

ENVIRONMENT-INDUCED DAMAGE IN CONCRETE BRIDGES

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ABSTRACT

The prevailing hot, humid and salt-laden environment of the coastal regions of Saudi Arabia is regarded as highly aggressive to concrete construction. Concrete bridges, being fully exposed, are subjected to the damaging effect of the environment. A large number of concrete bridges in Saudi Arabia have suffered damages attributable to the environmental conditions. In this paper, construction environment is briefly presented to highlight the difficulties. With this in background, various types of environment-induced damages commonly witnessed in concrete bridges are presented with the aim to increase awareness of the severity of the environmental problems and to focus the need to address these issues in design and construction.

KEYWORDS

Bridge decks, cracking, corrosion, concrete durability, concrete bridges, shrinkage and failures.

INTRODUCTION

The salt-laden hot and humid environment of the coastal regions of Saudi Arabia is regarded as highly aggressive for concrete construction. Premature deterioration caused by a variety of factors has focused a greater urge and need for durability based design which would ensure longer service life of concrete structures. In those situations where environmental conditions are highly unfavourable, durability considerations in design and construction often override the strength issues.

Bridge decks are more vulnerable to environmental actions due to their unrestricted exposure to environment. Damages induced by corrosion of reinforcement and by cracking due to other actions, structural and nonstructural, are so acute that serviceability

problem has become a major issue to be dealt with. Apart from widespread damage due to corrosion of reinforcement witnessed in the coastal regions, other commonly encountered problems are associated with cracking of concrete due to plastic and drying shrinkage, thermal effects and, importantly, live load actions which frequently exceed permissible limits.

In the last two decades, a significant number of concrete bridge decks in Saudi Arabia have suffered extensive damages, resulting in total replacement or substantial retrofitting (Al-Mandil et al., 1987). In this paper, environmental problems and environment-induced damages in concrete bridges in Saudi Arabia are highlighted. Cases of different problems which have been observed are cited with the aim of increasing the awareness of designers of the severity of the problems. This awareness would inevitably lead to better design and construction which would enhance the service life of the structures.

PROBLEMS IN PERSPECTIVE

Local Construction Environment

From the viewpoint of better concreting and concrete durability, the environment of the coastal belt is recognized as difficult and hostile (Rasheeduzzafar et al., 1984). The concrete construction in general suffers from premature deterioration and distress caused by a variety of independent or interactive factors, some of which are characteristically unique to this region. These factors range from materials to environmental conditions.

The construction environment is essentially characterized by hot and humid climatic conditions, non-availability of sound aggregates and existence of highly contaminated subsoil and groundwater and airbourne chlorides. A dubious construction practice flawed by use of less skilled manpower of diverse background and by a poor understanding of the durability issues epitomizes the current problem.

The Eastern Saudi Arabia in particular presents an extremely difficult construction environment in view of the ominous presence of all the above mentioned factors. But the most damaging factor of all is the salt-laden aggressive environment which together with its hot and humid climate ideally serves as a natural accelerated corrosion test site for reinforced concrete construction. Without a careful planning and design and greater quality control for hot weather concreting, a structure is likely to suffer from the premature deterioration.

Climate

The region experiences an extremely arid summer with negligible precipitation and temperature hovering around 40°C and humidity fluctuating considerably. Typical climatic data for the two main cities, Dhahran and Jeddah, are shown in Fig. 1 as illustrations of the seasonal variation of temperature and relative humidity. The intense heat over a prolonged summer accompanied by negligible precipitation is perhaps the best known feature of the local climate (CIRIA, 1984; STUVO). Although the interior is

relatively dry, humidity is high in the coastal regions where relative humidity often exceeds 80%.

