AN OVERVIEW OF CONCRETE DURABILITY
PROBLEMS IN THE ARABIAN GULF REGION

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: الخلاصة

يلاحظ تعرض الخرسانة المسلحة بمنطقة الخليج العربي لتدهور ملحوظ بخصائصها الأصلية تلخص المشكلة الأساسية بتآكل حديد التسليح وتأثير الأملاح المختلفة المصاحبة لعوامل الطبيعة . كما توجد عوامل تعمل على تردي الأسمنت المسلح مثال أملاح حامض الكبريتيك وتفاعل الحصى المستخدم مع المواد المصاحبة للخلطة الخرسانية وتشقق الخرسانة خلال فترة الصب من جراء الأنكماش وكذلك التشقق الناتج من التدرج الحراري داخل الخرسانة وهذه العوامل منفردة ومجتمعة تؤثر تأثيراً شديداً على مقاومة الخرسانة المسلحة لعوامل الطبيعة وخصوصاً بمنطقة الخليج العربي وذلك لإرتفاع نسب الأملاح ودرجة الحرارة المحيطة ولعدم وجود ركام ذو خصائص جيدة للإستخدام بالخرسانة المسلحة . يستعرض هذا البحث لجميع هذه المشاكل وكيفية إيجاد الحلول لها وبالخصوص تآكل حديد التسليح الذي يكون المشكلة الأكثر أهمية .

ABSTRACT

Concrete deterioration is a serious problem in the Arabian Gulf region. The primary problems are reinforcement corrosion and salt weathering. Sulfate attack, alkali-reactive aggregates, and cracking due to drying shrinkage and thermal gradients are also contributory. The particular severity of these problems in this region stem from the salt-laden environment, high ambient temperatures, and lack of high quality aggregates.

The problem areas are reviewed in detail in this paper with special emphasis on reinforcement corrosion. Suggestions for alleviating the problems are also provided.

AN OVERVIEW OF CONCRETE DURABILITY PROBLEMS
IN THE ARABIAN GULF REGION

INTRODUCTION

Portland cement concrete is the world's most versatile and economic building material. The raw materials from which portland cement is produced and the sand, stone, and water that constitute the remainder of the basic concrete mixture ingredients are among the commonest mineral materials in the earth's crust. However, the outwardly-appearing simplicity of concrete belies the extemely complex physico-chemical nature of the material. This, coupled with the wide variability in the properties of the major ingredients (the aggregates) and the virtual *in situ* batching procedures involved in its production, has produced a host of potential durability problems for concrete structures. Stated another way, the durability of concrete in any given set of environmental and exposure conditions is a function of the characteristics and proportions of the cement, aggregates, water, and admixtures used, and the mixing, placing, finishing, and curing of the concrete. It can truly be stated that no two concrete batches are identical, a fact that is abundantly obvious to those who have observed sumultaneous excellent and poor durability response in immediately adjacent areas of a single concrete structure. Furthermore, detailed chemical and microscopic examinations comparing specimens from the areas of differing performance often show differences that are, at best, subtle. This observation brings out the point that, relative to durability, we are often operating at or near the durability limits of the concrete for the given ingredients and proportions.

Striving for concrete durability, then, becomes a matter of carefully evaluating the environment and exposure conditions to which the concrete will be subjected, tailoring the concrete mixture ingredients and proportions to counteract potential problems, and batching, mixing, placing, and finishing the concrete in accordance with recommended practices.

DURABILITY PROBLEMS: GENERAL

On a global scale the non-structural sources of deterioration of hardened concrete may be classified as follows:

1. Freezing and thawing:
   (a) cement paste phase;
   (b) aggregates;
2. Chemical attack of the cement paste:
   (a) acids
   (b) sulfates
   (c) carbonation
   (d) leaching (solution weathering)
3. Abrasion and cavitation;
4. Corrosion of reinforcement;
5. Chemical reactions involving aggregates:
   (a) alkali–silica;
   (b) alkali–carbonate;
6. Physico-chemical processes that involve the transport of water and solutes within concrete (evapo–transpiration and osmotic pressure).

