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Abstract

The Gulf region is known to have one of the severest environments in the world. There must be differentiation between humid coastal and interior dry desert zones. The vast area of the Arabian Peninsula provides concrete specialists with the challenge of a wide range of environment not only from the viewpoint of climate but also concerning geotechnical and more generally the geomorphologic aspects. The paper discusses several issues regarding the environmental and climatic aspects in the Gulf region and the Peninsula. The author explains that the best and most economic approach to counteract the effects of aggressive environment is to breakdown the effects into three levels; namely at macro-meso- and micro-levels. This will provide the concrete only with as much protection as it needs. Available options are discussed with concentration on practical approaches that engineers and technology in the region can follow. The aim is to preserve existing structures and increase the confidence in future structures. This may be achieved by improving design and enhancing the quality and performance of concrete structures in the hot and severe environment of the Gulf coast and the arid region of the Arabian Peninsula. The ultimate goal of the precautionary measures is to extend the service life of concrete structures.

1. Introduction:
Concrete is affected by the environment – not just by climate, but topography and geomorphology as well. Despite extreme environmental conditions in the Gulf Region, not all buildings must deteriorate or become unserviceable after a short period of operation. Numerous buildings have survived for 30 to 40 years and more without major maintenance or repair. Traditionally, environmental considerations for concrete have included hot weather, cold weather, and salt contamination - that is, the macro- and even the micro-environment. In this regard, it is not logical to classify any geographic region on the basis of one environment. Differences in temperatures, humidity, and large variations in geological formations and geomorphology can exist within a single city. This is certainly the case in the Gulf region, where differences between regions of the Arabian Peninsula are noticeably distinctive.
Although international specifications and codes recommend procedures for placing concrete in a hot and cold climate, they do not adequately address the influence of the total environment. ACI 305R, "Guide to hot weather Concreting /1/.

The ACI 305 report considers neither topography nor geomorphology, which may have just as negative an effect on concrete as a hot or cold climate, both in the short and long term. In addition, "hot weather" is vague because the characteristics vary from one city to another according to the temperature and other climate parameters. The technical committee of RILEM International, TC-94, “Concrete in Hot Climate” takes a different approach /2/ specifying divisions and differences among hot climates, such as dry, humid or moderate, arid, desert coast, desert inland, and so on.

The design of concrete structures must be based on the evaluation of direct effects of a hot climate and local environmental conditions on the structure rather than on general environmental conditions of a vast area. That is, the design must consider weather, topography, geography and so on for the immediately surrounding conditions. This more specific approach differentiates three levels of exposure: macro-, meso-, and micro-levels. Macro-level represents the conditions prevailing in region as a whole. Meso-level may simulate those around the building or the structure, while micro-level represents the conditions immediately next to a concrete member or part thereof.

2. Environmental Conditions in Gulf Countries

For this article, "environment" means all external conditions that directly surround the concrete structure, including weather conditions, topography, earth crust, and geomorphology. These conditions affect the raw materials, production, fabrication, and reactions of concrete. In most technical literature about this region, reference is made to the “Gulf environment,” mentioning one country or another, but with no precise description. In one instance it means the environment of a Gulf coast city; in another, it means the environment of all Arabian Gulf countries including the entire Arabian Peninsula.

Let's consider the problem of steel corrosion and concrete deterioration in Arabian Gulf coast cities. A great number of active researchers in those cities, as well as some foreign companies, take a blanket approach to the environment of this area to include all the Arabia. It is quite clear that the climate and environment of Saudi Arabia and other Arabian Gulf Countries vary considerably from one region to another, and one cannot generalize climate characteristics of such a vast area. There are also many differences between the environments in Kuwait and that of Oman even though they both are located immediately on the Gulf. The differences in temperature, humidity, wind, rain, geology of soil and raw materials are clearly apparent in the Arabian Gulf Region, so how can one ignore the differences between east and west, north and south, and everywhere in between. Fig. 1 shows clear variations of such environmental parameters as maximum and minimum temperature, humidity, and wind speed for some interior and coastal cities. There are topographic differences among beach, coastal areas, and interior geological composition in hot-dry hot-humid areas. One may classify the climate into distinct regions:

- shoreline - 5 to 500m (15 to 1500 ft).
- the coastal region next to shoreline – 5m to a few kilometers (15 ft to a few miles), and regions between coastal and interior areas.

* Numbers between slashes / / indicate numbers of references shown at the end.
Fig. 1: Variations of environmental parameters in different areas of the Gulf Region.
One indication of the differences from region to region is the salt deposits on concrete, whose concentration depends more or less on the distance from the beach (Fig. 2). The effects of salts on structures diminish considerably as you move away from the coast because of the decrease in salt concentration.

