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Mr Chairman, ladies and gentlemen, when I was asked to prepare my paper for this symposium I was somewhat hesitant about accepting the invitation because I had never designed a concrete structure nor had I been directly concerned with the measurement of movements and strains in bridges or buildings. My only qualification is my experience of observing the behaviour of many types of concrete. Now that I have seen other papers printed in the Preliminary Publication and have read summaries of the reports submitted for the free discussion on this Theme, I am even more conscious that my contribution is quite different from what most members would seem to expect, and am therefore the more appreciative of the priviledge of being invited to give this address. I can only trust that my simple, philosophical and perhaps unconventional remarks will help to improve the art of designing concrete structures to take account of the effects of creep, shrinkage and temperature changes.

You may have also noticed that my paper includes references drawn only from British sources. I hope this will not be regarded as any discourtesy to those in other countries who have made notable contributions to the subject of this symposium - it is only a measure of my lack of familiarity with work in this field, other than recent developments which have been taking place in my own country.

I have suggested in the conclusion to my paper that I may have a morbid view of the present ability of engineers to design concrete structures to accommodate the effects of creep and of changes in temperature and humidity. I feel that I owe you an explanation of this attitude.

My early experience of concrete was derived from a study of its properties under laboratory conditions. This meant that we attempted to keep the ambient temperature and humidity constant throughout the life history of the material under examination because variations in either were known to affect our results measurably. Any loading tests were short-term, and creep was ignored. After some years, the equipment used for controlling the laboratory atmosphere gradually became less reliable, and experimentation of the conventional type therefore became more and more difficult. About the same time, we began to receive more requests for advice about unsatisfactory concrete in practice; the causes could only be discovered by visiting the sites to observe the circumstances under which faults had occurred. So the pattern of the work changed gradually from the experimental techniques of the laboratory to the experiential research of observation.

It soon became apparent that many of these unsatisfactory features - and especially the various types of cracking - were the result of the engineers' lack of appreciation of the importance of the changes in temperature and humidity which occur in practice. We then realised that research conducted in a laboratory, to study the relationship between the properties of concrete and its constituent materials and composition, was only of limited value in practice unless the results were interpreted in the light of experience of full-scale behaviour in normal environments. Hence, what appeared to be the misfortune of having to work in an unserviceable laboratory turned out to be a blessing because it forced us to a more realistic approach to research on the difficulties that occur in practice.

Although my own laboratory experience lies in the study of unreinforced concrete, my colleagues working on structural design problems have also found that it is convenient to work in laboratories where the variations in temperature and humidity are minimised. In recent years, too, the introduction of data loggers has enabled tests to be conducted so quickly that the time-dependent factors have been eliminated. These techniques have enabled the effects of particular man-made changes imposed on the test specimen to be determined more precisely than would have been possible if they had been obscured by the scatter in results arising from the effects of changes of temperature and humidity and from the effects of the time taken to complete the tests.

It is largely on the results of such laboratory investigations that criteria and recommendations for the design of structural concrete have been based. Doubtless, if all structures were built inside laboratories having controlled atmospheres and were used for only a short time, they would be perfectly satisfactory. But they are not; and it is quite unrealistic that the designer should depend so heavily on these results when he is going to build concrete structures under the varying conditions which exist in the natural world around us. It may be convenient for the research worker to do his tests under conditions controlled by man, because otherwise God would spoil his experiments and he would not have any well-ordered results on which to base specific recommendations. Designers should remember that the Scriptures say: "Vengeance is mine; I will repay saith the Lord": in the end, nature will have its own way and produce undesirable features in our structures if they ignore the predictable consequences of their actions.

I believe that research engineers have paid too much attention to the study of structural design problems by theoretical analysis and experimental techniques in laboratories at the expense of the more practical observation of structures in real life. We delight in the pursuit of more and more sophisticated theories to explain complicated phenomena, rather than in examining whether these phenomena are of any significance in relation to the simple practical factors what actually affect the behaviour of structures. Unfortunately, this attitude is also found so often in designers who are perplexed by faults that have occurred in their structures because of their lack of appreciation of the simple nature of concrete and its response to changes in its environment.

Prof. Wästlund has already referred to three RILEM symposia which have a bearing on this symposium; in each case, attempts were made to bridge the gap between laboratory and site experience. Two of these were arranged by Prof. Rüsch and his staff in Munich. The 1958 symposium dealt with "The influence of time upon strength and deformation of concrete" and that held in 1968 with "The physical and chemical causes of creep and shrinkage". Both were primarily for research workers, about 35 being invited on each occasion, and much of the information had still to be digested into a form suitable for designers. However, even at the earlier symposium, there was little doubt about the complexity of the problem of predicting the creep of concrete in a given situation. It was known to be affected by the type of cement, the degree of hydration of the cement, the amount of carbonation and the intensity of loading or unloading as well as characteristics of the concrete; and it was on this occasion that I first realised the significant effect that fluctuations in load, temperature or humidity had on the creep compared with the values to be expected under the average conditions if held constant. Although more data had been collected by the time of the later symposium, especially in the field of design of pressure vessels for nuclear reactors, there still seemed little prospect of providing a simple basis for reasonably accurate prediction of creep.

