Integrated Design and Environmental Issues in Concrete Technology

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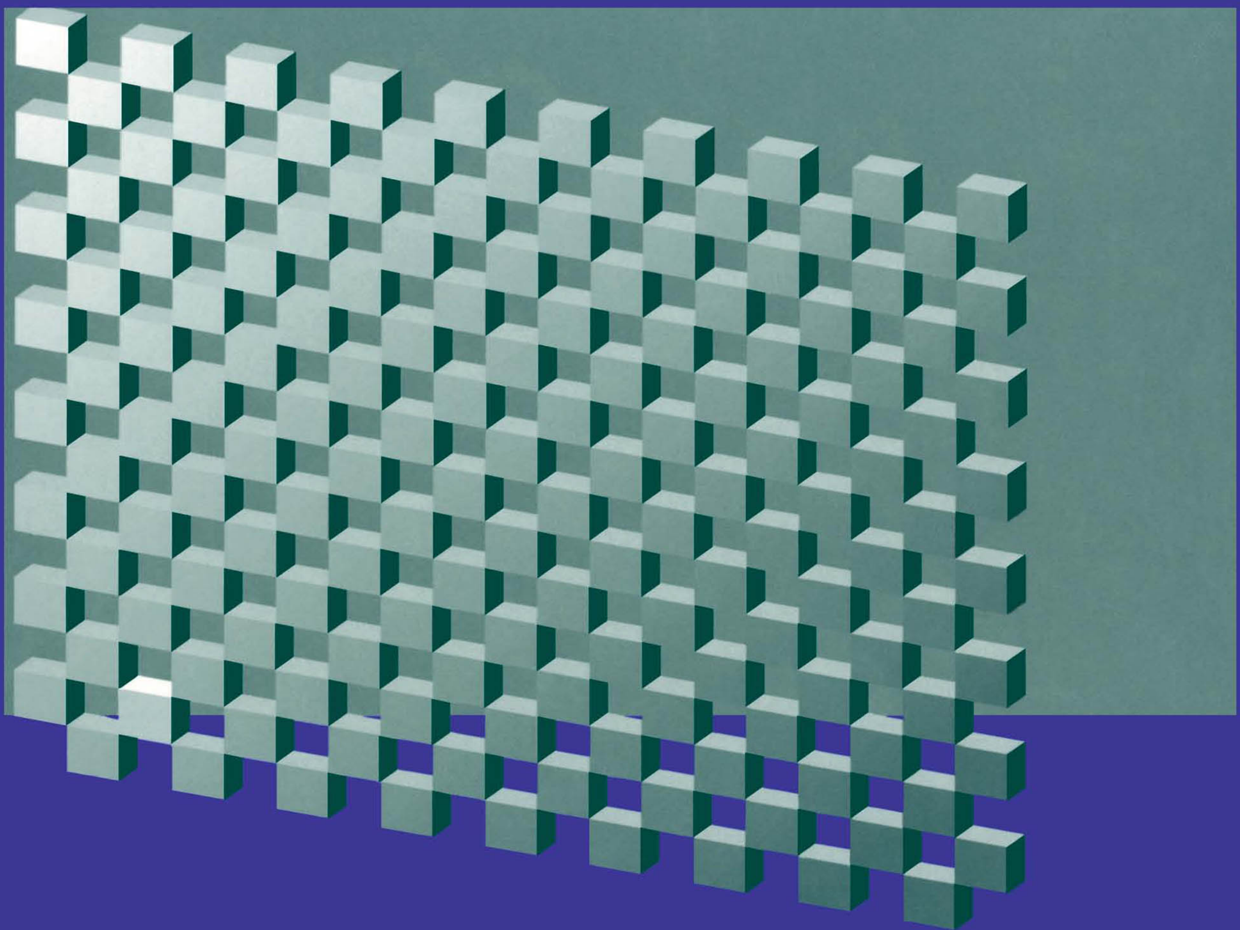

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Integrated Design and Environmental Issues in Concrete Technology

Proceedings of the International Workshop
'Rational Design of Concrete Structures under Severe Conditions'

Hakodate, Japan
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EDITED BY

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Preface

A workshop on "Rational Design of Concrete Structures" was held at Hakodate, Japan, during 7-9 August 1995. This book resulted from the papers presented in the workshop. The purpose of this workshop was to discuss concrete technologies towards the 21st century. There were two significant points in the discussions. One was integration of structural design and durability design as a rational method of design. The other was concrete technologies in relation to global environmental issues.

It is presumed that the next century will be the century of the environment. Concrete will not be an exception in this regard. It is obvious that we need to re-systemize concrete technologies, and to accomplish this, a new direction of research on concrete will have to be pursued. From this point of view, 27 papers were presented by distinguished researchers, which led to fruitful discussions. Based on the discussions, the following "Hakodate Declaration" was adopted:

1. We, concrete experts, shall place environmental consciousness at the center of concrete technology towards the 21st century.
2. We, concrete experts, shall change the framework of concrete technology by integrating structural design and durability design and by considering planned maintenance.

I hope that this workshop contributes to progress in concrete technology towards the 21st century.

The Civil Engineering Research Institute(CERI), Hokkaido Development Bureau, is conducting joint research with the Norwegian University of Science and Technology. It should be noted that this workshop was held based on the bilateral agreement between the Japanese and Norwegian governments. Full acknowledgement should be extended to the Science and Technology Agency in Japan and the Japan International Science & Technology Exchange Center for their financial support.

Finally, I would like to express my sincere gratitude to all participants for their significant contributions in this workshop. I also would like to thank my colleagues at CERI for their devoted support.

Koji Sakai
Civil Engineering Research Institute
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Sapporo
June 1996

1 CONCRETE TECHNOLOGY IN THE CENTURY OF THE ENVIRONMENT

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Abstract
As we move toward the 21st century, many industries have begun significant endeavors to preserve the environment. There is no doubt that concrete engineers also have to consider related problems and to clarify the role of concrete. In this paper, a direction for concrete technology in the century of the environment is comprehensively discussed. Firstly, it is emphasized that studies are needed to clarify the interface between durability and safety in the design of concrete structures. Furthermore, the importance of high-performance concrete in the construction of structures with long lives is described with an example developed by the author's research group. Finally, a concept of environmentally-friendly concrete is provided. The outline of the author's research group project on "eco-concrete" is shown.
Keywords: Concrete technology, durability design, eco-concrete, global environment, high-performance concrete, structural design.

1 Introduction

We have to realize that a battle for the survival of human life has already begun. We should not, therefore, hesitate to take prompt action. A significant challenge for all industries in the 21st century is the conservation of the environment. Concrete is not exceptional in this regard. This means that we are now at a stage in which we have to change the framework of concrete technology. For example, the significance of long-term durability in the efficient utilization of concrete structures has to be emphasized in concrete practice. However, do we know the true factors which govern the durability of concrete? Have we rationally considered the interface between structural design and durability design? In addition, have we paid attention to symbiosis

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or co–existence with plants, animals, insects, and other organisms? What potentials are there in concrete in this regard?

