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Consideration of durability of concrete structures: Past, present, and future

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ABSTRACT

The paper expresses durability in terms of the expected conditions of exposure as well as of the specified or traditional service life of structure. A brief review of deleterious actions is given. Consideration of durability means how ensuring durability is viewed by designers, and not detailed advice or rules. Thus, the paper reviews the past attitude, which relied on providing strong concrete, it being believed that durability was concomitant with strength. Changes in the properties of cement, in that, with the 'new' cements, the same strength as specified heretofore could be achieved at a higher water-cement ratio resulted in structures with a distinctly reduced durability. This led to a re-consideration of mix design procedures, so that both strength and durability are now explicity considered. The future approach has to rely on the use of a range of cementitious materials and admixtures and on a meticulous performance of all operations from batching to curing.

RÉSUMÉ

Dans cet article, la durabilité est exprimée en termes d'exposition et de durée de vie spécifiée ou traditionnelle de la structure. Une brève étude des actions délétères est présentée. On entend par « Considération de la durabilité » la façon dont la durabilité est vue par l'ingénieur, et non pas dans le détail des règles. Ainsi, l'article examine l'ancien point de vue basé sur l'opinion, selon lequel durabilité et résistance sont concomitantes. Des changements de propriétés des ciments font que notamment les « nouveaux ciments » obtiennent la même résistance qu'auparavant, avec un rapport eau-ciment plus élevé et une durabilité réduite. Par conséquent, la formulation des bétons a été modifiée, pour que la résistance et la durabilité soient toutes deux expressément prises en compte. À l'avenir, il sera nécessaire d'utiliser toute une gamme de matériaux cimentaires et d'adjuvants, et de s'assurer d'une exécution exemplaire de toutes les opérations, depuis le gâchage jusqu'à la cure.

Many an author, especially in an international journal, likes to impress his readers by telling them that he has long ago discovered the right idea, and that it is other people who have followed the wrong approach. I propose to do the opposite, and to tell you that, for many years, I was wrong about consideration of durability in design and construction. I should make it clear that this paper is about the attitudes to ensuring durability and not about specific measures and actions.

I will then give you my current ideas. As for the future, I was asked to include that word in my title, probably because it sounds attractive and intriguing, but all I can offer is to make some recommendations and to hazard a few guesses. Being old, I do not have to worry about the day when I am shown to be wrong because I shall not be there to be told that I had been wrong. In structural design, my parallel favourite remark is the following definition of the factor of safety: the number of years to retirement plus two.

1. WHAT IS DURABILITY

Before talking about my past views, and they were views held by most people at the time, I should define what I mean by durability of concrete structures. Durability means that the given concrete structure will continue to perform its intended functions, that is, to maintain its required strength and serviceability, during the specified or traditionally expected service life. It is worth

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analyzing this definition with some care. First of all, I referred to "a given structure" because there is no such thing as a durable concrete in the general sense: if I want to build a floor slab for a shed for gardening tools, which I intend to pull down in a year's time, a certain quality of concrete will be 'durable'. But the same concrete will not be durable for a major bridge, for a tunnel, or for an important dam. So, it is wrong to talk about 'durable concrete' or 'not durable concrete'. This is obvious but, acting as an expert in many legal disputes, which is a major part of my current activity, I hear lawyers talk about concrete which is 'not durable', without any reference to the specific conditions of exposure foreseen at the design stage.

In fact, there are two qualifications of the term "durability". I have already mentioned the first one, namely, the expected service life. The expectation may be specified as a given number of years, for example 120 years for a major tunnel, or may be simply traditional, like 25 to 50 years for an industrial building, or 50 to 70 years for the foundations for a single family timber home in a housing development.

The second qualification concerns the processes of deterioration to which a given concrete can be expected to be exposed. In some cases, like a cow shed, it may be the carbon dioxide breathed out by the cows; in other cases, like a bridge in a temperate climate, it may be the action of cyclic freezing and thawing. The point that I am labouring again is that concrete which is durable under one set of conditions of exposure may not be durable under another set of conditions. So again, there is no such thing as an inherently durable concrete.

Once spelled out, all this is obvious, but it is not always recognized, especially in legal disputes where there is sometimes a tendency to indulge in broad statements and even emotional pleas like 'my client's concrete is not durable'. Occasionally, the concrete is not durable because a change of use has occurred; for example, a floor designed to store paper is now subjected to spilling of noxious chemicals.