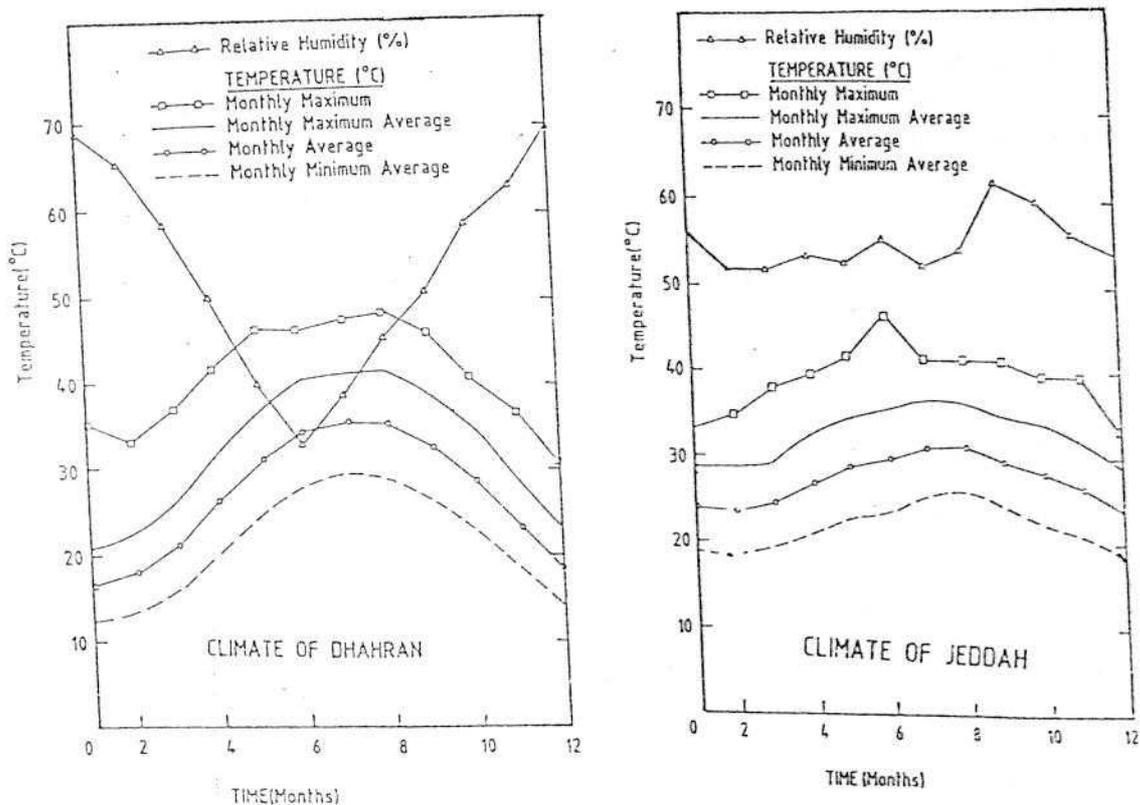


Fig. 1. Climates of Dhahran and Jeddah

The surrounding seas influence considerably the direction of the winds flowing across this vast land. In Eastern Province, the predominated direction of wind is North-North West. Frequently, such winds whip up sandstorms in its path, creating a dusty environment. Wind speeds vary considerably from about 10 to 30 km/hr, reaching occasionally to as high as 100 km/hr. In Riyadh, the wind comes mostly from North-North East direction during summer but varies considerably during the rest of the year. In Jeddah, the frequently observed direction is North-North West.

Presence of windy conditions in many days of the year makes concreting work more difficult as the rate of evaporation of moisture from fresh concrete increases rapidly with increasing wind speed, creating a greater demand for proper curing. Wind is also responsible for transport of sand and fine dust which are contaminated with harmful chlorides and sulphates. Consequently, aggregates become dusty and contaminated with deleterious materials.

Another source of problem in the coastal regions is the presence of excessive airbourne salts along the coastal belts, caused by the evaporation of highly saline seawater. Morning dews and condensations and occasional precipitations (most of it occurring in the winter months) become the means of transporting salts directly to the exposed

surfaces of the structure. Imprints of salt marks are frequently seen as the moisture dries up.