The categories of concrete deteriorative mechanisms, as set forth above, are not totally independent and, in fact, two or more are often mutually supportive, if not synergistic. For example, freezing and thawing deterioration of concrete containing frost sensitive aggregates, which is primarily caused by the generation of excessive hydraulic pressures within concrete, also involves physico-chemical potentials and, perhaps, osmotic pressure (item number 6) [1, 2]. In another case, corrosion of reinforcing steel (item 4) is known to be accelerated by the presence of carbonation (item 2b) which reduces the pH of the pore fluids in concrete.

DURABILITY PROBLEMS: ARABIAN GULF REGION

General

Premature deterioration of concrete in the Arabian Gulf region is a problem of serious proportions. According to a recent publication, condition surveys on structures in Eastern Saudi Arabia show an alarming degree of deterioration within 10 to 15 years [3]. In those surveys, 55% of the 168 observations made of 42 concrete structures 17 to 22 years of age showed at least some deterioration or extensive moderate deterioration.

The types of concrete distress in the Arabian Gulf

region, in general order of decreasing importance, are [3–8]:

1. corrosion of reinforcement with attendant spalling of the concrete cover;
2. salt weathering due to crystalization pressures brought on by capillary transport of soluble salts (principally chlorides and sulfates) and evaporation at exterior surfaces of the concrete;
3. common sulfate attack due to the sulfates present in the soils, ground waters, and aggregates of the region;
4. drying shrinkage and thermal-gradient-induced cracking due to the environmental conditions of the region;
5. aggregate–cement reactivity (principally alkali-silica).

Reinforcement corrosion and salt weathering are considered to be the most common, and the most serious, forms of concrete deterioration in the Arabian Gulf region.

Environmental–Exposure Conditions

While the mechanisms of deterioration cited previously are not, with the possible exception of salt weathering, unique to the Arabian Gulf region, the environmental conditions there are of such a nature as to greatly abet deterioration processes. These conditions include [3]:

1. High temperature–high humidity.
2. Drying winds off the arid interior.
3. Evaporation rates that very greatly exceed precipitation rates (average 124 and 5 cm/yr, respectively).
4. Soil, groundwater, aggregates, and atmosphere that are excessively contaminated with various salts, the most important of which are soluble chlorides and sulfates.

These conditions promote corrosion of reinforcement (due to the presence of chloride ion), salt weathering (soluble salts and environmental conditions that support evapo–transpiration concentration of salts in concrete), sulfate attack, and cracking induced by drying shrinkage and thermal gradients. Rasheeduzzafar, and others [3] eloquently bring across the point that the combination of climate and geology create a pessimum environment relative to concrete durability.

In the sections that follow, each of the five aforementioned types of concrete deterioration found in the

Arabian Gulf region will be discussed with particular emphasis on reinforcement corrosion, the most prevalent and serious condition.
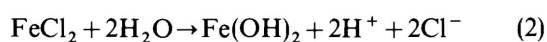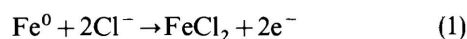
REINFORCEMENT CORROSION
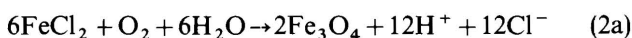
Mechanism of Corrosion

The corrosion of steel in concrete is generally considered to be an electrochemical process that results in the formation of macro-galvanic cells [9–11]. The pore fluids within concrete are normally buffered to at least the pH of saturated calcium hydroxide solution (pH = 12.5) and the presence of alkalies in the cement (K_2O and Na_2O) may even raise it higher. At pH levels above 11.5, a tightly adhering coating of gamma ferric oxide forms on steel surfaces, which normally prevents corrosion. However, the presence of chloride ion in concentrations above some threshold level destroys this passivity and corrosion cells develop. The threshold chloride concentration within the concrete at the level of the reinforcement necessary to initiate corrosion is generally taken to be in the range 0.7 to 0.9 kg/m^3 of concrete. Other ions from the halogen group of elements are probably also capable of depassivating steel in concrete, but chlorides will be most commonly encountered in soluble form. There are also indications that the bisulfide ion (HS^-) may initiate corrosion of reinforcement in concrete.