All that I have said so far was simply scene setting, but perhaps a little more should be said about the causes of deterioration consequent upon inadequate durability. Broadly speaking, the causes can be external to the concrete structure or they may be internal causes within the concrete itself. The external causes acting on the surface of the concrete are generally mechanical in action, namely, impact, abrasion, erosion, and cavitation. I do not propose to discuss these topics further.

The causes that I wish to consider are chemical or physical in action; sometimes, they are external in origin, in other cases, they are internal. The internal causes include the alkali - silica reaction and, in some parts of the world, the alkali - carbonate reaction, both of which are chemical actions. The most common chemical forms of attack arise from outside of the concrete, being the action of aggressive ions, such as sulfates and natural or industrial liquids. In addition, chlorides and carbon dioxide in the form of a mild carbonic acid are conducive to the corrosion of reinforcement. Corrosion requires also the ingress of oxygen at the cathode.

Physical action includes repeated cycles of freezing and thawing and the associated action of de-icing salts, and also temperature effects. These can be a high temperature of the concrete at the time of placing or a high temperature differential between different parts of a concrete member. A large differential between the coefficient of thermal expansion of the aggregate and of the hardened cement paste can be destructive if there are numerous cycles of temperature variation.

I have not presented an exhaustive list of factors affecting durability, nor a matrix of external and internal factors, and internal and external agents because this is a presentation of a broad view, and not a detailed technical paper. What I think is important to realize is that the various agents can act in a synergistic manner. Moreover, it is worth noting that the deterioration of concrete is rarely due to a single isolated cause. Concrete is a patient material, which can perform satisfactorily despite some adverse conditions but, with an additional adverse factor, deterioration can take place. So it behoves us to make as good a concrete as possible, especially with respect to minimizing the ease with which aggressive agents can penetrate into the concrete. As the aggressive agents act in solution, it is the penetrability of concrete by liquids that matters most. I am using the term 'penetrability' to cover the various mechanisms of ingress of fluids into concrete. These are: permeability, which is flow under a pressure differential, usually a head of water; diffusion, which is transport by a concentration gradient; and sorption, which is capillary movement in pores open to the ambient liquid.

2. PAST ATTITUDE TO DURABILITY

Following this rather lengthy introduction, let me look at the past attitude to durability. A good example is offered by what I said in the first edition of my book *Properties of Concrete*, which appeared as far back as 1963. I discussed various deleterious actions but the general impression given was that, at the design stage, there was no need to consider durability in an explicit manner. In the chart for procedures in mix design, included in the book, I indicated that the liability to chemical attack influenced the choice of the type of cement, but not that it influenced directly the choice of the water-cement ratio.

Although, in my book, I discussed some specific forms of attack, I wrote: "The usual primary requirement of a good concrete in its hardened state is a satisfactory compressive strength. This is aimed at not only so as to ensure that the concrete can withstand a prescribed compressive stress but also because many other desired properties of concrete are concomitant with high strength." That was then the generally held view. Indeed, in 1969, that is, six years after the publication of the first edition of *Properties of Concrete*, the British Code of Practice for Reinforced Concrete in Buildings, CP 114, said in a very sweeping way: "The greater the severity of the exposure the higher the quality of concrete required."

In the second edition of my book, *Properties of Concrete*, which appeared in 1973, I did better. I wrote: "Concrete of reasonable strength, properly placed, is durable under ordinary conditions but when high strength is not necessary and the conditions are such that high durability is vital, it is the durability requirement that will determine the water-cement ratio to be used." This is not incorrect, but it still gives the impression that adequate strength and adequate durability run hand-in-hand. This probably actually worked with the Portland cements used around the year 1970. A little later, the properties of cements manufactured in modern plants changed, and this had an adverse effect on durability.

Before I deal with that topic, I would like to emphasize the words in the second edition that I have just quoted, namely "properly placed". Of course, it is obvious to anyone experienced in concreting that as full compaction as possible must be achieved. It follows that if a particular batch of concrete with the specified water-cement ratio is delivered on site, and the concrete is too stiff to be compacted by the means available, it is necessary to add more water, so that the mix has the appropriate workability. It is no use adhering to the specified water-cement ratio so that the capillary porosity is low, and producing concrete *in situ* with large voids. If we do this, the theoretical penetrability of the hardened cement paste is low but the reality is that the large voids provide easy access for aggressive fluids. Of course, if the workability of the mix does not match the compacting equipment and manpower, then the mix needs to be re-designed.