An overview of the climatic conditions shows that prevailing prolonged hot temperatures coupled with windy conditions create extremely difficult environment for concreting, as it adversely affects workability and increases early shrinkage and thermal cracking. Rapid loss of moisture makes curing a problem. Due to prolonged summer months, the available time for concreting to avoid extremely hot hours is limited. Climatic conditions demand precautionary measures which must be enforced for *hot weather concreting*.

Geological Factors and Materials

Geological factors dictate to a large extent the sources and quality of aggregates, degree of possible contamination and the difficulty with the subsurface conditions.

The geological formation in the vast areas of the Eastern and Central regions is highlighted by weak sedimentary rocks which are predominantly limestones, the quality of which varies from very poor (Dhahran) to good (Riyadh) (Fookes and Higginbottom, 1980). These limestones are the primary source of coarse aggregates. Weaker rocks are more absorptive. A good portion are true dolomites and some contain chert and silica. Eastern Province has large areas of sabkhas (low-lying saline deposits) where the water table is at or near the ground surface. Sabkha areas are highly aggressive to concrete construction due to high level of salts and sulphates.

In wadis and areas close to mountain regions, where downward leaching takes place, as the rain or flood water disappears by percolation, uncontaminated, well shaped gravels provide source of good quality coarse aggregates. Igneous and metamorphic rocks are available in abundance and they have characteristics of good quality coarse aggregates, although weathering and other geological factors may affect the properties of some rocks which must be examined for their suitability as coarse aggregates (CIRIA, 1984).

The geological formation of Tabuk in the North and Jazan in the South presents some regional problems which were not fully recognized before. In Tabuk, prevailing formations are basically clayey shales and sandstone/siltstone. Clayey shales have remarkably high swell potentials in the region, causing problems to foundations. The swelling potentials of these deposits have caused extensive structural damages. The Jazan area is situated on an elevated terrain underlain by a large salt dome. Gradual dissolution or erosion of this salt rock at different places has caused subsidence thereby damaging the structures built on it.

With regard to aggregates for concrete construction, it is ironic to note that sand, although synonymous with the topological environment of Saudi Arabia, is found in many places to fall short of the quality and gradation required of a good concrete. In some regions (notably the Abha region), shortages of natural sand also exists.

Principal sources of fine aggregates are beaches, wadis, dunes and crusher plants. The quality and gradation of sands vary considerably from place to place, a vast majority of samples are too fine for use in concrete production (CIRIA, 1984; STUVO; Al-Tayyib et

al., 1985). Generally speaking, sand from a source may not be suitable as available due to two reasons: (i) too fine and contains dust and (ii) contamination with harmful salts of chlorides and sulphates.

For coarse aggregates, the geological formation of Saudi Arabian peninsula offers different types ranging from excellent to very poor. Eastern Province relies heavily on the weak limestone rocks which produce coarse aggregates of marginal quality, having weaker strength and high absorption. However, in the absence of an economically viable alternative, these aggregates are widely used, creating a problem for concrete durability. A better quality of limestone aggregates is available in the Central region.

In contrast, the coarse aggregates in the Western Province are of good quality and highly suitable for all construction, provided that they are not contaminated. The mountainous outcrops of Asir provide excellent sources of good quality aggregates for the Western and Abha regions.

For concreting, natural sources of water, free of contamination, with high level of minerals and salts, are rare. Ground water from wells or other natural sources is not suitable for mixing and wet curing due to high level of impurities. Desalinated water is extensively used for concreting. This creates an extremely difficult situation to be dealt with and the problem may be compounded further in those areas where water may have to be transported from a distant place.

Technical Environment

This refers to the general understanding of the local problems and the environment and their impact on concrete construction. Factors such as skill of construction workers, codes and specifications and their compliance, problems of hot weather concreting and awareness of local problems contribute to the technical environment (STUVO).

Not too long ago, design and construction of all bridges were performed by foreign companies using foreign workers who had hardly any understanding of the characteristics of local problems. Essentially, all knowledge and skill were imported, imposing principles and practices which unfortunately did not work well. Even today, construction activity often relies on semi-skilled or unskilled workers drawn from different parts of the world with different backgrounds.