Another symposium in 1968 was organised jointly by RILEM and Cembureau in Madrid just before the second Munich symposium; it was attended by 125 people having various interests. The subject was limited to "The shrinkage of hydraulic concretes", but even without having the complication of applied loading to contend with, it seemed that there were so many factors to allow for that the prediction of shrinkage was far from precise. In any case, shrinkage itself was of little direct interest: engineers were only concerned with its effects on deflection or cracking of members or on loss of prestress. It was generally agreed that one could not devise a realistic test for cement which could be specified by engineers to relieve them of the responsibility of worrying about the occurrence of cracking or excessive deflection of their structures. It was suggested that designers must still consider the proper questions relating to their designs - and to do this they needed to observe the structures they had built.

In my paper I have referred to "failure" rather than "faults" implying any aspect of design which has not been adequately fulfilled; and I have tried to show how the limit state concept can be used to encourage more logical thinking about design to take account of the effects of creep and of changes in temperature and humidity so that the risk of failure is acceptable.

I would now like to take these thoughts a little further and suggest that failure do not happen by accident - as though they were "an act of God" to use the language of insurance companies. I believe that all failures are designed to occur just like any other attributes of the structure, and that the designer is the only person who can really be held responsible for them. Quite simply, if the building had not been designed by someone it would not have been built and there would have been no failure. Most failures occur because the designer has misjudged either the causes of stress or the partial factors of safety required to provide a reasonable probability against failure.

The failures to which I am referring are generally of limited significance in terms of social or economic values; structural engineers have studied how to design so that there will be little risk of any calamitous failure by collapse of the structure. But they have not paid enough attention to the sort of failures which involve maintenance problems - because of deterioration of the materials - or which cause concern and annoyance to the client - because of inconvenience and anxiety over the quality of the work. Admittedly, designers have concentrated on the most serious problems; but they have rather ignored the causes of minor failures and have hoped that they could depend on the experience and expertise of material producers and contractors alike to compensate for their lack of interest in these details. However, this is no safeguard if they blatantly violate the principles of good design and detailing.

It is my experience that designers find it extremely hard to come to terms with the ideas that changes in the temperature and humidity of the environment in which concrete is placed can have a significant effect on the whole of their design concept. They are well aware of the effects of the force of gravity, both in terms of the dead load of the structural members and the live loads that are placed upon them, but they find it hard to conceive that the effect of the sun shining on a part of the structure, or of the drying of the surface of some concrete compared with the middle of that some concrete, can cause greater stresses within the material than those which they associate with conventional loadings.

I have gained the impression that most, although not all, of the reported measurement of existing structures has been undertaken with a view to determining only the deflexions that have occurred. It seems to me that there is still considerable scope for the investigation of the effects of environmental changes and of creep on the stresses developed within structural members. It may well be that experience has shown that, with our traditional factors of safety and methods of design, creep and temperature and moisture changes do not have a very significant effect on ultimate failure of the structure. Whether this will always be so as further refinements are introduced may well be a matter for investigation. But there is ample evidence from the observation of the structures that have been built in recent years that these factors play a very important part in design for the limit state of local damage as well as for the limit state of deflexion.

Local damage usually implies loss of integrity of the concrete by some form of cracking, while concrete, still in a high state of stress without cracking visibly, is regarded as being satisfactory. The distinction between the two states is not clearly marked as there is a gradual transition between them; a point of unacceptable behaviour has to be defined in some way as, for example, by specifying the maximum permissible width of crack at the surface of the concrete. Until such time as we have undertaken enough research to bridge the gap between the findings of the research worker in the laboratory and the results of observation of structures in practice, so that our design procedures for the limitation of local damage can be more formally codified, we must design intuitively.

It seems, therefore, that there is a considerable need for a reappraisal of the major influences affecting the design of structures. Fortunately this is being done gradually and our Codes of Practice are steadily being improved to give a better overall approach to the total design of a structure for all its functions whereas, hitherto, they tended to be limited to a rather specialised approach to one or two aspects which were of particular interest to structural engineers trained in the traditional way.