The purpose of this paper is to comprehensively discuss the direction of concrete technology in the century of the environment.

2 Concrete technology in the century of the environment

The more humans want to live in greater comfort and convenience, the more industrial ativities will develop further and larger amounts of resources and energy will be consumed, thus increasing the amount of industrial waste. When the total consumption of resources and energy was small, there were no problems or there were problems only in limited regions. However, with population increases and standards of living based on the consumption of large amounts of resources and energy, various distortions (i.e. global environment problems) have arisen.

There is a simple line of thinking that holds that concrete has destroyed the natural environment. However, is such a conclusion logical? Since human beings invented concrete, it has been used in great quantities to create comfortable living environments as well as to construct the infrastructure necessary for the the social systems that support our lives. The construction of structures requires changing the natural environment, and if building a structure is regarded as the cause of such destruction, it can be said that concrete has served to destroy the natural environment. However, it is an undeniable fact that environmental destruction is being accelerated due to delays in the establishment of infrastructure.

If concrete is seen as the cause of damage to the natural environment, it means that concrete's use by human beings has lacked wisdom. In fact, because concrete is less costly and more durable than other materials, it may be that concrete has not always been used properly. In other words, concrete has brought a great number of positive contributions to mankind, while it is also undeniable that its convenience has led to its inappropriate use without adequate consideration.

Despite the value of nature, assurance of a comfortable living environment comes first. Even without looking at the aftermath of the Great Hanshin Earthquake, we cannot go back to the state in which living outdoors is the norm. If so, we should start over and reconsider the future utilization of concrete in order to re–establish concrete technology.

Difficult global situations involve various problems, some of which are related to concrete. Global environmental problems, the roots of which are said to lie in the increase in population, extend over a very wide range. As engineers who are engaged in the concrete industry, we must first clarify the role of concrete in global environmental preservation and, if concrete itself or its utilization is a possible cause of environmental burden, formulate measures to mitigate it.

Thus, it is extremely significant to place environmental consciousness at the center of concrete technology when we manufacture and utilize concrete. Namely, in concrete technology in the century of the environment, the following things have to be emphasized:

1. Effective use of resources
   - Reuse of waste
   - Use of low-quality materials
   - Recycling of demolished concrete
2. Control of CO_2
   - Improvement of cement manufacturing methods
   - Use of admixtures
3. Development of high-performance concrete and its utilization
4. Development of environmentally-friendly concrete
5. Interfaces between durability design and structural design
6. Energy-saving construction methods
7. Rational maintenance system

In the following, rational design of concrete structures, high-performance concrete, and environmentally-friendly concrete are described.

3 Rational design of concrete structures

The basis for designing concrete structures is to secure the capacities required during their service life. The design of concrete structures is generally divided into durability design and structural design. Figure 1 shows the ideal design system for concrete structures. Environmental conditions are important as prerequisites to design. The environments to be considered are a) the global environment, b) the environments to which structures are exposed and c) amenity environments (aesthetics). Another important prerequisite is maintenance. Design levels differ according to future maintenance plans. To establish rational design methods for concrete structures, it is essential to clarify interfaces among these factors as shown in Fig. 1 and deal with them systematically.

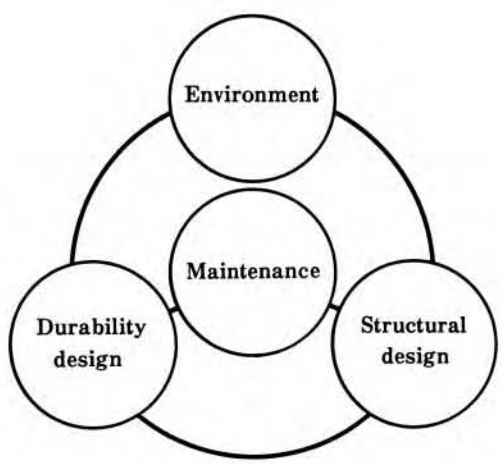

Fig. 1. Design system for concrete structures

Many studies on concrete durability have been conducted. However, it cannot be said that durability design which fully systematizes the results of these studies has been established. One of the reasons for this is that various factors affect the durability of concrete or concrete structures. In other words, it is believed that the following factors affect the durability of concrete or concrete structures.

1. Shapes of structures
2. Concrete cover and structural details
3. Properties of concrete (pore structure)
   - Mix proportions (water, water–cement ratio, water content, cement content and properties, admixtures, aggregates, etc.)
   - Workability
   - Surface treatment and curing
   - Workmanship
4. Environment

Deleterious substances which may be present in the environment include chlorides, carbon dioxide, oxygen, water, alkalis, sulfates and acids. These substances penetrate into concrete, chemically alter hydrates and corrode reinforcing bars. The types of deterioration include disintegration and/or dissolution of hydrated substances, micro– or macro–cracking, spalling and scaling. Besides these types of deterioration of concrete, cracking occurs due to plastic shrinkage or to strain caused by external forces, temperature changes, drying and other factors. The changes in mechanical properties by such deterioration affect the behavior of structural members, thus affecting the behavior of the overall structure.

Another obstacle to durability design is that no effective methods to evaluate durability have been established. It doesn't seem that such methods will be readily available in the near future. Although the permeability test is a possible method to evaluate durability, it is still in the development stage and has not yet reached the level of application to design. If durability of concrete can be properly evaluated and concrete of the quality required can be produced, then the mix proportion of concrete and details of concrete structures can be rationally determined according to environmental conditions. In other words, several design methods on different levels can be established, including one in which the deterioration of structures during their service life is not taken into account and one in which the deterioration which can be evaluated to some extent from an economic point of view is taken into account.

Thus, the realization of durability design depends on the establishment of effective methods to evaluate durability. It is greatly desirable to conduct studies with an emphasis on specific design methods.

Of the durability problems of concrete, the most important but least known is the quality of concrete in actual structures. The safety of concrete in structural design can be ensured by introducing a material factor (γ_c) to take into consideration variations in concrete quality. The compressive strength for design, which is used to check safety, can be represented by the following equation:

$$fcd = f'ck/\gamma_c \qquad (1)$$

where f'ck represents characteristic compressive strength of concrete. This means that for safety, the required strength of concrete is f'ck but the expected strength of concrete is fcd. In other words, it is assumed that the actual concrete strength may be lower in a certain location than the characteristic strength of concrete. It can be believed that in fact such a phenomenon sometimes occurs, thus affecting the durability of concrete. Furthermore, the deterioration of concrete quality makes it easier for chloride ions to permeate concrete, thus affecting the safety of concrete structures due to the corrosion of reinforcing bars. It can be said that the handling of this problem is an "interface problem" between structural and durability design.

The "Standard Specification for Design and Construction of Concrete Structures"[1] (Japan Society of Civil Engineers) shows that a material factor for concrete (γ_c = 1.3) takes into consideration the extent of quality control, differences between the strengths of specimens and of material in a structure, changes in the concrete over time, and other factors. The changes in concrete over time are basically considered to be deterioration. Such changes greatly depend on the quality of concrete produced. Therefore, it is not reasonable to consider these things by using only one factor. Furthermore, it cannot be said that the factor (γ_c = 1.3) includes the effects such as those of reinforcing bar corrosion due to the permeation of chloride ions.