In the third edition of *Properties of Concrete*, which appeared in 1981, I did not advance much, but soon afterwards I realized the effect of the changes in the properties of modern cements upon the development of strength and thus upon the microstructure of the hardened cement paste, which is a controlling factor with respect to the penetrability of concrete and thus its durability under given conditions. I would like to develop this topic.

It was actually in 1985 that I commented on the fact that concrete placed in the 1970s was more vulnerable to carbonation than older concretes, on an age-for-age basis. These concretes made with the 'new' cements also exhibited a higher penetrability. And yet, the 'new' cements were, according to their manufacturers, stronger; the implication was that the cement manufacturers were giving us a better product. In my opinion, this was definitely not so, or at least not so because the engineers did not fully understand the change. Let me elaborate.

It was customary, and it often still is, to specify a concrete mix by the 28-day strength of standard test specimens. In, say, the year 1960 and the year 1980, the structural designer specified the same 28-day strength and he or she was under the impression that he was obtaining the same concrete at all times. The prescriptive specification of mix proportions went out of fashion as being uneconomical, and rightly so. The performance specification, which replaced it, was on the lines: tell the ready-mixed concrete supplier what 28-day strength you want, and leave the mix proportioning to him.

So the specified 28-day strength did not change, but the composition of the mix did. Why? The answer lies in the change in the properties of the then modern cements. Not all cement plants in all countries changed at once, so it was even more difficult to know what was happening. First of all, the cements became somewhat more finely ground, so that they hydrated more rapidly and therefore developed a given strength at an earlier age. More importantly, the chemical composition changed in that there was much more tricalcium silicate and less dicalcium silicate; this, too, led to a more rapid hydration and a more rapid development of strength. In particular, this resulted in a higher strength at the age of 28 days and a much lower *increase* in strength at later ages. We could describe the situation by saying that the two strength – age curves, that is, one for the 'old' cement, the other for the 'new' cement, pass through the same value of strength at 28 days, and of course they both pass through the origin. However, the curve for the 'old' cement rises more slowly up to the value at 28 days, but continues to increase beyond that age, increasing by perhaps 25 or 30 per cent of the 28-day value at the age of one year. On the other hand, the curve for the 'new' cement rises steeply at early ages and flattens out near the 28-day value so that there is little increase in strength later on (see Fig. 1).

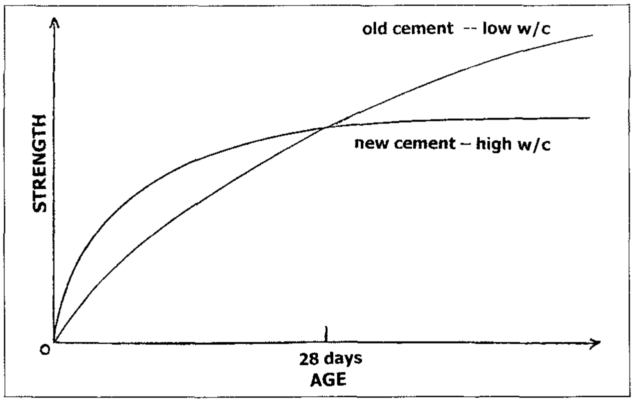

Fig. 1

The shape of the curve for the 'new' cement, that is, its early steep rise, can be exploited by using a higher water-cement ratio than before and still achieving the specified 28-day strength. In practical terms, for the ready-mixed concrete supplier, it means that less cement per cubic metre can be used, and this of course saves money, while the specification for the 28-day strength is satisfied.

What is the significance of all this with respect to durability? At a higher water-cement ratio, the hardened cement paste has more capillary pores and a more connected system of pores. In consequence, the penetrability is greater so that aggressive agents can enter the concrete more readily.

The remarkable thing is that this change occurred without those concerned knowing much about it. In a way, no one is to blame. The cement manufacturers improved the burning process in the kiln and generally increased the efficiency of cement production. The ready-mixed concrete suppliers increased their profits or lowered their price per cubic metre while adhering to the strength specification. And so it went on. All this could happen because, in most countries, there was no upper limit on the content of tricalcium silicate or on fineness. In actual fact, excessive fineness was rarely problematic because the high cost of grinding clinker discouraged the cement manufacturers from making excessively finely ground cement.