There is no single Gulf climate. It is more appropriate to define the Gulf environment as a series of meso-environments that represent topographical and geomorphologic conditions in each region. To account for environmental differences and the availability of suitable raw materials, contamination of soil and atmosphere with salts, and other elements harmful to the concrete, one must divide the Gulf states into several subdivisions. RILEM committee TC-94, "Concrete in Hot Climates," has taken some of these aspects into consideration in its draft documents.

Therefore, it should be recognized that parts of the same structure can have different exposures to aggressive environments. Fig. 3a illustrates a column in a causeway with five distinct exposure zones /3/. Whereas Fig. 3b depicts a building column with four zones /4/. Within these structural elements, each zone has a particularly micro-level of exposure.

* The objective of the author as member of TC-94 was to include more details regarding the Gulf region in a comprehensive document suitable for all the hot climates. Which will give general guidelines for macro- meso and micro-environments in hot climates. However, in order to develop and complete the required guidelines, specifications, and so on, a large and coordinated effort of engineers, contractors and other who work in the concrete industry in this part of the world is needed. This is also true for many other areas of the world.

![Fig. 2: Schematic chloride levels at concrete surface layer with a given distance from seashore.](image)

![Fig. 3: Practical Examples of micro-environments.](image)
3. Aggregate Properties in Saudi Arabia

In a detailed research project studying the properties of the aggregate in different regions of Saudi Arabia, the author showed that there are major differences in aggregate properties from one region to another /5,6/. These properties were compared with those required by given specifications. A summary of important results of this research, including geomorphologic variations, follows.

Geological formations—Aggregates in the western region (on the Red Sea) and west of the central region consist of crystalline rocks of Pre-Cambrian age such as basalt and granite. Aggregates in the middle and eastern part of the central region consist of crystalline rocks together with sedimentary layers, a geology more prevalent towards the Gulf. These sedimentary layers are mostly limestone. As for the eastern region, aggregate consists of sedimentary layers, mostly limestone, but of younger geological age than aggregate in the central region.

Density and absorption—Compared with eastern region soils, rocks of the western region are of higher density and absorb less water. Limestone of the central region falls in between. In some areas in the central and eastern regions, water absorption exceeds the allowable of 3 percent /7/.

Content and gradation of fines—In the western and central region valleys, the amount of fines is similar. As for the crushed aggregate, however, there is a clear difference. The crushing operations seem to produce fewer fines in the western region than in the central region because of higher durability rock. In the eastern region, more fines originate during the crushing process. For this reason, natural sand is used instead of crushed materials as fine aggregate in concrete. The percentage of fine sand exceeds the allowable levels in some parts of the three regions. In the eastern region, good gradation is difficult to achieve because natural sand is very fine, limited in grading, and missing many sizes. Figs. 4 and 5 show the aggregates of these regions compared to acceptable levels of two standards.

Fig. 4: Fine aggregate requirements (suitability triangle)

Fig. 5: Fine aggregates form the western, middle, and Eastern regions (suitability triangle)

Quality—Coarse aggregate quality is more often substandard in the eastern region than in the western and central regions. The quality of crusher—produced fine aggregate is lower than that of the coarse aggregates because the fine aggregate contains weathered particles. In the eastern region, the soundness of fine aggregates is better than that of coarse aggregate because they are Petrographically different—that is, the quality of the natural sands is better than the porous limestone dolomites.

Chlorides and sulfates—Chloride and sulfate (SO₃) contents in coarse aggregates increase from the west to the east, though more so in sulfates than in chlorides. In addition, there are more salts in the fine aggregates than in the coarse aggregates because of the higher content of fines where salts tend to accumulate. Chloride and sulfate contents of aggregates in the western region are within the allowable percentages, but limits are sometimes exceeded in the central region and more often in the eastern region.

4. Environmental Effects on Concrete Structures

Numerous reports on the corrosion problem in the Arabian Gulf have been published since 1975 /8,9/. It has been found that low-quality materials and severe environmental conditions combined with poor design and construction practices have caused most of the problems in existing structures. Other reports have said that Gulf weather is the worst in the world for concrete durability, and it is next to impossible to see structures survive their intended service life. Some researchers have more moderate opinions and suggest that problems are mainly due to poor mix design and a lack of quality control in the field. There are obvious problems of building deterioration from steel corrosion at early ages in the eastern coast of Saudi Arabia /10/ and other cities in the Arabian Gulf. Some
researchers who are trying to promote their companies’ products and services may exaggerate this problem, with or without intention. We cannot deny this problem, of course, but the problem must be put in the proper perspective. Assuming the quality of design and construction in the concrete industry are comparable throughout all regions, there must be other reasons that the eastern region has the worst problems; that is, that the problem is caused by poor-quality material, an abundance of salt (in weather and soil), plus some environmental conditions that are more severe in the eastern region than those of the western region.

