to make compaction fairly easy. Compaction was done by tamping by wooden utensils and by “slicing” using a block of steel, about ½ in. (13 mm) wide, attached to a rod, so as to fill the space near the surface of formwork (of course, made of timber) and especially the arrises and corners.

The remarkable thing is that it all worked well: the water-cement ratio, generally neither specified nor known, was not much above 0.5, and the quality of the resulting concrete was remarkably good. Some of the elements –
walls, floors, and even bridge beams exist to this day.

I have just referred to the water-cement ratio (w/c), and this concept, developed by Abrams in the United States in the second decade of the 20th century, and even earlier by Féret in France, was known, but it was not a practical parameter on site. Indeed, in my opinion, even today the w/c cannot be a primary parameter in the production of concrete. This may sound like an anathema; I will explain my reasoning in a later section.

All this was about the old low-tech concrete. Although, nowadays, we do not batch concrete by volume (with the exception of a continuous mixer), simple standard mixes containing prescribed weights of fine aggregate, coarse aggregate, and water (the latter actually batched by volume) are still used, and they produce a satisfactory concrete for many purposes. This is what I call low-tech concrete.

HIGH-TECH CONCRETE

Now, high-tech concrete is expected to have specific properties required for a given application. These may include: a minimum compressive strength at a very early age, or a particular coefficient of thermal expansion, a low rate of heat generation (due to the hydration of cement) so that a controlled temperature is evolved, or a specific modulus of elasticity, or specific creep properties, or a limited magnitude of shrinkage under certain conditions of exposure – the last three of particular importance in prestressed concrete. This list can be extended by durability requirements for exposure to cycles of freezing and thawing, and for resistance to attack by specific external aggressive agents.

All the above can be achieved because in the middle years of the 20th century an enormous amount of scientific work – much of it in the United States – resulted in an understanding of the physical and chemical properties of portland cement and of concrete made with that cement as the sole binder. In consequence, we were able to establish the properties of portland cement that would have the requisite features. I shall consider the requirements for aggregate later on.

PRECISE PROPERTIES OF CEMENT

Here, we come to a fundamental difficulty: we know what properties of portland cement we require in terms of, say, C,S, C,S, and C,A contents and of fineness, but can we get it? More than that: do we know what we are getting when we buy portland cement? The answer is “no,” and this is the first conflict between expectations of high-tech concrete and reality.

Some readers may be surprised by the above assertion and point out that there exists an ASTM classification into Types I to V of portland cement, and also a European classification into more than a dozen blended portland cements. This is, of course, true but the standard classifications are very broad. For example, standard composition requirements of ASTM C150 – 04 with respect to SiO₂, Al₂O₃, Fe₂O₃, and MgO are the same for Type I and Type III cements. It follows that two Type III cements may differ very significantly from one another. Moreover, a particular Type I cement may have a higher content of C₃S than a given Type III cement. It should not be surprising that making two concretes with, say, a Type III cement, may result in concretes with significantly differing properties. (Type III cement is what is often used in the precast concrete industry.)

My statement could be countered by pointing out that we can ascertain the properties of the cement that we are buying. First of all, ascertaining is not the same as ordering cement with specific properties. This is possible only for very large projects, such as gravity dams and major highway projects. Indeed, according to ASTM C183 – 02, Standard Practice for Sampling and the Amount of Testing of Hydraulic Cement, “not much cement is sold on the basis of such sampling and testing.”

Secondly, when we ask a cement manufacturer for a certificate listing the properties of the cement that we are buying, this certificate does not apply to the cement that we are receiving on site or in the plant. Rather, the certificate tells us the average properties of the cement produced over a certain period in a given cement plant. The qualification “average” refers to the fact that grab samples are taken in a specified manner over a period of time; they are then combined to form a composite sample representative of the cement produced during that period of time.

Moreover, it is not routinely possible to find out on which day the cement was manufactured and from which silo it originates. So, all in all, we have no more than a general idea of the properties of our particular cement.