To incorporate the degree of changes of concrete or concrete structures over time into design the life-span factor can be introduced or a member factor (γ_b), which is used to examine the safety of the capacity of the cross section, can be used. Figure 2 shows the relationships among quality, the environment and life span for concrete structures. It is important to establish design methods by making models of the

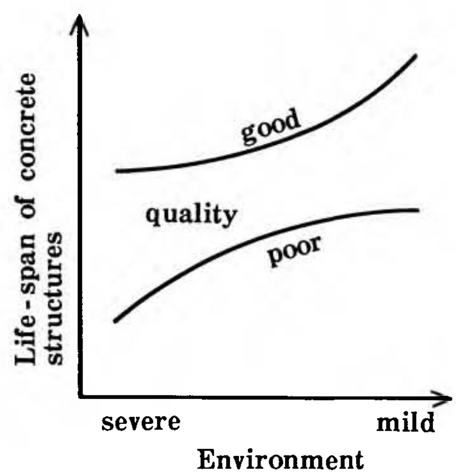

Fig. 2. Life-span of concrete structures

relationships based on data available now so that concrete structures can be constructed with an anticipated life span.

The design capacity of cross section (Rd) is represented by the following equation:

$$\mathrm{Rd} = \mathrm{R(fd)}/\gamma_b \tag{2}$$

where γ_b is a factor which takes into consideration the degree of uncertainty of the calculated capacity of the member cross section, errors in the actual dimensions of members, the degree of importance of each member and fracture properties of members (e.g. γ_b is increased in the calculation of shear capacity for seismic design). The factor can also take into consideration the decrease of the capacity of members due to material deterioration. The factor for reducing the capacity of members, which depends on the quality of concrete, grades of construction and environmental conditions, can also be introduced into equation (2).

Even when using quality concrete with an emphasis on durability, no design systems have been established in which the advantages of quality concrete can be incorporated into structural design. In many standards, the maximum values of w/c are defined in terms of durability according to environmental conditions. When the upper limit values of w/c based on durability dominate, actual concrete strength may have a large safety margin as compared with the design strength of concrete. When the actual strength is greater than the design strength, the safety regarding shear capacity may decrease due to the increase in flexural capacity. Therefore, it is rational in such cases to conduct structural design by regarding the compressive strength obtained as the design strength of concrete. It can be said that such design is one that considers the interface between durability and safety.

Furthermore, even when w/c is defined, there is no guarantee that concrete with the quality expected actually will be obtained. Therefore, it may be necessary to introduce a safety factor on the maximum values of w/c themselves, depending on the importance of the concrete structure.

The deterioration of concrete results in changes in its mechanical properties. Therefore, to establish rational design methods which fulfill required durability and structural safety, it is necessary to obtain information on the relationship between micro and/or macro changes of the properties or material defects and the mechanical properties. Some examples are shown below.

Figure 3 shows the effect of cycles of freezing and thawing on the tensile properties of high–strength concrete [2]. Apparently freezing and thawing decreases the tensile strength. The tensile strength of concrete affects the occurrence of cracking, thus greatly affecting the durability of concrete. Figures 4(c) and (d) show the effects of bending as shown in Figures 4(a) and (b) on the resistance to freezing and thawing [3]. It can be seen from Figure 4(c) that micro–cracks due to bending scarcely affect the resistance to freezing and thawing because AE effectively works. However, it is shown in the case of non–AE that the larger the loading level becomes, the faster concrete deteriorates and that the degree of micro–cracks due to loading affects the rate of deterioration.

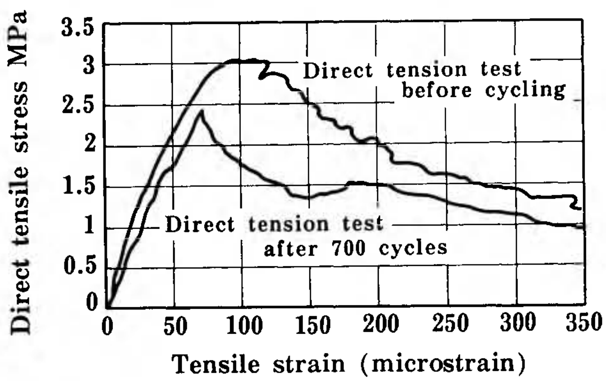

Fig.3. Effects of cycles of freezing and thawing on tensile properties of high-strength concrete [2]

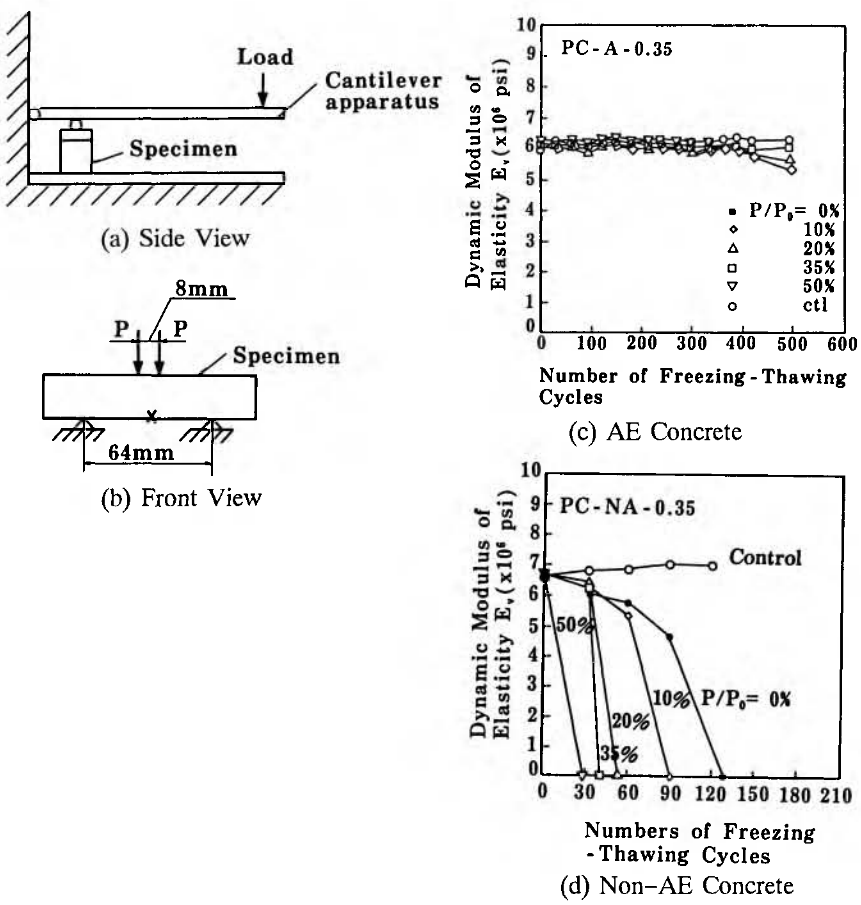

Fig. 4. Effects of bending on the resistance to freezing and thawing [3]

Figure 5 shows the effects of corroded reinforcing bars on the load–carrying capacity of reinforced concrete beams [4]. In the case of beams without lap splices, the load–carrying capacity decreases by about 10%. However, in the case of beams with lap splices, corrosion has an effect.