5. Historical Background

Although it is difficult to make generalizations about the experiences in Gulf countries, the obvious similarities between Arabian Gulf countries provide a historical background. The scale, importance, and priority may differ from country to another, but history can offer clear indicators of concrete-related problems in the region.

Prior to 1980

Available local materials were used without understanding their limitations, problems, and correct proportions. No tests were required to determine the suitability of materials used. Contractors, engineers, technicians, and laborers were inadequately trained and were not familiar with the local materials and environmental conditions. Furthermore, there were few construction standards and specifications, as well as a lack of proper maintenance.

As a result of the construction boom starting in the early 1970s, more negative aspects appeared and more developments took place in various proportions. Many designs were made hurriedly, accompanied by poorly planned construction with unqualified supervision. Owners were willing to accept low quality in return for fast profits. In the mid-to late 1970s more inexperienced contractors joined the industry, together with the entry of foreign design and construction teams. Over time, the experience of engineers and contractors increased, and their technical expertise regarding materials, specifications, and problem solving grew. A variety of specifications, guidelines, and technologies were utilized from Europe, the United States, and Asia. New environmental problems such as the rise of the ground water table in many cities appeared. Towards the end of the seventies, the industry began to realize the consequences of using foreign specifications that fail to address local problems such as hot weather, chloride and sulfate effects, and other problems ready-mixed concrete was widely used without proper quality control. Maintenance and repair work started to be considered for existing structures.

1980 to present

Research results started to appear, explaining causes of failures and deterioration of structures, and a greater focus was given to repair techniques. Deterioration of concrete buildings on the Gulf coast caused by reinforcement corrosion was a major issue, specifications and other guidelines became available, covering some environmental conditions but still not at the desired standards. Workers skill improved, especially on large projects. The use of ready-mixed concrete expanded, with the common belief that it would always have good quality control. Concrete deterioration cases increased, along with the use of remedial repairs but a lack of preventive maintenance. The negative ramifications of improper repair and maintenance became apparent.

6. Investigations of Distressed Buildings

To evaluate the size of the current problem, its causes and remedies. Let’s look at a summary of the situation as reported by various sources.

An investigation of 62 buildings on the Gulf coast revealed that steel corrosion caused most structural deterioration. This indicated that the lack of durability was due to low quality concrete with inadequate quality control poor construction supervision.

In another investigation of 42 concrete structures, it was found that inadequate concrete cover was one of the main factors that caused the deterioration of these buildings. From an examination of more than 100 specimens taken from different old buildings on the Gulf coast, it was found that deterioration decreased or even disappeared with increased cover /11/. It was also found that chloride contents in concrete and its constituents considerably exceeded the specified allowable values. Shortcomings in design and construction combined with poor-quality materials and exposure to the environment played a great role in the extent of damage to concrete structures.

Some researchers categorized the Gulf environment as the most severe in the world, and that it is impossible for a concrete structure to survive its required service life. Others were less critical, citing that the durability problem is caused by poor mix designs, not utilizing modern technologies, lack of quality control, improper construction practices, and untrained workers.

In some research projects, results tend to be exaggerated. Fig. 6a shows the results of one research project, where the problems encountered were divided into six categories. This division is confusing and impractical. Instead, one could divide the problems into three categories as shown in fig. 6d.
With fewer divisions the problem becomes more clear and is put in a more practical and realistic perspective.

Most durability problems could have been avoided if preventive maintenance had been applied. The problems could have been less severe had the buildings been designed properly and constructed according to proper standards that provide impermeable concrete.

An investigation into the quality of ready-mixed concrete in the three main regions of Saudi Arabia concluded that most ready-mix plants do not produce good quality concrete. In a study of 70 buildings in some districts in Makka, the damages found in these buildings were mostly cracks and deflection caused by design and construction errors, hot weather, and a lack of supervision and quality control for hot weather concreting conditions.

In the literature review, no investigation reported the ratio of damaged structures to undamaged ones in a region, city or neighborhood. From personal experience, there is high percentage of good structures on coastal areas of the Gulf. Some of them have survived 30 to 40 years without problems, even with very little or no maintenance /12-15/.

The matter requires various studies to survey cities representative of different micro-environments. These studies should consider buildings and structures, comparing damaged structures to undamaged ones over the entire area. This would give a clear and accurate picture of the magnitude of the problem. Studies should indicate the true average age of structures in the Arabian Gulf.