All the above is not a criticism of the existing methods of manufacture and supply of portland cement. Rather, it is a reflection of the fact that cement is a relatively low-cost material, and to achieve elaborate refinements in the process would result in a considerable increase in price. Moreover, the cement produced by a given plant is strongly affected by the raw materials and by the fuel used in the kiln. The fuel is relevant in so far as the sulfates in the clinker are concerned because the solubility of the sulfates influences the compatibility of a given cement with superplasticizers.

CEMENT-RELATED PROBLEMS

So far, I have discussed the limitation that the exact properties of the portland cement impose on the person proportioning the concrete mix. Nowadays, portland cement is rarely the sole binder, although it is a necessary component of the binder. There are several reasons for this:

First, by using additional binders, that is, cementitious materials (in the broad sense of the word) the properties of the combined cementitious material can be varied widely. Specifically, we are able to lower the rate of development of the heat of hydration and, therefore, of the rise in temperature of the concrete, with a resulting reduction in thermal cracking. We can also reduce the vulnerability of concrete to some forms of chemical attack. The benefits are numerous but under some circumstances such as cold weather, too slow a gain in strength may be harmful to desired stripping strength.

Second, many of the additional cementitious materials are either natural materials or else they are by-products in the manufacture of other materials (such as blast furnace slag, which
is formed in the production of iron) or waste products (such as fly ash, which is the fine ash formed in burning pulverized coal in a power station). Thus, these materials already exist and do not need to be manufactured expressly, with a consequent expenditure of much energy. It is the energy saving that represents an economic advantage. In addition, disposal of fly ash represents an environmental problem.

Third, it could be thought that these waste materials should be cheaper than especially manufactured cement, but often this is not the case.

**FLY ASH**

Fly ash is probably the most widely used binder in addition to the portland cement, and as such deserves special treatment in this paper. I am saying “in addition” because we must include a certain proportion of portland cement in the binder, if only because the hydraulic action of fly ash stems from reaction with calcium hydroxide produced by the hydration of portland cement.

The greatest protagonist of the use of fly ash in concrete is V. M. Malhotra in Canada. He has developed a methodology in which the binder contains 60 percent of fly ash. It is thus clear that fly ash is a major ingredient in the binder (which I prefer to call globally “the cementitious material”); it follows that to refer to fly ash as a supplementary material is to misrepresent its quantity as well as its technical importance. Likewise, to classify fly ash as a mineral admixture is misleading: salt is an admixture to a steak and kidney pie, but both steak and kidney are the essential ingredients. Let us, therefore, refer to fly ash as a binder or, better still, as a cementitious material.

Fly ash is a particulate emission, precipitated electrostatically, in coal-fired power-generating stations. It is largely siliceous in composition, in glass form, and thus reacts with calcium hydroxide, as mentioned above. In other words, fly ash is a pozzolan. But equally important is the physical action of fly ash in a concrete mix.

The fly ash particles are largely spherical in shape, with a diameter between 1 and 100 μm; those smaller than 45 μm are beneficial. The very small particles improve packing, especially in the transition zone at the surface of the aggregate. They also reduce the flocculation of the particles of portland cement, and thereby reduce trapping of water. In consequence, fly ash acts as a kind of water reducer.

These are the main technical benefits of using fly ash in concrete. There are also environmental benefits: if not used, the fly ash would have to be dumped, and also more portland cement would have to be produced, with the concomitant use of energy and emission of carbon dioxide.

On the economic side, the preceding might lead us to expect fly ash to be given away free. Indeed, it was when I was a young engineer: all you had to do was to send a truck, and the power station would fill it with fly ash at no charge! Nowadays, fly ash, per ton, may be more expensive than portland cement, but of course it has to be good fly ash.

“Good” means that the particles are predominantly spherical, that they are appropriately small, that the carbon content is acceptably low, and that their characteristics are constant from day to day. To achieve these desirable features, the power station has to use coal from the same source and the burning temperature has to be high and constant. The requirements with respect to temperature necessitate that the power station be a base-load station, and not a peak-load one, that is, one coming on stream from time to time. This almost means that the power station has to be connected to a large power grid.