It is obvious that durability and safety have to be secured by integrating them in concrete structure design. However, researchers of concrete structures do not pay much attention to the effects of material deterioration. It seems that researchers of durability are not very interested in understanding how information on durability is utilized in the structural design. A small number of studies similar to the one above have been conducted. It is expected that such studies will grow more common. Without such studies, durability design and structural design cannot be integrated.

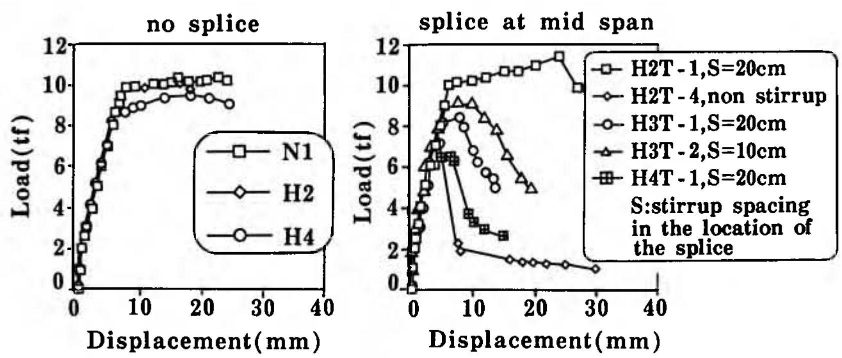

Fig. 5. Effects of corroded reinforcing bars on load–carrying capacity of RC beams [4]

The Great Hanshin Earthquake on January 1995, an earthquake of unprecedented scale in Japan's recent history, revealed that seismic design in Japan was not necessarily appropriate. It is expected that important structures will be designed to withstand earthquakes according to more stringent standards. However, it is also necessary to examine how the deterioration of materials affects the behavior of concrete structures which may be hit by earthquakes. Such examination is very important for the repairs and/or strengthening of the existing buildings.

4 High–performance concrete

Concrete engineering may be able to offer a solution for global environmental problems by constructing structures with long lives. There is much expectation of high–performance concrete (HPC) regarding the construction of such structures. High–performance concrete has a broad definition. Carino and Clifton [5] list the following characteristics as features necessary to define a concrete as "HPC":

1. Ease of placement and compaction without segregation

2. Enhanced long–term mechanical properties
3. High early–age strength
4. High toughness
5. Volume stability
6. Long life in severe environment (durability)

It can be said that high–performance concrete has no standard definition. The term was first used as a synonym for high–strength concrete. However, it is generally believed these days that high–strength concrete is not necessarily high–performance concrete because increasing the strength of concrete can cause other problems.

In general, high–strength concrete is produced by decreasing w/c with high–range water-reducing agents. However, this type of concrete has a higher proportion of cement, thus generating high temperatures during curing. Therefore, the author's study group has been involved in the development of a low–heat high–strength concrete [6,7]. Efforts were finally successful in developing an extremely high–performance concrete. This type of concrete is produced by mixing moderate–heat Portland cement or belite Portland cement, very finely–ground granulated blast–furnace slag, and silica fume. Figure 6 shows an example of the results. The compressive strength of 90 MPa was obtained at the age of 3 days. This type of concrete has the following characteristics: remarkable early–strength development, extraordinary strength development under low–temperature curing, and an extremely small adiabatic temperature rise, as shown in Figure 7.

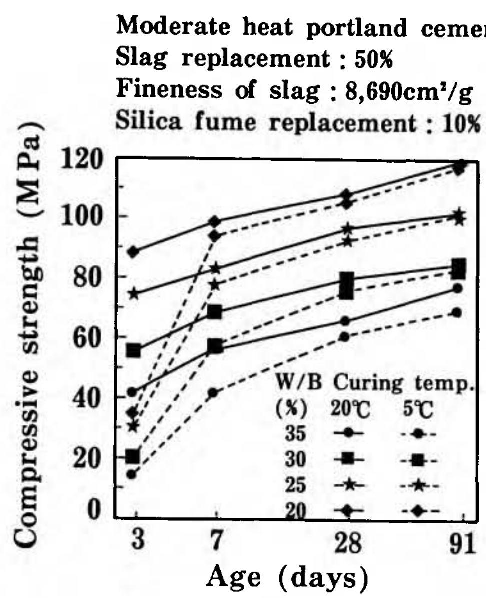

Fig. 6. Compressive strength of concrete developed by the Civil engineering Research Institute, Hokkaido Development Bureau

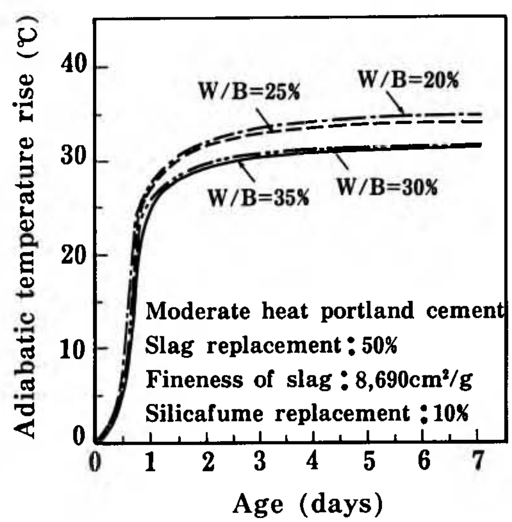

Fig. 7. Adiabatic temperature rise of concrete developed by the Civil Engineering Research Institute, Hokkaido Development Bureau

The utilization of blast-furnace slag is an effective utilization of industrial waste. Reducing the consumption of Portland cement contributes to reducing the amount of CO_2 generated. Therefore, it can be said that this type of concrete is high-performance concrete which suits this century's emphasis on the global environment.

5 Environmentally-friendly concrete

With global environmental problems recently becoming serious, people have begun to move toward a new understanding of the importance of cycles of substances and of the food chain. Ecosystems exist in the balance between these factors. Therefore, people can understand the burden on the environment by returning to the starting point.

The recent development of materials is characterized by the idea that research and production are promoted not by seeking high-performance materials which consume large amounts of energy but by focusing on reducing the burden on the environment. "Life Cycle Assessment" (LCA), which aims to evaluate the burdens on the environment quantitatively and comprehensively at each stage of product production, consumption and disposal, has been gaining attention. Furthermore, the "Zero Emission Plan" of the United Nations University is being executed to transform the consumption-oriented industrial society that consumes large amounts of resources into a recycling-oriented one. The plan is a grand one which aims to create a waste-free social system.