Metal loss and the build-up of corrosion products occurs at the anodic area of corrosion cells. The resulting corrosion products occupy about 2 to 8 times the volume of the original steel from which they were formed (depending on the form of the corrosion products) resulting in stresses that crack the concrete and eventually cause the concrete cover between the reinforcement and the nearest free surface to spall (see Figures 1 and 2).
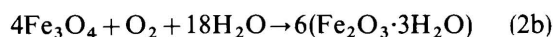
The chemical reactions that occur at the anode (corroding area) are believed to be as follows:

$$Fe^0 + 2Cl^- \rightarrow FeCl_2 + 2e^- \qquad (1)$$

$$FeCl_2 + 2H_2O \rightarrow Fe(OH)_2 + 2H^+ + 2Cl^- \qquad (2)$$

Or, if any oxygen is present:

$$6FeCl_2 + O_2 + 6H_2O \rightarrow 2Fe_3O_4 + 12H^+ + 12Cl^- \qquad (2a)$$

and, with excess oxygen:

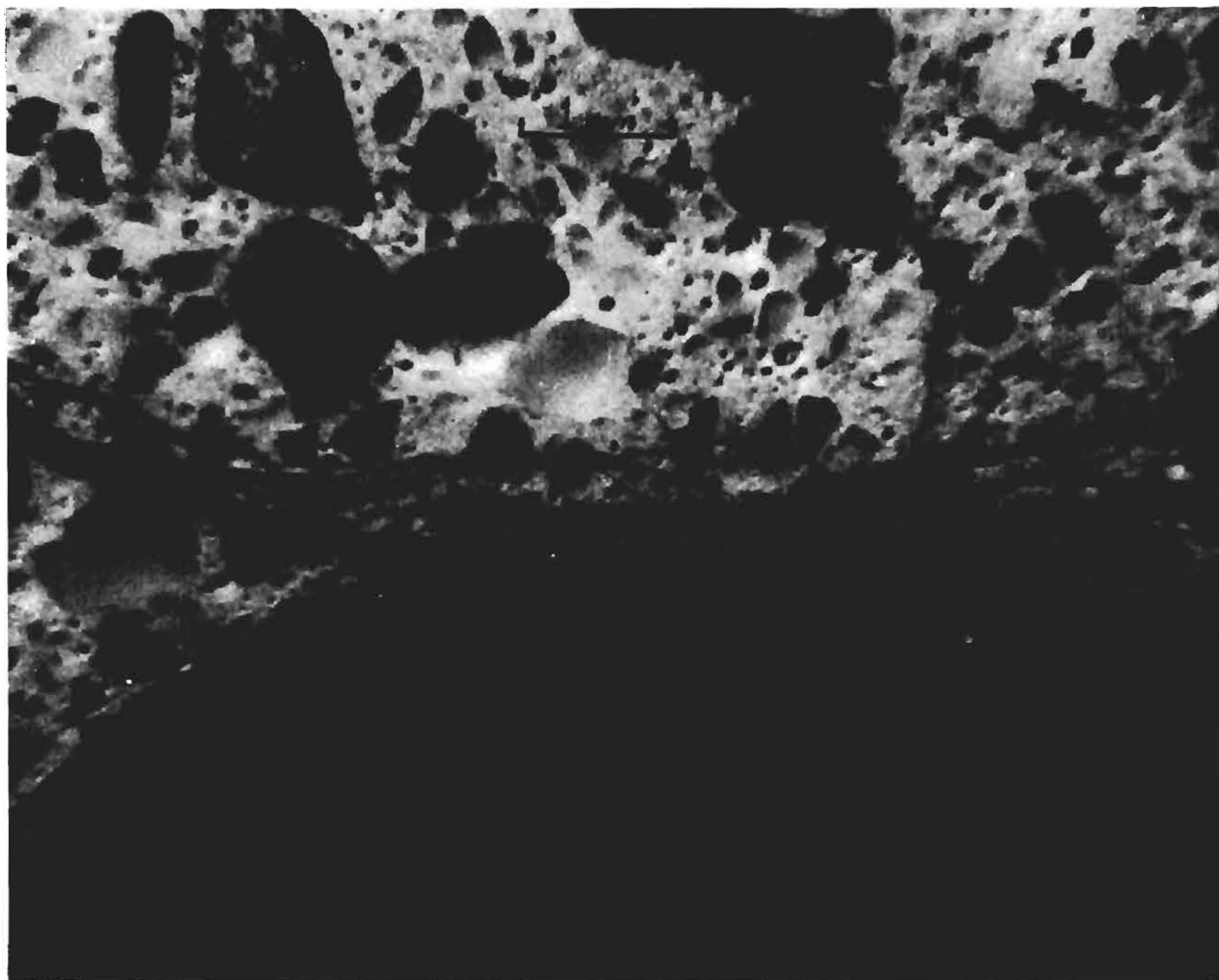$$4Fe_3O_4 + O_2 + 18H_2O \rightarrow 6(Fe_2O_3 \cdot 3H_2O) \qquad (2b)$$