The high emission temperature results in the emission of NO, gases. For this reason, in the last ten years or so, health regulations in The Netherlands and some other countries have forced power stations to reduce the emission temperature, with a consequent increase in the carbon content in the fly ash and a reduction in the proportion of spherical particles. So, what the future will bring I do not know.

In the meantime, good quality fly ash is well worth paying for. The resulting concrete generally has: lower shrinkage; lower permeability, and therefore better durability; a lower rate of heat development, good pumpability and properties suitable for use in self-compaction, good finishability. The final set is delayed by two to three hours, and the strength is developed more slowly, which may or may not matter. Finally, fly ash imparts to concrete a somewhat darker color. The influences of fly ash on shrinkage and on the rate of development of strength are very relevant to presscast/prestressed concrete.

There is one other aspect of using fly ash in concrete: it needs early and good wet curing. This instills in personnel a curing discipline. As I consider good curing to be of great importance in all types of concrete, the use of fly ash has a salutary effect: a contractor that uses fly ash on one job will acquire the habit of good curing on all jobs!

Fly ash is used extensively in some countries but not so in others – at least not yet. I view the importance of including fly ash in the mix to be so significant that it merits a moderately extensive treatment in this paper.

Fly ash and ground granulated blast furnace slag have been used to produce concrete with a 28-day compressive strength of more than 16,000 psi (110 MPa).

**TERNARY BLENDS**

Binders consisting of three, or even more, cementitious ingredients are becoming increasingly common. In this paper, I shall limit myself to the use of silica fume in addition to fly ash and portland cement.

Interestingly, silica fume is also a waste product: it is the particulate exhaust emitted during the manufacture of silicon and ferrosilicon alloys from high-purity quartz and coal in a submerged-arc electric furnace. Silica fume is always expensive because its supply is geographically limited.

Silica fume improves early-age performance so that its use with fly ash is advantageous. Silica fume has a high water requirement, thus counteracting the improved workability induced by fly ash. Indeed, generally, inclusion of silica fume in the mix requires the use of superplasticizers. These are expensive, but a ternary mix with a superplasticizer is what makes the production of high-performance concrete possible. This is a high-tech concrete, and this is the way of the future, as I see it.
High-tech concrete need not have a high strength but, to achieve consistency of a very high strength, high-tech control is necessary. This can be achieved much more easily in a precast concrete plant than on an ordinary construction site. Bridge members, with strengths of 16,000 psi (110 MPa) or even 17,000 psi (120 MPa) have been routinely fabricated in France and in the United States.

Such high strength concrete, with a very low water-cement ratio, down to less than 0.30, requires meticulous moist curing, starting at a very early age; otherwise, there is a danger of autogenous shrinkage cracking in the interior of concretes. Again, a precast concrete plant makes this possible.

**MIX SELECTION**

Selection of appropriate cementitious materials and their optimal combination require skill and knowledge of the behavior of concrete in service. In fact, this applies also to other ingredients: aggregate in its various size fractions and chemical admixtures, these days more numerous and varied in their action. This selection is an art as well as a science.

All this should be done by an experienced concrete engineer. Alas, few such people are available these days, and there has been an increasing tendency to resort to computerized mix designs. I am dubious about abdicating direct personal approach to mathematical formulas, if only because the properties of aggregates vary enormously from place to place, even in the same geographical area and are influenced by the crusher used.

Often, we do not know which aggregate will be used. This need not be a major problem with respect to, say, workability, but properties such as creep of concrete or its modulus of elasticity, relevant to loss of prestress, are likely to be greatly affected by the details of the mix composition.

It follows from the above that there would be an advantage in the designer and the precaster being linked. This, however, militates against competition in the choice of the precaster, and, therefore, against economy. Many years ago, when I was involved in creep tests for the prestressed concrete containment vessels in the very early British atomic power stations, the government, which paid for these stations, applied a system of rotational selection.

For each station, the contractor was chosen ahead of the design so that, for example, creep effects could be predicted following tests using the aggregate that the contractor planned to include in the mix. To be fair, the government chose a different contractor for each project. This meant that there was no competition and, therefore, no economy. More importantly, individual contractors could not build upon their experience.