Lack of well defined codes and specifications which reflect the local needs, coupled with a relaxed view of quality control, also contributes to the poor concrete construction. Specifications which followed developed countries' specifications often failed to address adequately the problems of environment and hot weather concreting. Overseas contractors often imported techniques and methodologies without a full realism of local difficulties and lack of skilled work force. Some of the bridge design and construction truly reflected this and they were soon recognized as deficient or not suitable.

Bridge Loading

One of the major contributing factor to the damage sustained by bridges is the heavy truck loads. In the earlier phase of the development of highway network, a vast number of bridges were designed using AASHTO + 10% loading as no reliable truck data was available at that time. This proved to be fatal as the adopted design load was considerably less than the actual truck load and consequently, a large number of bridges suffered damages to the extent that they have to be either replaced or reinforced. The damage inflicted by the heavy trucks was so widespread that the Ministry of Communication (MOC) had to take drastic action soon. Truck loading was quickly increased to MOC 400 kN and this increased load proved to be still far short of the heavy truck loads.

The loading was subsequently replaced by much heavier truck load (MOC 600 kN) and lane load, increasing the load by 50% to account for heavy trucks. Additionally, numerous weighing stations were installed at strategic corridors to control the overweight problem by imposing stiff penalty on the violators. Although this dual-approach of heavier design load and regulatory controls have been successful to a large extent in containing the stress-induced problems in bridges, heavy truck load problems have not been totally eradicated. Recent studies (Parvez, 1997; Azad and Al-Harbi, 1997) have shown again that a large number of violators still abound and scrupulous drivers find innovative ways to beat the system. The acceptability of the current MOC (Ministry of Communication) loading for bridges, which was adopted with less rationality, is currently being reviewed through a major study (Azad and Al-Harbi, 1997).

DAMAGE CATEGORIES

A cursory review of damaged and failed bridges shows that all categories of conventional damage forms can be witnessed. However, the following *four* are the most prevalent ones: (a) corrosion of reinforcement, (b) stress-induced cracking due to overloads, (c) shrinkage plus thermal cracking, (d) local punching-type failures.

Like any reinforced concrete structures, corrosion of reinforcement is the most menacing problem for concrete bridges in the coastal regions. A vast majority of the concrete bridges in the Eastern Saudi Arabia are suffering from corrosion problem, demanding greater resources for maintenance. An adverse combination of an aggressive environment and constructional anomalies virtually created a havoc with earlier built concrete bridges. The corrosion rate is so severe in some cases that total loss of some reinforcements was observed. Although in most cases, the corrosion damage is confined mostly at the top of the deck, the soffit of deck has also suffered from corrosion damage in some bridges (Fig. 2). In the inner part of the country where environment is not corrosive, the bridges have remained almost unaffected by corrosion. Uptil now, corrosion repair has focused on the conventional methods, although the viability of cathodic protection was examined in a trial test (Al-Mandil et al., 1995).

Numerous bridges have suffered extensive cracking due to overstress. Fig. 3 shows the extensive crack print on the soffit of a slab-type bridge deck. This problem was much common to bridges designed with old design load. As the heavy trucks weighed considerably higher than the design load of AASHTO + 10%, members were subjected

frequently to a much higher level of tensile stresses, and this resulted into development of well formed, deep cracks. Crack widths in some cases exceed 5 mm. Such extensive cracking adversely affect the safety factors and more importantly, they accelerate the process of corrosion in bridges situated in corrosive environment. Cores extracted by drilling through well formed cracks showed that in many cases crack depth reached almost 75% of the depth of the slab (Fig. 4). This shows the severity of the cracking of the deck slab.