Figure 1. Photomicrograph Showing Cracking of Concrete Due to Corrosion of Reinforcing Bar

Notice that:

1. It is *not* necessary that oxygen be present at the anode for the corrosion process to proceed.
2. Once the threshold chloride ion concentration is achieved and corrosion commences, it is *not* necessary that additional chloride be supplied to sustain corrosion—the chloride ion is regenerated in the corrosion process, Equation (2).

The two points highlighted above are of importance because they point out that once concrete has become critically contaminated with chloride, attempts to arrest the process by blocking access of further chloride or oxygen are futile (at least with respect to the anodic reaction).

The cathodic reaction consists of the electrolysis of water due to the emergence of electrons that are generated at the anode (Equation (1)) and travel through the steel to the cathode, as follows:

$$\tfrac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2\ OH^- \qquad (3)$$
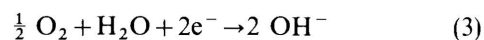
Notice that in order for the cathodic reaction to proceed, sufficient oxygen *must* be present. Otherwise, polarization occurs at the cathode due to the formation of an electrically insulating layer of hydrogen and the corrosion current is stopped. It is generally held that oxygen diffusion through concrete to depolarize the cathode is the *rate-controlling* process in the corrosion of reinforcing steel in concrete.

Figure 2. Cracking and Spalling of Concrete Due to Reinforcement Corrosion in a Marine Atmospheric Environment

The final element needed to complete the galvanic cell circuitry is an electrically conductive ground path (through the concrete) between the anodic and cathodic areas. This, in turn, requires the presence of moisture in concrete of sufficient extent to reduce its resistivity below 60 000 ohm-cm. This may also be the rate-determining factor in some instances, but generally, even in arid regions, concrete contains sufficient moisture at the depth of the reinforcement to meet this criterion.

In addition to the three prerequisites for initiation and maintenance of corrosion of steel in concrete already discussed (critical chloride concentration exceeded, sufficient oxygen at cathodic areas to prevent polarization, and sufficient moisture to produce a conductive ground path), a fourth exists.

Differences in electrochemical potentials must exist at the surface of the reinforcement or between the reinforcement and a remote, but electrically-coupled, cathodic area. There is probably never any difficulty in satisfying the latter criterion, since the electropotential differences can be created by differential concentrations of ions, breaks in mill scale or protective coatings, or differential aeration, to mention a few.