So, we have to use a performance specification, which has to be translated into a mix for a specific purpose. One difficulty is that tests are not always available. The structural engineer knows the required properties in service but he is ignorant about translating them into mix ingredients. The precaster may be able to do so but he has to build up his experience on the basis of feedback about the performance of previous mixes. Often, the only feedback is a complaint.

It follows that we need sustained cooperation between the concrete producer and the structural engineer but, as I have already said, in a free-market economy, established relationships do not develop because we repeatedly look for the lowest initial cost. The trouble is that this may result in a structure that needs repairs. Of course, the answer is to use the life cycle cost but this is rare.

Sometimes, the reasons for looking at the initial cost only seem to be valid: for example, the first owner intends to sell the structure at a very early age; also, government funds are often separate for capital expenditure and for operating costs, which include repairs. It is difficult to get away from the lowest-bidder syndrome, but maybe the time has come to rethink the situation. Someone said that there are three desirable factors in construction: lowest price, best quality, and fastest completion. Seemingly, we can achieve any two of these, but not the three of them, at once.

**CONCRETING OPERATIONS**

I have already said that w/c is not a parameter that can be insisted upon because it may be overruled by workability. I am not denying that, from the structural design viewpoint, not exceeding a certain w/c is important but if, for some reason such as a delay, the workability is inadequate, then water must be added because unworkable concrete would produce honeycombing, which is even worse than having too high a w/c.

There is a tendency to believe implicitly that the specified w/c has been implemented, but we cannot verify w/c in hardened concrete with a precision better than ±0.05. Also, according to British Standard BS 1881: Part 124, the cement content in hardened concrete can be determined at best with a difference of not more than 70 lb per cu yd (40 kg/m³) in 95 percent of cases when testing identical samples of the same concrete by one analyst; this is called repeatability. With two analysts in different laboratories, the figure is 100 lb per cu yd (60 kg/m³); this is called reproducibility. Precision is even less good if the binder contains several cementitious materials.

The only parameter that can be verified by testing is the compressive strength. Sometimes, the specification lays down the compressive strength as required by the structural designer and the w/c as required for durability purposes. At times, these may be incompatible: for example, 3600 psi (25 MPa) and 0.45. There was once a case of fraud where the ready-mixed concrete supplier ensured that the concrete had the requisite strength but used a much higher w/c than specified, knowing full well that it could not be verified once the concrete had left the mixer. Clearly, precast concrete plants routinely produce concrete with w/c of 0.30 to 0.40.

There are other reasons why w/c should not be relied upon too heavily: the allowance for moisture on the aggregate based on periodic “snapshot” determination is not reliable, and moreover w/c varies inevitably within a structure, both horizontally and vertically, owing to segregation and bleeding. Significant improvement in the control of water content on the aggregate...
would be achieved by the use of in-line moisture meters; this way, the amount of water on the aggregate in each batch would be known and could be allowed for by varying the amount of water put into the mixer. Various types of in-line moisture meters have been developed: those measuring electrical resistance, those determining capacitance, and those measuring the absorption of the transmitted microwave signal. Alas, their use is not as widespread as it should be, but the benefits of moisture control in each batch, especially in precast concrete, are large in terms of the penalty of excessive variability of concrete; I shall refer to this in a later section.

When several mixes are used in a single structure, it is vital to ensure that the right mix gets to the right place. This is obvious, but problems may arise when different mixes are specified for different parts of foundations. This is, for example, the case with the requirement for sulfate resistance given in the recent BRE Digest in the United Kingdom.

Such fine-tuning is good in theory but if a truckload of concrete arrives on site and it cannot be placed in the right part of the foundations, it is bound to be diverted and used in a different part, which might require a different mix. Purists can argue that the agitator truck should be sent back but this is rarely done in practice because of cost and because dumping of concrete is forbidden for ecological reasons.

In the case of precast concrete, some of the procedures, such as transportation, should not be problematic, but nevertheless vigilance (continuous or continual) is necessary.