It may be worth adding that there was one other consequence of the higher rate of gain of strength of concrete at early ages. We know that in order to remove formwork we need a particular minimum value of strength. If this is achieved earlier, the contribution of the formwork to water retention within the concrete ceases. Unless active wet curing or membrane curing is applied, and this is rarely done on vertical surfaces, the external surface of the concrete is more porous and less durable. And it is *this* part of concrete that is exposed to any possible aggressive agents. On the other hand, the contractor likes the 'new' cement because it permits a more rapid rate of construction.

3. THE PRESENT VIEW OF DURABILITY

The present is, by definition, ephemeral because in a day or in a month the present will have become the past, and the future will become the present before this paper has been published. Thus, the boundaries between the past, the present, and the future, as listed in the title of this paper, are not clear-cut and writ on tablets of concrete. Nevertheless, I am able to say that the durability of concrete with a given strength is now worse than it was in the past.

It could be argued that we should remedy the situation by specifying a lower water-cement ratio than is necessary to achieve the strength required by structural design. However, if we do that, we should not, at the same time, also specify the level of strength required by the structural designer. My reason for saying this is that it is confusing to the ready-mixed concrete supplier to be confronted by two incongruous items in the specification: a relatively low strength and an unconnected low value of the water-cement ratio. There is a practical consequence of such a pair of specified values: strength is routinely checked by standard test specimens crushed at the age of 28 days, so that the ready-mixed concrete supplier knows that he must not make concrete with too low a strength. On the other hand, once the materials have been batched into the mixer, the water-cement ratio cannot be readily verified. So there is a temptation not to pay too much attention to the specified maximum value of the water-cement ratio. It follows that if we really want to specify a certain maximum value of the water-cement ratio, we should specify a corresponding value of strength, even if the structural designer does not need that strength. But, of course, if we specify a high value of strength, there is no point in specifying the water-cement ratio as well. Moreover, it would be logical to establish the higher value of strength required from durability considerations right at the outset of the design, so that the structural designer can possibly take advantage of it.

The second possibility is to specify the cement content per cubic metre of concrete. This approach is sometimes favoured by cement manufacturers, but there is no intrinsic merit in it. The cement content is a measure of the amount of cement in a given volume of concrete, but it is only the amount of cement in a given volume of cement paste that affects the durability, the amount of water being controlled by the required workability. It follows that, if the volume of aggregate in a cubic metre of concrete is larger, then the cement content in a cubic metre of concrete may be lower. Such an approach is used in the British and French codes by means of factors for cement content allowing for the maximum size of aggregate. The rationale of this is that, with larger aggregate, there is a higher total aggregate content in the mix. I am not discussing the properties of aggregate because we have adequate knowledge to ensure the use of good aggregate.

It seems to me that the approach discussed in the preceding two paragraphs is workable but only if the mix contains exclusively Portland cement. Durability is not controlled directly if other cementitious materials are included in the mix. These days, in many parts of the world, what I call 'serious' concrete contains more than just Portland cement. In consequence, the approaches mentioned previously are inadequate.

As for my published views, I recognized the past error of my ways in the fourth edition of *Properties of Concrete*. I wrote: "In many situations, durability is of paramount importance." And later on: "It is now known that, for many conditions of exposure of concrete structures, both strength and durability have to be considered explicitly at the design stage. The emphasis is on the word 'both' because it would be a mistake to replace overemphasis on strength by overemphasis on durability."

4. FUTURE IMPROVEMENTS IN DURABILITY

This brings us to the future. I am not looking to spectacular developments arising from revolutionary research. I do not believe that we shall see such developments in the next few years. I am also not convinced that we need them. We have at our disposal a whole gamut of good cementitious materials, as well as admixtures: what we need is a judicious and intelligent use of these materials and good quality execution of the concreting operations.

In my opinion, the preceding statement about an appropriate choice of the ingredients of the concrete and about a high quality of concrete in the structure tells us all we need to know in order to ensure durable concrete in the future. The materials mean principally the cementitious materials because it is generally the hardened cement paste that undergoes deterioration. Even in those cases where the aggregate or the steel is involved in deleterious reactions, it is still the hardened cement paste that enables the aggressive agents, ions or carbon dioxide, to travel from outside into the interior of the concrete. In cases when no outside chemical agent is involved, as for example in the case of the alkali - aggregate reaction, water is essential for the reaction to take place. If the concrete is dry and no water from outside can enter into the interior of the concrete, no further alkali – aggregate reaction will take place. So it is the low penetrability of concrete that is crucial to minimize deleterious chemical action.