Effect of Concrete Properties

From the preceding discussion, it is evident that any variations in the concrete that reduce the permeability to water, chlorides, and oxygen will work toward prevention of reinforcement corrosion. Relative to concrete mixture proportioning, this immediately suggests reduction in water/cement ratio. Figure 3
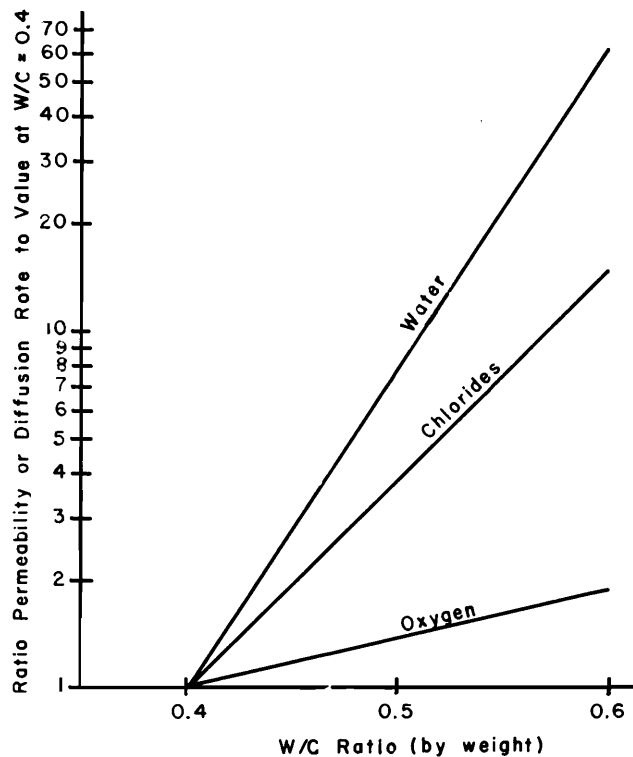
Figure 3. Effect of Water/Cement (W/C) Ratio on Water and Chloride Permeability and Oxygen Diffusion [9, 10].

illustrates the effect of water/cement ratio on water and chloride permeabilities and oxygen diffusion rates [9, 10].

The aggregates contained in the concrete mixture, in general, have only a minor, indirect effect on the reinforcement corrosion problem to the extent that the aggregate gradations affect segregation, bleeding, and water/cement ratio. However, if the aggregates are contaminated with soluble chlorides, they can have a significant effect on reinforcement corrosion.

The cement content of the concrete also has negligible effect except for possible influence on bleeding and water/cement ratio. However, the *type* of portland cement used can have a more significant effect. Aluminates in the cement react with chloride ion forming insoluble tricalcium chloroaluminate and thereby improve the resistance to reinforcement corrosion. Type I cement, containing approximately 12% tricalcium aluminate (C_3A) is three to five times more effective in removing chloride ion than Type V, which contains about 4% C_3A.

Pozzolans, in general, will tend to reduce the susceptibility to reinforcement corrosion because their use

tends to reduce permeability. This effect outweighs any reduction in pH that might result from the reaction between the pozzolan and the free lime in the concrete. Water-reducing admixtures, by virtue of their effect on permeability, may also be expected to reduce susceptibility to reinforcement corrosion. Calcium chloride, added to the concrete mixture at the rate of 2% by weight of the portland cement, is often used as a set-accelerating admixture in cold climates. However, mounting evidence indicates that this should not be done, especially in concretes exposed to deicing chemicals or other chloride sources.

It should be obvious that the water used in batching concrete should not contain appreciable amounts of soluble chlorides. As a general rule, in this regard, any potable water should be satisfactory; seawater and brackish water should be avoided.

Effect of Construction Variables

The construction variable that has the major influence on reinforcement corrosion is depth of cover. Depth of cover is actually, of course, a design variable. However, design cover and actual amounts of cover achieved in the field are often two different things. Clear cover of reinforcement should be at least 5 cm, and preferably 9 cm, for concrete exposed to chlorides. It should be noted that corrosion of reinforcement in totally submerged sea water exposure is rare, due to oxygen starvation relative to depolarization of cathodic areas. However, the portions of marine structures that extend into the tidal and splash zones are highly vulnerable.

Another construction practice that can increase susceptibility to reinforcement corrosion is 'retempering' — adding additional water to the mix at the job site to recover slump losses, especially during hot-weather concreting operations. This, of course, increases the permeability of the concrete.

Finally, the importance of adequate curing can not be overstessed. Concrete should be kept moist for at least 14 and preferably 28 days, especially in arid climates, if permeability is to be minimized. The effectiveness of membrane-forming curing compounds under arid conditions is questionable—moist curing is preferable.