In studies to assess more than 400 buildings all over Saudi Arabia, it was found that the primary cause of deterioration in concrete is poor-quality construction practices, especially during the early age of concrete /13-15/. Secondary causes are related to soil, underground pipes. Other causes are corrosion due to a salt-laden environment and hot weather. The results of the studies also indicate that corrosion of reinforcement is worst in the eastern region and on the Arabian Gulf coast. Corrosion becomes less severe as on moves toward the interior of the Arabian Peninsula.

![Fig. 6: Exaggeration in presenting research results](image)

**Ready-mixed Concrete**

In a detailed study on ready-mixed concrete in the three regions in Saudi Arabia, it was found that concrete quality falls short of that required, even concrete produced by big companies /16/. Only 12 percent of the factories included in the study produced good concrete, 24 percent of factories produced good-quality concrete, 24 percent of factories produced concrete of acceptable quality, and about 64 percent of them produced poor-quality concrete. Sixty percent of the factories included in the study produced concrete with strength less than that specified at a given time or at different times throughout the year. In 50 percent of factories, aggregates did not have the properties required in the general specifications in one or more categories /16/. Meanwhile, 38 percent of factories used water that is not in accordance with specification. There were no clear variations in the concrete industry in the three regions, but the higher percentage of substandard materials used was in the eastern region.
Salts in concrete

Between 1985 and 1999, Central Laboratories for Material Testing of the Ministry of Public Works tested 851 concrete samples from structures throughout Saudi Arabia. Results showed that 289 samples contained chloride exceeding allowable levels. Fig 7 shows the distribution of samples tested.

The highest percentage of samples that contain chlorides above the allowable belongs to the eastern region (57%), followed by the western region (19%), central region (14%), and the south (10%). Fig 8 depicts the distribution of samples containing sulfates exceeding allowable levels.

![Distribution of samples containing chlorides or sulfates](image)

Fig. 7: A study on the distribution of defective reinforced concrete cases in Saudi Arabia (1985-1999)

Fig. 8: Distribution of 851 concrete samples with high sulfate content between provinces

Again, the highest percentage is in the eastern region (56%), followed by the northern (25%). Fig. 9 shows how samples were affected by chlorides and sulfates in the eastern region, especially near the coast. This effect is decreased towards the central and western regions. These results support the conclusion that the environment surrounding concrete structures plays a major role in the maintenance and operation of buildings.
One of the most comprehensive picture to indicate the dawning effects of salts in soil when they are permitted to migrate into concrete is depicted by Fig. 10. They cause the corrosion of steel.

The same figure also shows that good impermeable, sound concrete is capable if gritting the reinforcing steel.
7. **Solutions & Options**

This section provides recommendations for preserving existing buildings and improving design and construction of future structures with the intent of enhancing the quality and performance of concrete structures and extending their useful service life /17,18/.

One of the leading efforts in this field will culminate in the publishing of a guide to the maintenance and repair of reinforced concrete structures in the Arabian Peninsula.

This effort is spearheaded by the Concrete Society in Britain /19/. The sponsoring organizations include the Saudi Ministry of Public Works and Housing and the Bahrain Society of Engineers.

**Existing Structures**

Buildings already in service cannot be left without treatment, especially on the coast. Existing structures require routine inspection, regular maintenance, and repairs when required, with due consideration on the structure’s micro-environment, improves the performance and life span of structures. Specific recommendations include the following:

- For government buildings, qualified agencies should perform routine inspection, and supervise preventive maintenance and needed repairs every three to five years /20/.

- Private buildings should be inspected by municipalities or qualified consulting offices. This should be done at reasonable intervals depending on the severity of the climate and environment.

- Engineers should raise awareness of how substantial long-term saving can be achieved through proper preventive maintenance and repair. The money generated from these savings should be directed to building owners and those in charge of financial appropriations. Promotion of proper maintenance and repair can be made through media campaigns and other means. Design and application of repairs should be carried out and approved by qualified and experienced agencies and contractors. Fig 11 depicts the principles mentioned above.

![Fig. 11: Maintenance of existing building deterioration](image-url)
New ordinary structures

Ordinary structures include small budget residential and commercial buildings with a limited number of floors. These projects are usually constructed by contractors, technicians, and laborer who have little expertise in the most modern technologies. Therefore, it is unreasonable to specify stringent, high technology requirements because this renders a project expensive and unprofitable. The positive benefits desired from such specifications will be lost, and some negative ramifications may even appear. For example, when using new types of cements that contain slag, fly ash, or silica fume without proper mixing, placing, consolidation, and curing, these cements become ineffective or of less value than ordinary Portland cement. Similar problems might occur by using coated steel bars if they are mishandled or not improperly.