Concrete is a construction material important to various structures. An important point in distinguishing concrete from ordinary materials is that many concrete structures come into direct contact with nature. This is one reason that, in many instances, people have a negative image of concrete structures. Concrete's hardness generally gives people the impression that the material is out of harmony with nature. In fact, few efforts to improve this situation have been made. To make concrete an eco-material, ways of understanding the situation and of solving the specific problems become important.

There is no doubt that locating concrete structures in certain areas results in changing the ecosystem in those areas, thus often making the lives of plants and animals more difficult. When symbiosis or coexistence of man and nature is considered, it is significant to evaluate the acceptable degree of environmental change. At the present time, it is very difficult to conduct such an evaluation. Therefore, the best method now is to give concrete a certain "interface function" at the point of contact between concrete and animals or plants to minimize the burden on the environment. Furthermore, it is desirable for concrete to have a form which can minimize interference with the cycles of substances, such as of water. When the limits of structural design prevent concrete from having such a form, it is important to compensate for the burdens.

When environmentally-friendly concrete is called "eco-concrete", eco-concrete can be defined as a type of concrete which contributes to reducing the burden on the global environment and which has ecologically-conscious interfaces between concrete and all living things, including humans. Figure 8 schematically shows the above concept. Porous concrete is such a type of concrete.

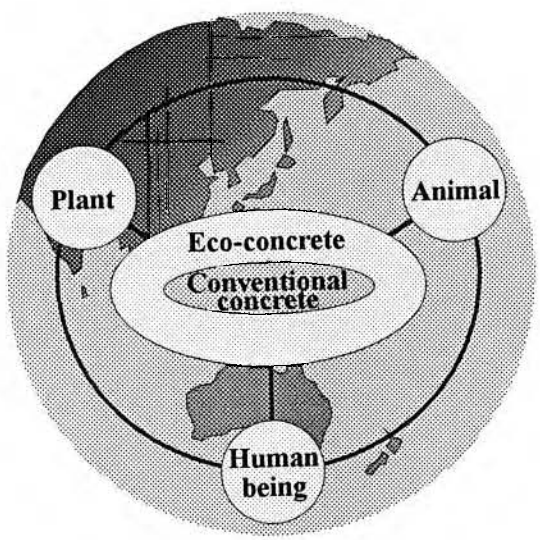

Fig. 8. A concept of eco-concrete

The author's research group has conducted an underwater exposure test of porous concrete specimens as shown in Photo 1 to clarify what role this type of concrete can play as a part of the underwater environment.

The dimension of specimens are ϕ 150 x 800 mm. Normal Portland cement and blast–furnace slag cement were used. Table 1 shows the mix proportions of concrete.

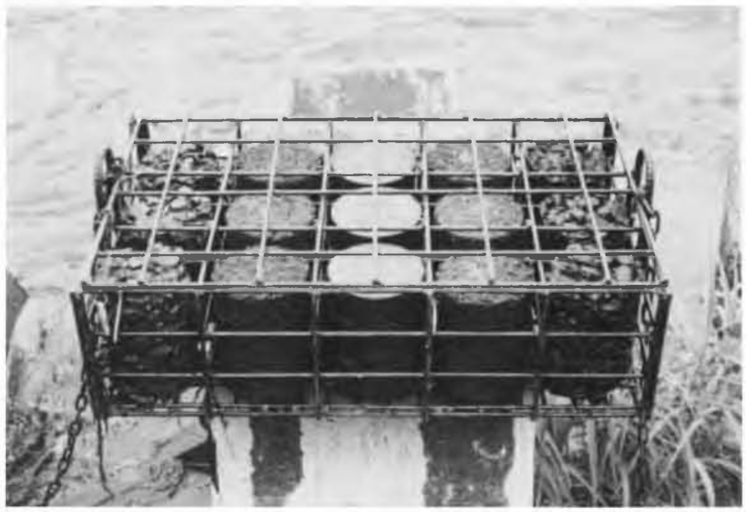

Photo. 1. Underwater exposure test specimens

Regardless of the types of cement and the sizes of aggregates, the percentage of voids was set at 25%.

Table 1 Mix proportions of porous concrete for underwater exposure

No.	Concrete	Type of cement	Size of coarse aggregate (mm)	Water–cement ratio (%)	Water (kg)	Coarse aggregate (kg)
1	Porous concrete	Normal portland cement	20 ~ 40	28	88	1506
2			2.5 ~ 5.0	28	103	1455
3		Blast–furnace slag cement	20 ~ 40	28	87	1506
4			2.5 ~ 5.0	28	101	1455
5	Normal concrete	Normal portland cement	25*	52	144	1193

* Gmax

Figure 9 shows the numbers of the aquatic insects that were commonly found in the specimens during 2 months of exposure. Many aquatic insects had already appeared during the first month of exposure. The number of aquatic insects clearly increased over time. It is evident that normal concrete, which has no voids, and porous concrete differ in the number of aquatic insects in the specimens. However, it is not clear whether the types of concrete and the size of voids affected the number of aquatic insects.

Thirty–six types of algae were observed during the first month of exposure. In particular, many diatoma elongatum and fragilaria construens were observed. The types of cement and concrete did not affect the number of algae. Observation during the second month of exposure basically showed the same results.

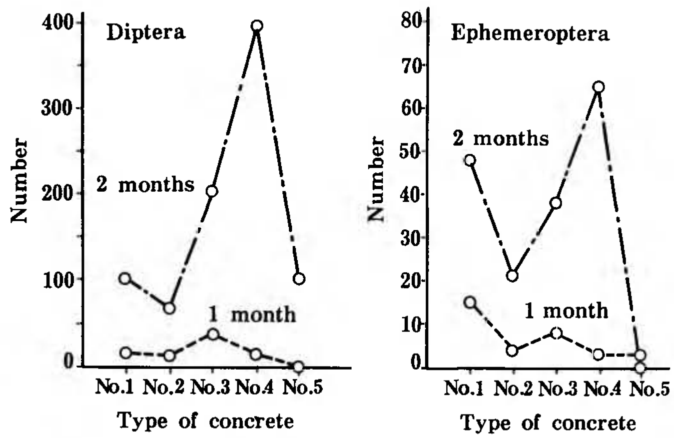

Fig. 9. Numbers of aquatic insects in porous concrete specimens

This project will be conducted for 2 years. This project incudes not only the observation of living things in the specimens but also measurement of water temperatures, pH, BOD(Biochemical Oxygen Demand), DO(Dissolved Oxygen), COD(Chemical Oxygen Demand), and SS(Suspended Solid). The effects will be evaluated comprehensively. There is no doubt that civil engineers must consider symbiosis with nature in carrying out their work. However, many obstacles hinder the realization of symbiosis with nature. In this context, although the possibilities of porous concrete are as yet unknown, it is important to gather data steadily.