Finishing is a skilled operation but it should not present problems. Nevertheless, it is not uncommon for over-finishing with a steel float to produce a beautiful-looking surface, which is too rich and has too high a w/c. This may lead to cracking and to vulnerability to chemical attack, as well as to dusting.

**PLACING OF REINFORCEMENT**

It is obvious that the reinforcing steel has to be positioned correctly but there is no unique way of prescribing the cover. Sometimes, nominal cover is specified; in other cases, minimum cover is given without a maximum value; in yet other cases, tolerances are prescribed, but it is not obvious whether they have to be observed at every point or on average over a certain distance.

Some time ago, I came across a case where cover in precast concrete panels with 1 in. (25.4 mm) diameter bars was given as 2 in. (51 mm) from two sides, and the panels were only 5 in. (127 mm) thick; “negative cover” resulted (see Fig. 1).

Even if the cover is correct at the instant of placing of reinforcement, the steel may become displaced during the concreting operations by the workmen standing on it (see Fig. 2).

**SELF-CONSOLIDATING CONCRETE**

Everything that I have discussed so far applies to traditional concretes that have been in use for many years. There is, however, a new development in the construction industry with a curious history: self-consolidating concrete or SCC. Like the use of robots in concreting operations, self-consolidating concrete was first developed in Japan. In
both cases, the motive was to minimize the use of semi-skilled or unskilled labour, of which there was little in Japan (without allowing immigration).

Self-consolidating concrete is a mix that expels entrapped air without vibration and that travels around obstacles, such as reinforcement, to fill all space within the formwork. This is useful with intricate patterns of prestressing tendons and poorly accessible areas near anchorages. Vibration is noisy and, therefore, objectionable to workers and neighbors, especially at night and on weekends. Avoiding this noise is the second argument for the use of self-consolidating concrete.

There is also a third reason, and that is the health effects of immersion vibrators on operatives: holding the vibrator damages nerves and blood vessels and causes the so-called “white finger” or “hand vibration” syndrome. This is obviously socially undesirable, and the European Union has prepared a directive aimed at reducing the incidence of the hand vibration syndrome. It is expected that this will be translated into a law in the United Kingdom in 2005, but as yet self-consolidating concrete is not widely used in the United Kingdom; in addition to Japan, Sweden and The Netherlands are leaders in the field. In the United States, the PCI already has a guide on SCC, and the ACI is in the process of developing such a guide.

Because self-consolidating concrete is not well known everywhere, a brief technical description may be useful. The means of achieving self-consolidating concrete are: use of more fines (smaller than 600 µm); appropriate viscosity achieved by a controlling agent; w/c of about 0.4; and use of a superplasticizer; less coarse aggregate than usual (50 percent by volume of all solids); and good aggregate shape and texture. Clearly, very good batching controls are necessary.

Self-consolidating concrete is very useful for heavily reinforced members of any shape and with bottlenecks, both in precast concrete and in situ, and also for casting concrete sculptures. The only limitation is that the top surface must be horizontal.

I am convinced that self-consolidating concrete will become more widespread in the very near future and we should prepare for it by developing appropriate mix ingredients and mix proportions.

CURING

Curing is always specified but wet curing is rarely executed well. I am a strong believer in wet curing especially at low values of w/c because water has to be added into the hardened concrete, and not simply prevented from being lost, which is what membrane curing does. With very low values of w/c, curing must start almost immediately after placing, as otherwise autogenous shrinkage will develop. The resultant cracking is not visible because it occurs within the concrete mass and this negates the benefits of a very low w/c.

I am well known for preaching about curing but this operation continues not to be done well, if at all. Many people do not believe in curing and they know that it is not possible to prove or disprove that curing had been applied. If curing were a separate item in the Bill of Quantities, it might be easier to enforce it.

Of course, fresh water must be used in curing but I have seen in the Middle East some precast concrete structures that were cured by immersion in seawater. The mistaken argument was that the precast concrete would be floated out and immersed in seawater anyway. However, at a very early age and in hot dry weather, filling the pores in concrete with seawater would facilitate penetration of chlorides into the interior of the concrete and encourage corrosion of reinforcement. The use of calcium chloride and sodium chloride as an accelerator is expressly forbidden in prestressed concrete.