However, I would like to emphasize my earlier choice of the expression "high quality of the concrete in the structure." Making good concrete in the laboratory is not all that difficult: the ambient temperature is kind to the concrete and to the laboratory worker. The mix ingredients can be weighed with precision that would satisfy a pharmacist. The laboratory mixer is good enough for a top confectioner. The compaction is performed meticulously. Curing is effected at a closely controlled humidity. And so on.

Not so on site. It is not necessary for me to describe the vagaries of the weather or the physical difficulties facing the worker because of the shape and position of a concrete member; contrast this with a factory worker under a roof in air-conditioned space. More than that: the place of work of the latter is always the same, and does not change every few months from one site to another. There is another difference at play. I do not know whether it is the consequence of work conditions or simply the consequence of historical development, but the worker on a construction site is much less well trained than his counterpart in a factory. If a worker does not understand why he should not move concrete horizontally in the form because this may result in segregation; if he does not understand the consequences of adding more water to the mix so as to make it easier to compact; if he is not aware of consequences of using a sledge hammer to 'adjust' the position of reinforcement; if he does not displace the steel by standing on an unsupported bar; and so on; then why should he do better? Moreover, he knows that, once the concreting has been finished, his 'sins' will be hidden.

In many countries there is no recognized trade of concretor requiring training, examinations, and certification. It is often thought that anyone standing idle can be directed to place or compact concrete. I am describing this situation for the purpose of drawing the conclusion that in the future we must have properly qualified personnel involved in concreting. I recognize that this cannot be achieved overnight, but we must move in the right direction without delay. One way forward is to put in the conditions of contract that, for example, in any concreting gang, there must be at least one person with specified trade qualifications; otherwise, the contractor is liable to a financial penalty. A year later, the contract may require that at least one-third of workers are so qualified; and progressively on until there is no unqualified concretor, just as there is no unqualified welder.

Such improvement in the training of concretors would make it possible to achieve the use of correct placing methods, compaction techniques, finishing operations, and curing. In my experience, achieving durable concrete requires all the operations of concreting to be as nearly perfect as possible. This does not sound like a high-tech recommendation. But what use is a high-tech approach to, say, mix proportioning, if a perfect mix is so badly compacted that the actual concrete in the structure is honeycombed? The answer is obvious.

5. MAINTENANCE

Maintenance is not covered by the title of this paper, and yet maintenance is essential for concrete to continue to satisfy the durability requirements.

In the past, proponents of concrete, and especially cement manufacturers, prided themselves on the 'fact' that concrete needs no maintenance, unlike steel, which needs repeatedly to be painted. As late as 1969, the British Code of Practice for Reinforced Concrete in Buildings, CP 114, stated: "No structural maintenance should be necessary for dense concrete constructed in accordance with this code."

We now know that this is not true and can never be true. Both corrective maintenance and preventive maintenance are essential. This may be unpalatable to some people but it is not really surprising: all construction materials, as well as all natural materials, which are subjected to moisture or to temperature variation deteriorate. In the fullness of time, rocks disintegrate and so will concrete, however good. Maintenance ensures that concrete does not do so in our lifetime or that of our children.

6. CONCLUDING REMARKS

You may be surprised at the seemingly simple content of this paper. My views on ensuring the required durability can be summed up by: the use of appropriate ingredients, including the various cementitious materials and admixtures, by a good, or very good, execution from batching, through mixing, transporting, placing, compacting, finishing, up to curing. We must not assume that achieving the desired strength ensures an appropriate durability, but neither should we be preoccupied with durability to the exclusion of strength. Strength and durability are two separate aspects of concrete: neither guarantees the other.

Lest I am accused of not providing a recipe for concrete with an appropriate durability, I would like to remind you that this paper was intended to review the *consideration* of durability, in the past, at present, and in the future. This is what I have done. The present paper is not the place to give detailed recipes for concrete that will prove durable under various conditions of exposure. Once we have established the principles of making durable concrete, appropriate details are not difficult to establish: the first step is to read the fourth edition of *Properties of Concrete*.

This paper was substantially presented as the opening keynote address at a conference, of which the author was Honorary President, on Concrete at the Dawn of the New Millenium, held in Krakow, Poland, on 9th an 10th November 2000.