Carbonation

Carbonation of concrete can increase the tendency for reinforcement corrosion by reducing the pH below passivation levels. This comes about because carbon-

ation involves the combination of the free lime in the concrete with carbon dioxide in the atmosphere to form calcium carbonate. Also, under certain conditions of relative humidity, carbonation can result in shrinkage, producing cracking that provides avenues of ingress for the agents of reinforcement corrosion. It is generally held that carbonation rates are so slow in quality concrete that this is not a significant factor in reinforcement corrosion. However, Rasheeduzzafar, and others [3] warn that the climatic conditions of the Arabian Gulf region may render this mechanism more significant, and suggest that research is needed in this regard.

SALT WEATHERING

Salt weathering is a process of deterioration of concrete related to a very specific set of geomorphic, geographic, and climatic conditions [3–6]. The Arabian Gulf region, and the Middle East in general, are among relatively few areas where the conditions leading to salt weathering exist. Those conditions, as described earlier in this paper, are very high evaporation rates coupled with low precipitation (arid climate), high temperatures and wide diurnal and seasonal temperature variations, and soil, groundwater, aggregates, and atmosphere that are excessively contaminated with soluble salts. Under these conditions, with concrete structures in contact with waters containing soluble salts (e.g. brackish groundwaters), the salts are precipitated in near-surface, exposed zones of the structures. Eventually, stresses produced by the accumulation and growth of salt deposits within the concrete causes fracturing along planes parallel to the evaporative (exposed) surfaces. The presence of excessive quantities of soluble salts in the aggregates and mixing water, of course, aggravates the situation.

The mechanisms of the mass transfer of water through the concrete, which form the basis for salt weathering, clearly involve capillarity and evaporation, i.e. evapo-transpiration. Vapor transmission cannot be involved except in the evaporation zone if transporting of the solutes is to occur. Therefore, the most important property of the concrete, for given exposure conditions and salt contents of the mixture ingredients, is the capillary porosity of the concrete, which may be expressed in terms of permeability and which is a direct function of the water/cement ratio. Such mass flow of liquid through a porous medium is relatively rapid and follows the Rideal–Washburn equation,

where rate of flow varies inversely with the square root of time [12]. Ionic diffusion (Fick's Second Law) is not of consequence here due to the thermodynamics of the situation. Also, diffusion is far too slow to account for the observed effects in salt weathering.

SULFATE ATTACK

General

Calcium, sodium, and magnesium sulfates extensively contaminate the soils, groundwater, and moisture-ladened atmostphere of the Arabian Gulf region [3]. Soluble sulfate contents (as SO_4) of 0.2 to 2% in soils or 0.15 to 1% in water will produce severe deterioration of concrete [3]. Since magnesium and sodium sulfates, are about 150 and 200 times, respectively, more soluble than calcium sulfate, they will generally be of more concern relative to sulfate attack than calcium sulfate. However, water in equilibrium with the most common mineral form of sulfate in nature, gypsum ($CaSO_4 \cdot 2H_2O$), will contain about 0.14% sulfate, close to the lower limit for severe attack.

Mechanisms

It is generally believed [1, 14] that soluble sulfates attack concrete by reacting chemically with the free lime to produce calcium sulfate and with aluminate hydrates to produce calcium sulfoaluminate. Both of these are expansive reactions, but the latter is of far greater consequence, particularly if the form of the reaction product is ettringite ($3CaO \cdot Al_2O_3 \cdot 3 CaSO_4 \cdot 32H_2O$) as opposed to the monosulfate ($3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O$). The result of these expansive reactions is severe cracking and disintegration of the cement paste.

Given the ubiquitious nature of sulfates in the Arabian Gulf region, it seems quite likely that the 'salt weathering' deterioration mode is enhanced by sulfate attack. Notice that near the salt deposition zone in concrete subject to the salt weathering mechanism, pore fluids will be saturated with salts and if some are sulfate salts, conditions will be favorable for sulfate attack.

It is probable that the severity and extent of sulfate attack in the Arabian Gulf region would be even a much greater problem than it is were it not for the high concentrations of chloride salts which tend to mitigate chemical reactions between soluble sulfates and cement hydration products.

Sulfate attack of at or below grad concrete (e.g. heaving floor slabs) is occasionally encountered in the region [5, 6].