6 Concluding remarks

There is no doubt that the preservation of the global environment will be the most important problem of the 21st century. Therefore, concrete engineers must review concrete from this perspective. In other words, we will have to establish a new framework for concrete technologies. This paper focuses on a small number of problems. However, based on the discussions in this paper, subjects for future study include:

1. Establishment of a design system that integrates durability design and structural design
2. Development of high–performance concrete and clarification of the benefits of using this type of concrete

3. Development of methods to evaluate the durability of concrete
4. Development of methods to incorporate into design systems the life–span of concrete structures and the effects on the life–span of repairs and strengthening of structures
5. Clarifying the role of concrete in preserving the global environment
6. Development of eco–concrete

7 References

1. Japan Society of Civil Engineers. (1986) Standard Specification for Design and Construction of Concrete Structures, Part 1 [Design].
2. Marzouk, H. and Jiang, D. (1994) Effects of freezing and thawing on the tension properties of high–strength concrete. ACI Materials Journal, V. 91, No. 6, pp. 577–586.
3. Zhou, Y., Cohen, M.D. and Dolch, W.L. (1994) Effect of external loads on the frost–resistant properties of mortar with and without silica fume. ACI Materials Journal, V. 91, No. 6, pp. 595–601.
4. Katayama, S., Maruyama, K. and Kimura, T. (1995) Flexural behavior of RC beams with corrosion of steel bars. Extended Abstracts; The 49th Meeting of JCA, pp. 880–885.
5. Carino, N.J. and Clifton, R. (1991) High–performance concrete: research needs to enhance its use. Concrete International, V. 13, No. 9, pp. 70–76.
6. Sakai, K. and Watanabe, H. (1993) Development of low–heat high–strength concrete. Concrete 2000, (ed. R.K. Dhir and M.R. Jones), E & FN Spon, London, pp. 1539–1550.
7. Sakai, K. and Watanabe, H. (1994) High–performance concrete: low–heat and high–strength. ACI SP–149, pp. 243–268.

2 TOWARD RATIONAL DESIGN OF CONCRETE STRUCTURES – INTEGRATION OF STRUCTURAL DESIGN AND DURABILITY DESIGN

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Abstract
This paper discusses an approach that should be followed if the integration of durability design into the structural design process is to be successful. The inclusion of durability requirements in national codes and standards is probably the surest way to get uniform acceptance of these requirements by both designers and constructors. There is a definite need for shorter code and standard revision cycles, however. More definition of the environment in which the concrete structure will perform is necessary. Realistic service life requirements are necessary for every structure. Performance criteria should focus on the transport properties of the concrete as it is the ingress of the environment into the concrete which is the major problem. Combinations of both performance and prescriptive specifications are necessary to insure adequate durability. The evaluation of concrete performance should use national standards whenever possible rather than the vast array of tests proposed by many different researchers. Changes in the education process, both at the university level and for experienced engineers, would help remove resistance to changes in the design process. The need to include the durability considerations into the project planning is essential. Closer collaboration of the designers and the constructors with a view to eliminating structural details which can lead to durability problems is needed. The need for rigorous quality control and quality assurance on projects is essential to insure satisfactory durability in the future.
Keywords: Codes, concrete, constructability, detailing problems, durability criteria, education, environment, project timing, service life, specifications, standards, structural design, test methods.

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1 Introduction

Concrete is the most extensively used material in the $400 billion per year construction industry in the U.S. It is also the most extensively used material in most other regions of the world. This common use contributes to the continuing problem of poor concrete durability as nobody wants to pay the extra attention and the little extra initial cost it takes to provide a more durable, longer lasting concrete. Because we use so much concrete, and because concrete has competing materials (eg., steel, wood, asphalt) for many applications, the tendency is to provide the concrete at the lowest possible cost. This is achieved by minimizing the materials required to produce the concrete, using the cheapest (and probably the least trained) labor, and eliminating the good practices (eg., quality control, consolidation, curing) that are necessary to produce good concrete.

What does this type of approach bring us? A 1990 National Research Council report in the U.S. indicated that it will cost $2 to $3 trillion over the next 20 years to repair all the U.S. concrete structures which are now deteriorating from corrosion or are poorly made and maintained. This is not to say that the competing construction materials survive any better. In fact, most do worse than even the poorest of concretes. A long running television commercial in the U.S. promoting the sale of automobile oil filters, concluded by having the auto repair mechanic saying "You can pay me now or you can pay me later!". The inference was that if you initially paid a little more for the oil filter that you used in your automobile, you wouldn't have to pay for costly repairs in the future. A similar analogy exists for concrete.

The need for a more durable concrete has not been lost on the global engineering community. As a result, most countries now have their own programs to develop "high-performance concrete" because they recognize that there is a great potential to minimize expense each year in maintenance, repair and replacement of poorer quality concrete. What exactly is high-performance concrete?

Many definitions have been proposed for "high performance concrete." In general, high performance means behavior above and beyond what we would normally expect from concrete. This tends to be somewhat of an anomaly because when we order concrete from a supplier, we expect it to have satisfactory performance with respect to both strength and durability. We certainly don't order "low performance" concrete but that is often what we get. We typically order concrete by strength requirements. Strength is quantifiable. If we order 40 MPa, we can measure it. How do we order durable concrete? If we ask for concrete that will last for 100 years, how do we or the concrete supplier know that it will? We won't be here to check and see that it has performed satisfactorily and, most likely, the concrete supplier won't be in business to compensate us for any non-performance if it fails in less than 100 years.

Indications are that high performance concrete is having a successful evolution, at least at the laboratory level. However, the money being spent on developing and evaluating high performance concretes is, for the most part, distributed among many researchers in many countries doing relatively small, uncoordinated studies. It is estimated that in the U.S. in 1994, there were 3000 concrete studies being done in 500 to 1000 laboratories or organizations. How this information gets disseminated and integrated into actual practice is a major problem.

Dissemination of information is a simpler problem than the integration of that information into the design process. Meetings of the type that this presentation is being made at, are helpful for information dissemination in that researchers are advising other researchers of their work and results. Normally researchers have trouble tracking what other researchers are doing as is evidenced by that fact that many papers on well researched durability problems (eg., reinforcing bar corrosion) reference only the work done on that subject by the author of that paper. However, the results from this meeting and the many similar meetings on concrete durability generally do not cause any significant changes in design or construction practice. Why is this? The following sections explore a few of the authors views on this problem.

It is also the author's belief that some of the major stumbling blocks to acceptance of durability considerations in design are education, timing of the introduction of durability considerations into a project, and the reluctance, by constructors, to change existing practices to accommodate durability requirements. All have a financial impact on a project as an insured durability comes at an initial higher cost. Some aspects of the influences of these topics are described below as catalysts for further discussion. Bryant Mather, world renowned expert on concrete durability, has often stated that based on what we know about concrete and its behavior in given environments, the only reasons concrete should deteriorate are ignorance, stupidity or fraud. Hopefully, we can change the first two of these within some reasonable period.

2 Implementation

Designers do not have a financial incentive to use the new technology being developed by the researchers on high performance concrete. Using or specifying new technologies tend to increase the designers cost and also the risk of doing business without any appreciable benefit or financial reward. A similar problem exists for the constructors as they generally are not a part of the design process and can only execute work in accordance with the documents of the contract. Occasionally, "value engineering" clauses exist in contracts which allow the constructor to use innovative construction materials and techniques to produce cost savings on a project. These savings are shared by the owner and the constructor, but these contract provisions are rare and there are numerous critics of this approach. For a constructor to deviate significantly from standard practice to implement innovations increases his risk which is a strong disincentive when most contracts are awarded on a least price basis.