For these reasons, the design of concrete elements in these structures should follow ACI recommendations and severe micro-environment requirements to ensure impermeability of the concrete and provide sufficient concrete cover to protect reinforcing steel.

These guidelines are sufficient until an alternative document more appropriate for the Gulf environment, such as the one proposed in Ref. 21-29, is developed and approved. Municipalities (if they have the labor force) and qualified consulting offices should act as neutral qualified bodies to approve the design, monitor the supervision of the construction, inspect the concrete quality in the plant and proper execution of construction at the site.

New Special Structures

Owners of those properties with greater value and higher cost should spend accordingly during the design and construction stages of their structures. This up front expense will be offset by the potential reduced cost for maintenance, repairs and improved structural performance. The planning design and construction, occupancy stages, and so on should follow the hot weather recommendations detailed in Ref. 2 and described, briefly in this article; in addition a clear and comprehensive quality assurance and quality control system should cover the entire life cycle of the structure in accordance with the systems given in ref.(22-24).

Accordingly, modern methods, new technologies, and the latest materials make new projects profitable and should be carefully evaluated and seriously considered. These include proper protection by reinforced plastic layers, permanent forms, coated reinforcing bars, and cathodic protection for reinforcement.

Fig. 12 gives a flow diagram of the building development process.

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**Fig. 12: Future design and construction of building**
8. Coordination of Efforts

There is little coordination of information regarding concrete construction practices in Arabian Gulf countries. One of the main objectives of this article is to stimulate action for developing a comprehensive database to provide information to researchers involved in solving local problems.

Engineers and others concerned with concrete in Gulf countries should serve the construction sector, particularly the concrete industry, which is the cornerstone for construction in the Gulf. This can be achieved by attending and taking an active role in the technical committees that prepare reports on hot weather, such as ACI Committee 305, RILEM Technical committee TC-94 and the Concrete Society Guide /19/. At the moment, there are very few representatives from the Gulf region involved with these committees, so the concerns of the Gulf region are not adequately addressed.

Establishing an institute in the Gulf to serve this important function is long overdue. Such identity is important to pioneering scientific research and developing suitable specifications, guidelines, and methods for improving the quality of concrete, protection and maintaining buildings to extend their life span in the hot and aggressive Gulf environment. It could be useful to establish a Gulf organization, subordinate to the Council of Gulf Ministers for Housing and Public Works, with the responsibility of unifying the efforts of the concrete industry by developing a database and information system for concrete practices in the Gulf, including a general survey covering the points mentioned in this article. Gulf countries should coordinate efforts to actively participate in international organizations that are interested in concrete in hot weather and severe climates.

9. The Future

1- Local building codes must consider the severe environmental conditions in the Gulf region.
2- Quality control and assurance systems for concrete in the plant and at the site must be prepared in accordance with procedures of ASTM and ACI and approved by proper authorities. Inspectors must be qualified. One such QA/QC system is proposed in Ref.22.
3- Agencies must be assigned for approving and implementing codes and QA/QC systems.
4- Responsible bodies should assign structured training programs because not all engineers and technicians are qualified to deal with concrete work in plant and on the site.
5- Applied research should be directed to serve the concrete industry through research of hot weather and aggressive environmental effects on concrete, evaluating appropriate sources for raw materials, applying new technologies in design and construction, and developing maps for various micro-environments in the Gulf.
6- Routine protective maintenance and proper repair should never be forgotten as it is the basic factor that saves concrete from deterioration in the Gulf region. Sufficient funds should be allocated for such purposes.
7- Manuals and specifications should be prepared for maintenance and repair methods. Exposure to the environment must be accounted for at the appropriate level, be it macro-meso or micro-environment.

10. Conclusions

Consideration of hot and cold environments (macro-environment) is not sufficient for the design of concrete structures. It is very important to include other detailed environmental factors surrounding the structure (meso-environment) and those in close contact with a structure's concrete member (micro-environment). Adopting such an approach will provide more economic concrete structures where measures to combat aggressive environment are applied only where needed and not for the entire concrete frame. It is of utmost importance to consider local environmental conditions in the specifications for design, construction, and maintenance of structures. It makes sound economic sense to design, build, and maintain structures to withstand severe environmental conditions to which it is exposed, thus improving its structural durability and extending its service life.

References

1- ACI Committee 305, “Hot Weather Concreting” (ACI 305R-91), American Concrete Institute, Farmington Hills, Mich., 1991.