DRYING AND THERMAL CRACKING

The severe drying conditions and temperature extremes of the Arabian Gulf region result in inordinate problems with cracking of concrete [3, 5, 6]. Sharp thermal gradients, such as in building walls with air conditioning inside and the hot climate outside, are probably also contributory. While this cracking is not usually of structural significance, it tends to promote the other forms of deterioration, discussed previously. The cracks provide the means for ingress by aggressive chemical species involved in reinforcement corrosion and sulfate attack.

With regard to drying shrinkage cracking, it should be observed that this is ubiquitous to all concrete (though usually microscopic in scale); so we are speacking of a matter of degree, not uniqueness, here. Drying shrinkage of concrete is a function of the total water content of the mix (not water/cement ratio). Therefore, leaner, stiffer concrete mixtures will tend to exhibit less drying shrinkage. The extent to which concrete is cured before being subjected to the environment also affects drying shrinkage (in an inverse manner).

Thermal stresses, in general, can and should be taken into account in the structural design phase. However, the potential does exist for disruptive thermal stresses to occur as a result of differential thermal coefficents of expansion between aggregates and the hardened cement paste of concrete mixtures [15]. Theoretical calculations of stresses based on this mechanism almost invariably show values in excess of tensile strengths due to temperature variations well within the normal operating environment of the structure. However, these dire predictions are almost never evidenced in actual practice. Therefore, thermal cracking is not considered to be a materials problem (as initially stated) and should be delegated to the purview of the structural designer.

AGGREGATE – CEMENT REACTIONS

General

A wide variety of potential reactivity problems exist between aggregates and portland cement in concrete.

Sulfate minerals (e.g. gypsum, alum, epsom salt, Glauber's salt) can result in sulfate attack, as previously discussed. Sulfide minerals such as pyrite, pyrrhotite, and marcasite are potentially deleterious as well. Base exchange minerals such as montmorillonite clays and zeolites can expand destructively through reaction with cement paste. Magnesia (MgO) can be particularly destructive, even when present in relatively small quantities. Fortunately, with the exception of gypsum (which has already been discussed under sulfate attack), the deleterious materials mentioned usually are either not encountered with rock types commonly used as concrete aggregates or have lost much of their potency through natural weathering before entering concrete. There is, however, a classification of reactive aggregates that can be very troublesome and that is certain aggregate species that react with the alkalies normally found in portland cement.

There are two types of alkali-reactive aggregates — alkali–silica and alkali–carbonate. Alkali–silica reactive minerals are generally amorphous or microcrystalline to cryptocrystalline varieties of silica present in such rock types as opaline and chalcedonic cherts; some siliceous carbonates and shales; rhyolites, dacites, and andesites in combination with tuffs; phyllites; and fractured or strained quartz. The susceptible silica minerals react with alkalies (Na_2O and K_2O) in the cement paste to form alkali–silicate complexes which hydrate readily to form voluminous silica gels, an expansive reaction which produces 'map' cracking and, often, total destruction of the affected concrete. Alkali–carbonate reactivity is less well understood. Only carbonate rocks of strikingly similar lithology and mineralogy appear to be affected. They are extremely fine-grained, calcitic rocks containing interstitial clay minerals and isolated dolomite rhombs. The mechanism involved in alkali–carbonate reactivity is believed to involve dedolomitization, base exchange, and alteration of the clay minerals, producing swelling [1].

Reactive Aggregates of the Arabian Gulf Region

The lithology of the outcrop of the Arabian Gulf region is described as weak rocks that are almost entirely limestones and dolomites of tertiary age [3]. Alkali–silica reactive chert and flint occur as nodules in the limestones [3], and some dolomites are subject to alkali–carbonate reaction [3, 8]. While a number of potentially reactive aggregate sources have been identifed in the Arabian Gulf region, documented events of destructive alkali–aggregate reactivity in actual structures appears to be rare [5, 8].