When the designer is reluctant to specify new technology and the constructor is reluctant to implement it as his own discretion because of risk or cost, the typical tendency is to think of the government, at all levels, as the solution to the problem. Governments are in a position to lead in the development and demonstration of improved concrete technology by implementing constructions that use technology that may be outside of the provisions of codes and standards. This is due to the fact that governments are self- insuring and that they are entrusted with providing safe structures for public use using the publics money.

However, in many governments, the motivation for providing long-lasting materials does not exist. The principal motivators in taking action are a fear of disaster (eg., a bridge collapse) and lowest costs. You cannot sell the politicians on the concept of durability because the material only has to last as long as their term in office. Life-cycle costs are generally not considered. In private corporations, similar attitudes often exist because stockholders expect business to be performed at lowest costs. There are many examples of developers doing the minimum needed in construction because they do not intend to be the long term owner of the structure and hence do not care what happens to the structure in the years to come.

Would the designer, the constructor, and the government be more willing to adopt improved durability innovations if they could do it by reference to accepted codes, standards, and specifications? The answer is probably "Yes" because there is a general underlying faith by the industry and the general public in these types of documents. The codes and standards currently determine technology acceptance. If the accepted codes, standards, and specifications require it, then it puts all competing parties on a level playing field. Risks become the same and the durability innovations become part of the cost of doing business for everyone.

In support of this premise, the US Civil Engineering Research Foundation (CERF) conducted a survey of 600 members of the highway community, including public sector officials, construction companies, entrepreneurs, and research facilities to determine what were the most common barriers to adopting innovations in highway construction technologies. The ranking was 1) constrained standards or specifications (23%), 2) current limitations on proprietary product usage (18%), 3) lengthy processes or high costs (17%), and 4) known evaluation inadequate (12%). If the standards or specifications do not allow the use of new technology to improve the performance and service life of concrete, then that is a problem we certainly have the capability to fix.

3 The standardization process

Structural design of concrete typically never considers the durability aspects of the concrete. Strength is the primary consideration along with modulus of elasticity and other related mechanical properties. The integration of structural design and durability design can be approached from two directions: higher strengths lead to improved durability or improved durability leads to higher strengths. Neither approach is universally correct and exceptions can always be found. From a practical standpoint, it may be simpler to concentrate on improving the durability aspects as changes to codes and standards with respect to improved durability may be accomplished in a more timely manner than changes to structural provisions. Many structural requirements in codes and standards were developed for concretes of strengths 40 MPa or less. When higher strengths are used, these requirements may or may not become more conservative. Changes in the structural provisions need supporting data from tests of structural members and the production of such data is a long and expensive process, more so than for durability evaluations. However, if improved durability design results in routinely occurring higher strengths, the designers will, in time, adjust their procedures to effectively use this additional strength.

It is the author's belief that standards must be the place to begin to integrate durability requirements into the design process as many specifications simply refer to the standards. As noted above, constrained standards or specifications are a significant barrier to the implementation of new materials and technology into the design and construction process. Why are they constrained or restrictive? The existing design codes and standards are usually conservative because their underlying basis is to protect the public while providing a functional structure. They tend to restrict the use of new materials until, and unless, a substantial data base about them has been established. They are also flavored by the perception of what the industry can realistically produce. This is a dangerous perception because experience has shown that with a little training and education, high quality concrete production and construction can be achieved on a routine basis.

The preparation of codes, standards, and specifications are done differently in various parts of the world. Some countries use the "consensus standard" approach where representatives from all aspects of the industry, including academia, jointly prepare and approve the standards. Some countries use government agencies or teams of specialists to prepare the standards. Other countries simply adopt the standards of other countries and modify them for their local needs. All of these preparation methods run the risks of influence by special interest groups or individuals, or, even more commonly, having uninformed individuals either doing the standard preparation or approval or both. In general, these risks are reduced in the consensus standards approach because of the checks and balances provided by a very broad representation of the industry in the standards preparation.

How can we improve the standardization process to expedite durability requirements into the design process? The first step should be the timely and efficient evaluation of the durability data base being developed by the research and development community. This should be complimented by demonstration projects of the new technology when they exist. Unfortunately, when public funds are used, demonstration projects are not viewed favorably because they tend to benefit only a limited segment of the community instead of everyone who helped pay for it. The key word here is "timely". It is not very effective if the inclusion of new technology into standards takes 7 to 10 years, yet that time period is typical for many code and standard reissue cycles. A classic example is the preparation, in the US, of a standard for silica fume, a major contributing material for improving durability. After 10 years of development, Draft 16 of the standard is being balloted in 1995. Interim procedures for adopting new technology into standards must be invoked so that once a new technology or material has been satisfactorily demonstrated, it can appear in the standards within 12 to 18 months. This may be an impossible task in the short term but is something that needs serious consideration by the industry.

If we are to include more stringent durability requirements into our codes and standards, two approaches are possible: performance requirements and prescriptive requirements. Both have their advantages and disadvantages and perhaps combinations of the two can supply the best solution.

4 Performance and prescriptive specifications

Performance specifications are promoted as providing flexibility and encouraging economic mixture proportioning. "Economic mixture proportioning" infers that either the least amount of material will be used in producing concrete that will satisfy certain performance criteria or that less expensive materials than the conventional concrete materials will be used. The establishment of "performance criteria" assumes that we understand the nature of concrete and its interaction with both the environment and service loads. It also assumes that we can adequately define the environment and also predict the service life of the structure. This is doubtful although we are making progress in all of these areas. Realistically, we are only making educated guesses for most aspects of "performance criteria". There is also an uncertainty about the methods we use to measure "performance". While the concrete technologist may be aware of these limitations, the concrete designer assumes that if the concrete meets the performance criteria set forth in standards or specifications, the concrete when used in a structure in a given environment will have sufficient durability for the service life of the structure. Unfortunately, it is very difficult to provide a general criteria which meets all possible uses of concrete.

Prescriptive specifications, those that tell you exactly how much of each ingredient to put into the concrete, used to be common and still exist in many parts of the world. The mixing water is typically the only variable and is adjusted to suit the conditions of the construction. These would be ideal if all the ingredients used to make concrete were the same world-wide. They are not, so the best we can do, based on our present research on concrete durability, is to define minimum amounts of binder material and maximum amounts of water to be used with that binder so as to provide a dense matrix to resist the intrusion of the environment. We can also require portions of that binder to be supplementary cementing materials, e.g., fly ash, silica fume, and blast furnace slag. These supplementary cementing materials further densify the binder. The use of chemical admixtures that allow the reduction of water while maintaining adequate workability can also be prescribed. These admixtures may be necessary when using some of the supplementary cementing materials. Prescriptive specifications tend to be in conflict with the concept of "economic mixture proportioning" for performance specifications but are more easily understood by the user.