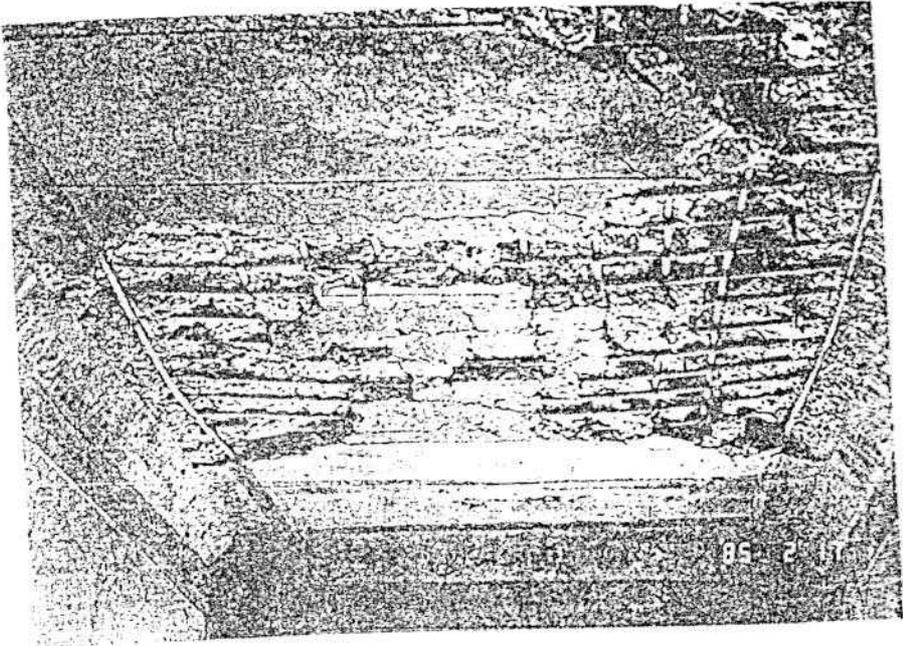


Fig. 2. Corrosion damage at soffit of deck slab

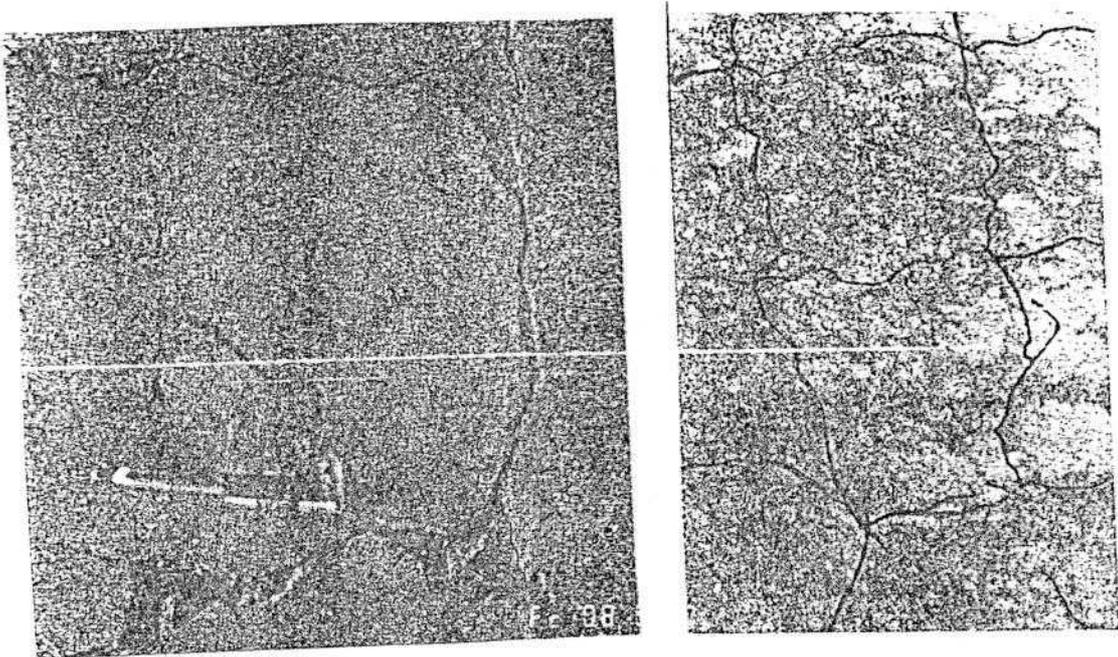


Fig. 3. Stress induced cracking at soffit of deck slab

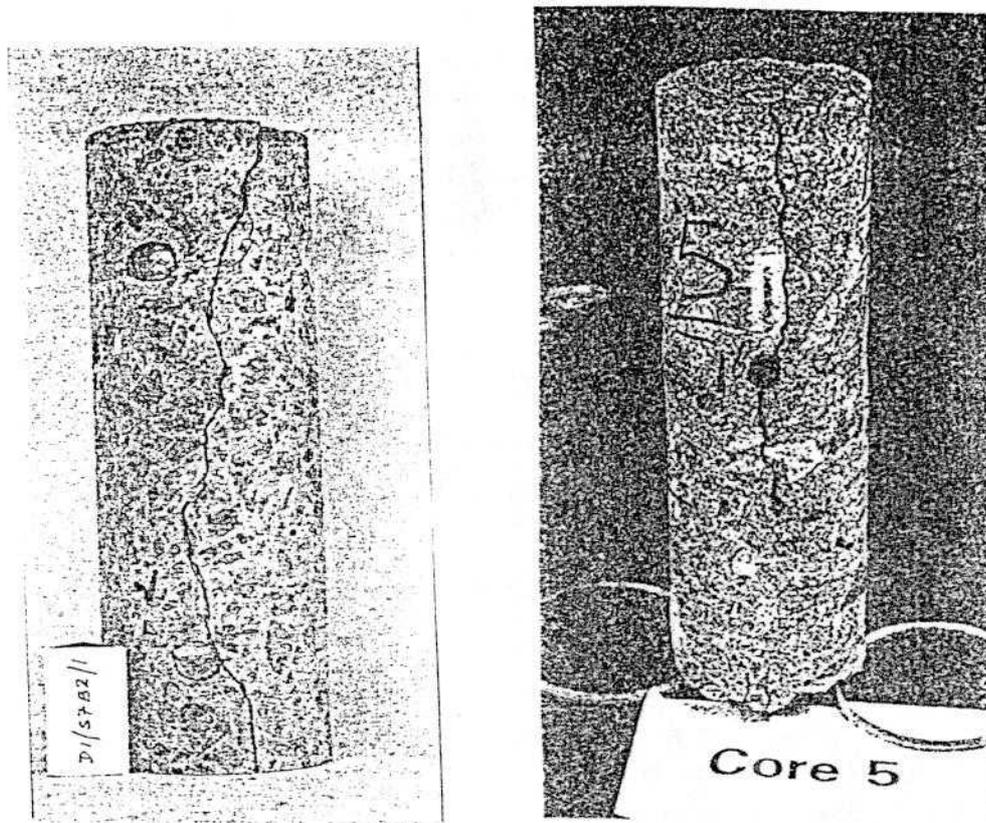


Fig. 4. Depth of cracks as seen by coring

Shrinkage and thermal cracking are also widespread due to poor mix design and lack of adequate and timely curing. Problems of hot weather concreting were not fully recognized by the contractors and this led to adoption of improper mix design, either too rich or too lean, and casting and curing not consistent with the recommended practices. Pouring of concrete took place at higher temperature in hot days, aggravating further the shrinkage problem. Even in temperate weather conditions of Abha, several bridge decks soon after construction developed numerous surface cracks which were sealed by epoxy injection. The cause of such cracking was attributed to windy conditions and no precautionary measures were taken to combat the situation. The shrinkage and thermal cracks from the early stage are driven further by stresses from heavy vehicular loadings.

In some cases, severe shrinkage and thermal cracking resulted from methods of construction. As an example, a larger part of Jamarat pedestrian bridge was constructed using prefabricated concrete planks (to avoid form work), on top of which fresh concrete was poured in hot environment (Al-Mandil et al., 1996). The restraint on free shrinkage provided by the planks induced tensile stresses which caused lot of surface cracking (Fig. 5).