CONCLUSIONS

Durability problems with concrete in the Arabian Gulf region are largely traceable to the combined effects of the geologic and climatic characteristics of the area. The most prevalent and serious problems are reinforcement corrosion and salt weathering (probably combined with sulfate attack). Reinforcement corrosion results from the abundance of soluble chlorides in the groundwater, soils, and atmosphere coupled with a warm climate that accelerates corrosion rates and promotes drying shrinkage and thermal gradient cracking to assist the ingress of the chlorides to the steel. Salt weathering is promoted by the same agents, augmented by soluble sulfates, which probably also induce sulfate attack. Sulfate attack is also evidenced below grade, due to the high sulfate content of the soils and groundwater in the region.

In addition to the above deteriorative mechanisms, the aggregates of the Arabian Gulf region show potential for deleterious alkali–silica and alkali–carbonate reactivity.

The keys to the amelioration of the concrete problems in the Arabian Gulf region are:

1. Use the lowest possible water/cement ratios consistent with placability and finishing (the use of high-range water-reducing admixtures can assist in this regard).
2. Use moist curing for as long as practical, 28 days if possible.
3. Test and certify aggregates for acceptability relative to reactivity and salt contents. Wash aggregates if necessary.
4. Enforce accepted practices for hot weather concreting operations, such as ACI 305 (16).
5. Use vapor barriers and coatings on concrete below grade.
6. Use epoxy coated reinforcement.
7. Design concrete structures to minimize stresses due to drying shrinkage and thermal gradients.

REFERENCES

[1] ACI Committee 201, 'Guide to Durable Concrete', *Journal* of the *American Concrete Institute*, **74**, (12), 1977 pp. 573–609.

[2] P. D. Cady, 'Mechanisms of Frost Action in Concrete Aggregates', *Journal of Materials*, **4**, (2), (1969) pp. 294–311.

[3] Rasheeduzzafar, F. H. Dakhil, and A. S. Al-Gahfani, 'Deterioration of Concrete Structures in the Environment of the Middle East', *Journal of the American Concrete Institute*, **1**, (1984) pp. 13–20.

[4] P. G. Fookes, and L. Collis, 'Problems in the Middle East', *Concrete* **9** (7), (1975) pp, 12–17.

[5] P. G. Fookes, 'A Plain Man's Guide to Cracking in the Middle East', *Concrete*, **10**, (9), (1976), pp. 20–21.

[6] P. G. Fookes, and L. Collis, 'Cracking and the Middle East', *Concrete*, **10** (2), (1976), pp. 14–19.

[7] P. G. Fookes, and L. Collis, 'Aggregates and the Middle East', *Concrete*, **9**, (11), (1975), pp. 14–19.

[8] I. Sims, and A. B. Poole, 'Potentially Alkali–Reactive Aggregates from the Middle East', *Concrete*, **14**, (5), (1980), pp. 27–30.

[9] P. D. Cady, 'Corrosion of Steel in Concrete,' in Significance of Tests and Properties of Concrete and Concrete-Making Materials, STP 169B, American Society for Testing and Materials., ch. 19, pp. 275–299, 1978.

[10] ACI Committee 222, 'Corrosion of Metals in Concrete', *Journal of the American Concrete Institute*, **82**, (1), (1985), pp, 3–32.

[11] J. E. Slater, 'Corrosion of Metals in Association With Concrete', STP 818, American Society for Testing Materials., 1983, 83 p.,

[12] C. D. Lawrence, 'Durability of Concrete: Molecular Transport Processes and Test Methods', *Technical Report 544*, Cement and Concrete Association, 24 p., 1981.

[13] U.S. Dept. of the Interior, Bureau of Reclamation, *Concrete Manual*, 8th Ed., Supt. of Documents, U.S. Government, Printing Office, Washington, D.C., 627 p., 1975.

[14] D. E. Shirley, 'Sulfate Resistance of Concrete', 2nd Ed., *Publication 45.034, Cement and Concrete Association*, 6 p., 1983.

[15] S. D. Venečanin, 'Influence of Temperature on Deterioration of Concrete in the Middle East', *Concrete*, **11** (8) (1977), pp. 31–32.

[16] ACI Committee 305, 'Hot Weather Concreting' *ACI 305R–77 (Revised 1982), in ACI Manual of Concrete Practice, Part* 2. American Concrete Institute., 1985.