SPECIFYING A MINIMUM CEMENT CONTENT

Some codes of practice and some specifications prescribe a minimum cement content, presumably because it is thought that this ensures a “good” mix. I see no scientific reason for the belief that a higher cement content produces a better concrete.

Better concrete means strong enough and durable. As for strength, this is a function of w/c provided full compaction has been achieved. If the concrete has been compacted, then the cement content is irrelevant to strength. However, more cement may facilitate the compaction because more water per cubic yard of concrete can be used without exceeding the requisite value of w/c. So, it is to ensure a low enough w/c at a convenient workability that the minimum cement content is specified. Overall then, specifying minimum cement content is a means of ensuring a maximum w/c in a roundabout way.

I believe that the required w/c at the mixer can be ensured by automated controls, which will measure the water on aggregate as it enters the batcher. Methods relying upon microwaves have been developed, but their use is not as widespread as it should be. At a precast concrete plant, such controls are particularly useful as they minimize the variability of the mix.

VARIABILITY OF CONCRETE

I have dwelt on tight controls in batching and on adhering to the specified w/c. The reason for this is that the variability in the mix ingredients affects the w/c and, therefore, the compressive strength. Variability of the compressive strength means that it has a higher standard deviation, and a multiple of the standard deviations represents the difference between the average strength and the specified minimum or characteristic strength (see Fig. 3). The greater this difference, the higher the cost of the mix for a given characteristic strength. This is where cost lies and this is where economies can be made.
SUSTAINABILITY

Sustainability is the “in” word in construction, so much so that this paper might be deemed incomplete if a section on sustainability were not included.

The purpose of structural design is to produce structures that are safe, durable and economic. “Safe” means that a given structure resists the loads that it is intended to be subjected to and also some unknown loads whose occurrence cannot be excluded. “Durable” means that the given structure will function in the manner intended during the planned life (stated explicitly, for example for bridges) or during its customary life (as in the case of dwellings). “Economic” means that the given structure is adequate for the intended purpose but not the best one that money can buy. This last limitation is sometimes forgotten but, as Neville Shute – an engineer as well as an author – wrote, “An engineer is a man who can do for five bob (two bits or a quarter) what any bloody fool can do for a quid (five dollars).”

A recent addition to the above requirements is sustainability. As I understand it in broad terms, this means that we should not use more materials or more energy than necessary so that there is something left for our great grandchildren. I have some serious doubts about this line of reasoning, particularly as in the 1960s there was the so-called Club of Rome, which predicted that, if we continued to use materials at the rate we were then doing, then they would all run out quite rapidly.

In the event, many materials such as metals in domestic fittings were replaced by other materials such as plastics. One could postulate that, when a material becomes short in supply, another material is introduced as a replacement.

The same applies to energy but, more surprisingly, every new source of energy is at least as expensive as the old one. Perhaps this is inevitable because it is the increased price of the first source that makes it economic to develop the second one. An example of the above is oil from Polar Regions whose exploration was facilitated by the increased price of oil from traditional areas.

Having said all that, it is certainly right to conserve materials and energy but, in my view, this will be hard to achieve if there is a resultant increase in cost.

Turning specifically to concrete, we should use fly ash and also recycle the aggregate. I have already discussed the technical benefits of fly ash and expressed the view that we should include it in the mix even if it is more expensive than portland cement. To put matters into perspective, we can note that the manufacture of one ton of cement produces one ton of carbon dioxide.

The worldwide demand for cement is such that its production generates about 7 percent of all carbon dioxide produced by human activity. Another useful figure is to note that about half the carbon dioxide generated originates from transportation, and about half is produced in North America. As the Chinese and Indians en masse will soon be driving many millions of motorcars, a drastic reduction in the generation of greenhouse gases is unlikely unless fiscal measures are used in the present developed world.