It is doubtful that more durable concrete can be achieved by minimizing the amounts of the more expensive ingredients of concrete (namely Portland cement) while still obtaining adequate strengths. As noted earlier, concrete strength is, however, the primary consideration for the designer. Strength is, at best, an indirect measure of concrete quality from a durability viewpoint. Historically, most standards and specifications have used the water-binder ratio as the main parameter to define concrete for durability, with the 28-day compressive strength consistent with the water-binder ratio providing the field control of the concrete. For marine concretes, minimum amounts of cementing material are also specified. The extensive research being done on high-performance concrete, however, indicates that all these requirements for improved durability, while necessary, may not be enough. What is needed is a very dense matrix of ingredients that are compatible with the aggregates and resistant to the environment in which the concrete is to used. In this regard, the use of low water-binder ratios, high binder contents, and supplementary cementing materials (eg., silica fume, fly ash, blast furnace slag) in conjunction with portland cement have typically shown superior performance to conventional concretes under many different environmental exposures. Most of these modifications to improve durability will not produce a more "economic" mixture. With the cost of the concrete materials being only 5 to 15% of the cost of the concrete in-place, it is also foolish to consider using insufficient amounts of material when considering what future maintenance costs will be.

5 The environment

There is one school of thought that believes that durability is not a property of the concrete but is a function of the environment. It postulates that all concretes are durable provided they are kept in an environment consistent with the composition of the concrete. Ancient concretes, made with natural cements, lasted for thousands of years in a benign environment. With the advance of civilization, the environment was changed as pollution increased and the concrete began to deteriorate. This can be witnessed in the ancient monuments in populated areas of Greece, Italy, Egypt and Mexico. Similar monuments in other regions of the world that have not seen significant pollution have not experienced this same level of deterioration. Concrete which survives in one environment may not survive in another environment. Concrete used in the interior of buildings may not survive when used in a marine environment, a sewage treatment plant, or for the containment of hazardous waste.

When concrete is put in a difficult environment, it will deteriorate at rates governed by that environment. If the rates of deterioration for that environment can be predicted, then sufficient material can be added to achieve a prescribed service life or the concrete constituents can be modified to reduce that rate and extend the service life. As an example, the corrosion of reinforcements has received extensive study for some time. Most of the principal factors that reduce the long-term integrity of reinforced concrete are well understood. The use of adequate concrete cover, dense concrete matrices, crack control measures, anti-corrosion admixtures and additives, and other techniques have resulted from this knowledge. Unfortunately, these are still relatively short term solutions. Few studies have been made that can help predict the longevity of reinforced concrete over hundreds of years. Very little information in the literature is helpful in relating, in a quantitative way, the rate of degradation of concretes subjected to the principal characteristics of the environment over the long term.

Do we know enough about our environments to establish a universal criteria for performance specifications? Our specifications presently address marine environments, sulfate soils, freezing and thawing, and a few other phenomena which can be quantified. But what about pollution, acid rain, hazardous wastes and other environments. While the present answer to a universal criteria is probably "no", I am confident that, with time, individual criteria can be established for almost all aggressive environments. If we had this information today, we would still be at risk in designing structures with very long service lives because we don't know what our environment of the future will be. If we design concrete to last 1000 years based on our environment today, do we have any guarantees that the environment will not become worse in the future? Hopefully it won't, but we can not be sure.

6 Service life

Service life of engineering structures has been a hot topic within the engineering community for the last several years, but it still lacks adequate definition. In general, service life of a structure is a questionable concept. Very few concrete structures have a precise service life. Offshore concrete platforms have a service life that is determined by the amount of hydrocarbon in the reservoir it is producing and the rate of production. Yet, concrete platforms built in the 1950's for a service life of 20 years are still in service because the technology of extracting the hydrocarbons from the earth has improved over the years so that much more is being produced than was originally planned for. Buildings designed for 40 years are still in service after 70 years while similar buildings are removed in 10 to 15 years to make way for more modern buildings or other facilities.

For the sake of the designer, do we need to specify a service life for a structure? The answer is "yes" even though we don't know how realistic it will be. Requiring that a structure should have a specific service life must also be accompanied by performance criteria which gives the designer a quantitative objective in the design process.

The service life of concrete is usually dependent on a slow rate of deterioration which results from combinations of the environment, the concrete quality, and the size and configuration of the concrete element. In addition, service life is also a function of the failure criteria which is used. A practical service life may also depend on the competition that concrete may receive from alternative materials. If a pavement is designed to last 100 years, it will probably never be built because the cost will not conform to most budgets of the agencies who fund highway construction. Cheaper materials than concrete will be used without regard to service life. Structures whose basic function and utility doesn't change with the passage of time, such as bridges, buildings, marine structures, dams and navigation structures, certainly should be designed to last at least 100 years. Other structures whose capacity will be exceeded within reasonable time periods because of increasing population or which will become obsolete due to changing technology, can have shorter lives. Whatever service life we specify, it should be on the conservative side because we can't anticipate all of the factors which might influence the structures longevity.

7 Performance criteria and measurements

Although properties such as compressive strength, modulus of elasticity, and porosity are indirectly related to durability, the transport properties of diffusivity and permeability are probably the most important factors relating to durability. Unfortunately, these properties are not simple things to measure. The major degradation parameters that exist in a service environment include sulfate ions, chloride ions, leaching of calcium hydroxide by water, carbon dioxide reactions, alkali-aggregate reactions, freezing and thawing, wetting and drying, and these various parameters in combination. If the transport of these degrading phenomena into the concrete can be reduced or eliminated, the long-term performance of the concrete can be greatly enhanced. Only by establishing criteria which demonstrates that the environment is not penetrating the concrete at unacceptable rates, can we make an estimate of the service life of the concrete.

Having once established the criteria, we must have realistic methods to evaluate the concrete to ensure conformance to the criteria. Traditionally, concrete durability has been assessed by measuring either the strength, weight change, length change or change in structure by non-destructive techniques of specimens subjected to a corrosive agent or a specific difficult environment. The corrosive agents are generally applied at the external boundary of the specimen but may sometimes be included in the concrete during mixing. Difficult environments typically include extremes of temperature and varying moisture conditions which are varied throughout the test, usually for time periods which are more suited to the test procedure than the real world environment. Results from these types of tests may not be applicable to predictions of long term durability and are generally not sensitive to the design geometry of structural members.

The durability renaissance of the 90's has led to an abundance of performance test methods for specifying durability as concrete technologists have endeavored to move away from strength as a durability guide. In a quick scan of test methods related to the permeability or diffusion rates of concrete, the author found 11 different methods by which these phenomena could be quantified. Tests of this type that have been developed in the laboratory using a small range of trial concretes may not translate well to other laboratories, other concrete, or the variety of environments that exist in the real world. Test specifications that have not been formulated by national associations may be flawed in technique or description. In our specifications, we should use national standard tests wherever possible.

Initially, including durability performance criteria and the methods by which to measure them in the specifications will meet a great resistance from both the designer and the constructor who are not used to working towards a "durable structure". The criteria will be "too severe". The test methods will be "impractical". These are legitimate concerns and caution must be exercised to ensure that what