Our terminology may also have to be improved: for example, British codes have recommended minimum amounts of what is called "distribution" reinforcement for different types of structure. This word "distribution" gives no indication whatever that this reinforcement is required to control the tensile stresses which develop near the surface of a concrete member so that cracking will not occur there. The amount of this reinforcement is usually required to be a stated percentage of the cross-sectional area of the member, to satisfy typical situations. If it had to be calculated according to some formula which involved the drying shrinkage of concrete and the thermal contraction associated with the removal of formwork I am sure that engineers would have had a better appreciation of the effects of environmental changes even though the design may still have been somewhat arbitrary. As it is, designers tend to follow the recommendations blindly without appreciating the significance of the statements and they do not seem to realise that the minimum amount recommended for general purposes may be quite inadequate in some particular circumstances when the thermal and moisture gradients are excessive.

While the amount of reinforcement may be governed by the amount of tensile stress that is likely to be developed, the distribution of the reinforcement is governed by the need to control the width of cracks at the surface of the concrete. Cracking cannot be eliminated entirely. The designer's objective must be to distribute the tensile stresses arising within the concrete from all causes that at no point is there greater disruption of the concrete than that described as microcracking, which is neither serious in its consequences nor objectionable visually. The designer must therefore try to induce as many cracks as possible in the concrete so that they will all be little ones - and not, as many believe, try to reduce the number of cracks! Thus, the detailing of the design, which is often left to the draughtsman, can also be a vital factor in the occurrence of such failures as I have in mind. Again more attention is being paid to improving this stage of design and to disseminating the information by the publication of relevant advisory literature and by training.

In my paper, I have referred in some detail to the visual observation of plain concrete: I make no apology for doing so even though the symposium is concerned with structural concrete. Structural concrete is surrounded by plain concrete; and plain concrete is the flesh which protects the skeleton of reinforcement or pre-stressing tendons. It is the plain concrete at the surface that suffers the first and most violent consequences of all variations in temperature and relative humidity. It is affected by carbonation and by attack from any adverse environment, whether it be wetting or drying, frost, chemical action, abrasion, impact or fire. And it is the first part of the concrete to suffer cracking. As I have explained in my paper, I believe that the flesh may even have a skin on it and that this too plays a vital role in the proper behaviour of the structural concrete. And whether or not it is true to say that "beauty is only skin deep", it is certainly true that the appearance of structural concrete is very much affected by the initial and weathered qualities of the concrete skin.

I would like to show two slides to illustrate my remarks about the skin on the surface of some types of concrete; these slides also illustrate the value of observing the behaviour of concrete in practice as a technique for understanding its nature.

The first may be aptly entitled "footprints on the sands of time" (to quote from a poem by Longfellow). It shows, I believe, how the same concrete can have a skin which is either weak and ineffectual in preventing attack on the underlying concrete, or one which is strong enough to protect the concrete against external hazards. I imagine that a man walked across the concrete within an hour or two after it has been laid, thus recompacting the surface concrete sufficiently to give the affected areas increased resistance to temperature and moisture changes.

The second slide shows an area of an experimental concrete road slab which was used for trials of concrete joint sawing equipment. At the time of casting, during one summer, little care was taken to protect the surface of the concrete and, as a result, so-called "plastic cracking" occurred within a few hours of laying the slab. The sawing trials had been completed some time before the following winter. The photograph, which was taken after frost damage had occurred, shows cracking parallel to the saw-cuts but none parallel to the plastic crack. It would appear, therefore, that in sawing the hardened concrete the skin had been broken and the underlying concrete was damaged by the expansion of water as the temperature fell. On the other hand, as the plastic crack had formed in fresh concrete, the surface of the sides of the crack had become durable probably as a result of compaction under the influence of the surface tension of the moisture on the surface of the concrete.

This brings me conveniently to my analogy between concrete and human beings. Concrete is a creature whose behaviour is governed partly by heredity and partly by environment. Its hereditary characteristics are determined by the nature of the constituent materials of which it is composed. As these can be many and varied, concrete is a genus which includes very many species, races and nationalities, all with their distinctive individual characteristics. Conception of the new child takes place when the ingredients are brought together as a result of a mariage - by arrangement, in love or of convenience. After a short gestation period in the mixer concrete is born, as soft and pliable as a baby. The shape of its future can be easily moulded at a very early age; but nevertheless it rapidly gains strength and independence provided it is kept in a proper environment. In its youth it can accept a certain amount of ill-treatment without undue suffering but it is more likely to live a useful and active life if it is reared with care and sympathy. As it gets older it becomes harder and more brittle and less able to accept shocks without cracking under the strain and tension. Not only does it have a skin to protect it from disease, but it breathes or transpires, and as it does so it varies in weight and size. It has a wealth of experience behind it and its greatest attribute is that it will talk to you if you will only listen. I believe that concrete can grow old gracefully: but it will only do so if designers study its personality by observing its behaviour as it grows up in the world it seeks to serve.

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