Pothole type failures of a number of earlier built concrete bridge deck slabs such as the one shown in Fig. 6 caused a great deal of concern to MOC. A study (Al-Mandil et al., 1987) initiated to find the probable causes concluded that such failures are the result of impaired punching capacity of a cracked deck slab in which cracking caused by various factors was formed in a critical manner, making the slab unable to withstand heavy wheel

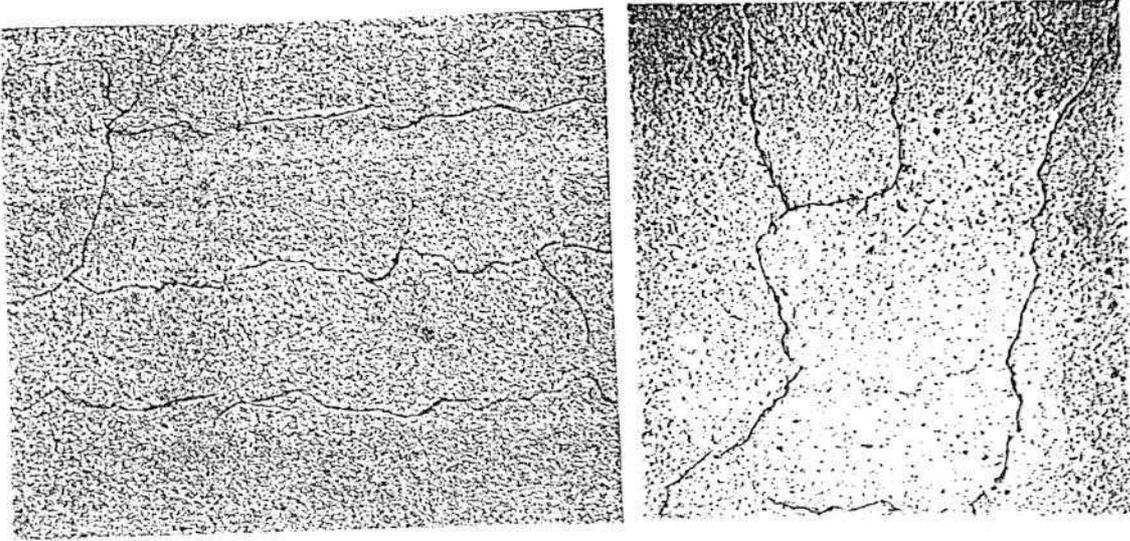


Fig. 5. Shrinkage cracking in deck slab

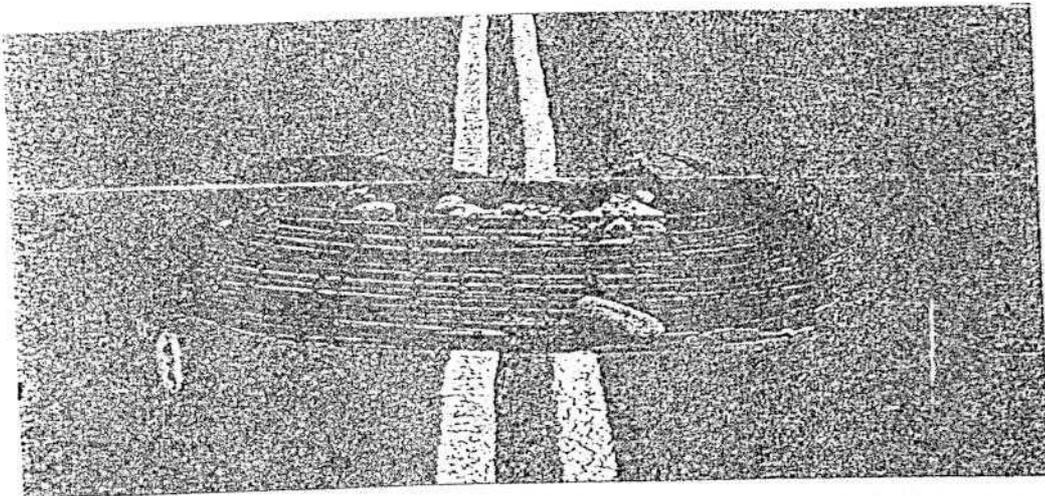
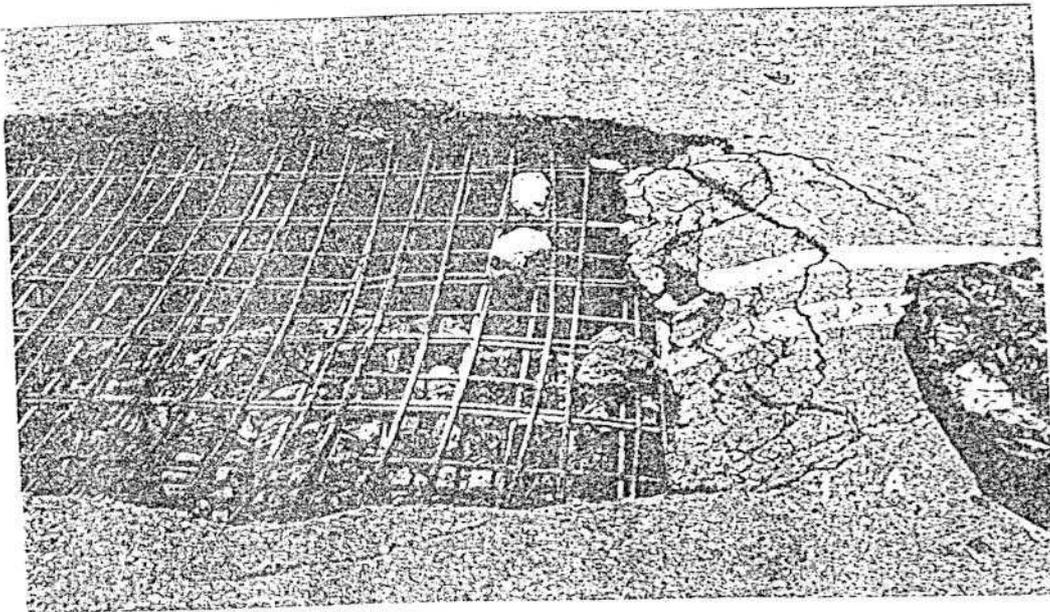


Fig. 6. Punching type failures of deck slab

loads. The cracked pattern and crack depth, if critically formed, impair the punching capacity of a deck slab by adversely influencing the failure plane under a concentrated load. All pothole type failures were witnessed in girder-slab type bridges, as the slab thickness for such decks are considerably smaller than the slab-type bridge decks. The mechanism of such a failure has been postulated in ref. (Azad et al., 1993). This problem since then has been overcome by increasing the slab thickness and the design axle loads.

Based on a study (Al-Mandil et al., 1987) which captured various types of damages sustained by a number of concrete bridges, an attempt was made to categorize them into different groups (Al-Mandil et al., 1990). Currently, crack-induced and corrosion-induced damages are the only two major problems confronting the bridges. While the former has been controlled in new construction due to awareness and superior construction, corrosion damage is still a major problem. As the structures are aging, their vulnerability to corrosion damage becomes more apparent.

As the structures must be designed to endure the adverse environmental conditions, a durability based design must be adopted right from the outset. Design, construction and maintenance must be considered collectively as an integral part of a system approach. Some of the recommendations in this direction have been made by ref. (Azad et al., 1989 and Azad et al., 1990).

CONCLUSIONS

The construction environment of Saudi Arabia is presented to highlight the regional problems and difficulties associated with construction of concrete bridges. As the bridges are exposed to environmental actions, they suffer the most damaging impact of the environment.

Four types of environment-induced damages which include corrosion of reinforcement, stress-induced cracking from heavy loadings, shrinkage plus thermal cracking and punching type failures, have been witnessed as common forms of damages. With the exception of corrosion which is still widespread, a greater awareness of the environmental and material-related problems and regulatory control on truck loads have sharply curtailed other types of damages.

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