Fiscal measures with respect to cement mean a tax on the carbon dioxide generated. As far as the recycled aggregate is concerned, some measures are already in place. For example, in the United Kingdom and in some other countries, there is a tax on quarried rock and there is also a tax on demolition waste turned into landfill.

It follows that converting demolished concrete into aggregate saves two taxes, as well as being a sustainability gesture, but there are some constraints. Specifically, the aggregate has to be crushed so as to have a good shape for the workability requirements and also good grading.

This may mean carting the aggregate from the demolition site to some central location. It also requires removal of reinforcing steel, which represents a resource for producing new reinforcing steel. In consequence, large-scale economic, as well as ecologically desirable, applications are limited to highways where a crusher and a classifier can move along as the old highway is “converted” into a new one.
Furthermore, especially careful control of the amount of moisture on the surface of aggregate is necessary, and the aggregate should be wet to facilitate movement of fine material. On the positive side, secondary hydration of the “old” cement in the crushed concrete makes a small contribution to strength.

None of the above should be interpreted as my not supporting the application of sustainability criteria, if only because the production of concrete generates much carbon dioxide and uses much energy. Next to water, concrete is the most used material on a per capita basis in the world: two tons of concrete per capita per annum.

These days, the fuel in the cement kiln can come from a variety of sources including old tires and other waste, but some of these materials produce a sulfate with a low reactivity. Therefore, for the same content of sulfur trioxide in the cement clinker, the sulfate with a low reactivity will behave differently when superplasticizers are used in the mix. This is why the compatibility of a given superplasticizer with a given portland cement is an important issue.

Sustainability should be taken more broadly than in terms of the materials used in concrete: we should seek the best solution from the concept of a project, through design and the use of right materials, so as to produce a “green” building.

This concept includes insulation properties and also long-lasting construction. It follows that the quality of construction and the durability of structures should improve. This, then, is sustainable construction, which also has the benefit of producing less disruption through repairs. At present, in the United Kingdom, more of the construction expenditure is on repair than on new-build.

**SPECIAL ASPECTS OF PRECAST CONCRETE**

Precast concrete offers some additional benefits with regard to control of the various processes in the production of concrete.

First, the location of placing the concrete in the forms is generally fixed, so that there are no problems with a variable transportation time, and therefore workability, or premature hydration. The quality of formwork can be superior, finishing and curing can be standardized and consistent. The quality of cement can be uniform, all of it originating from a given silo; the processing of aggregate can be standardized, both with regard to grading and to moisture content. Supervision is easy to provide.

Self-consolidation makes it possible to precast elements with complex and heavily reinforced shapes. Early and consistent wet curing can be applied, and so can steam or accelerated curing.

These days, very large and heavy units can be precast and transported; in the case of bridges with a double curvature, “mating of surfaces” (also called “match casting”) can be provided by using a preceding element as a “formwork” surface.

Very high strength concrete can be achieved and the concomitant need for very early curing can be satisfied.

The list of advantages of precast concrete is long. In summary, most of the needs for a seamless process are brought into one location, and this is conducive to high and uniform quality of precast concrete.

While the contents of this paper are applicable to all concrete – whether precast or in situ – there are three aspects of particular relevance to precast concrete. The first of these is the considerable advantage of including fly ash in the mix. Second is the meticulous control of moisture content on the aggregate that can be ensured by in-line moisture meters. Third, and last, proportioning the mix so that the concrete is self-consolidating bestows particular benefits in the process of precasting.

**CONCLUDING REMARKS**

This paper is not a denigration of concrete: how could I belittle concrete when it has fed and watered me over more than 50 years. (The verb “water” should not be taken in too restricted a sense.)

The preceding pages have been a high-speed review of the various activities and decisions necessary to produce a satisfactory concrete structure. Of necessity, no more than the barest discussion has been possible, and, of course, an intensive discourse was not intended. Nevertheless, I hope that I have shown the multiplicity of activities and decisions involved, and the importance of each of them being correct and well executed. This is the only way to achieve a satisfactory structure: ignoring or treating lightly any one step ends up in a deficient end product.

Alas, the latter is not uncommon: we must do better!