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Engineering Performance of Sulfate-Bearing Soils in Iraq and Their Impact on Concrete Foundations: Mechanisms, Evaluation Methods, and Mitigation Approaches: A Critical Review

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ABSTRACT

In Iraq, which has a very wide distribution of sulfate-bearing soils, especially in the central and southern regions, these present a continuous issue for the concrete base's durability and service life. Also, we see that in areas with elevated sulfate levels in the soil and groundwater, together with high temperatures, salinity, and the wetting and drying cycles, we get enhanced chemical and physical degradation. Into the concrete go the sulfate ions, which in turn react with the hydration products, mainly tricalcium aluminate and calcium hydroxide, to produce expansive compounds such as ettringite and gypsum. These reactions produce internal stresses, cracking, and long-term structural integrity issues. This review brings together available geological, geotechnical, and materials research to look at the spatial distribution and classification of sulfate soils in Iraq, the chemical and mechanical processes which underpin soil – concrete interaction, and what those issues mean for shallow, raft, and pile foundation systems. In this study, both traditional and advanced evaluation techniques, which included chemical sulfate analysis, expansion testing, durability indices, and field-based non-destructive methods. Also, we went in-depth into mitigation approaches, which covered sulfate-resistant cements, supplementary cementitious materials, optimized mix design, soil stabilization, and protective barrier systems. This review also reports that present-day Iraqi engineering practices fall short in some areas, which in large part is a result of the low use of durability-based design frameworks and also the lack of in depth long term monitoring.

1. Introduction

In Iraq, we see that infrastructure is breaking down in a large scale due to very aggressive soil conditions. In the central and southern regions, which make up the greater part of the country, you see soils rich in sulfates, which we find in arid and semi-arid climates [1, 2]. In those systems, what happens is that soil interacts with concrete foundations through chemical reactions that produce expansive compounds, ettringite, and gypsum [3, 4], which in turn cause cracking and a progressive loss of structure. Also, we see large economic issues in Iraq related to this – early failure of concrete, fallen bridges, potholed roads, and unstable building foundations [5].

Sulfate attack is a major issue for the durability of concrete, which we see in assets exposed to aggressive soils and groundwater. Many studies report that the use of Supplementary Cementitious Materials (SCMs) such as fly ash, slag, and calcined clay greatly

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improves concrete's resistance to sulfate attack. What they do is reduce the permeability of the concrete matrix and also decrease the amount of calcium hydroxide, which reacts with sulfate ions. Also, reports in[6] say that the use of pozzolanic materials improves concrete durability by fine-tuning the pore structure and also by reducing the formation of expansive reaction products. Also in[7], we see that Blended cements, which have slag or fly ash in them, do better in terms of sulfate resistance, by which they reduce the formation of ettringite and gypsum in hardened concrete.

Although sulfate soils are very common, we still see poor integration of durability-based foundation design into routine engineering practice, and a large gap between research and field application [8, 9]. In recent years, research across the globe has developed the knowledge of sulfate attack, which includes the role of supplementary cementitious materials and the effect of temperature and humidity [10]. Although we have several studies on Iraq, what we don't have is a large body of research specific to that area. Also, most design codes play it safe and use thresholds based on temperate climate settings. This review fills that gap by bringing together local and international research, a reference for engineers and researchers working in the Iraqi setting.

2. Methodology

2.1 Distribution and Classification of Sulfate Soils in Iraq

2.1.1 The Geological Background and Geographical Application

In the south and central regions of Iraq, which include the Mesopotamian plain, large areas of soil that contain sulfate. Also in these areas, evaporation and shallow groundwater tables play a role. In many areas, high levels of sulfate are present in rocks that have had gypsum as a primary component (e.g., the Fatha Formation) and also in plains affected by the Tigris and Euphrates rivers. In the area of mineral composition, we have gypsum, which is $CaSO4•2H2O$, anhydrite, which is $CaSO4$, and at times we see bassanite, which is $CaSO4•0.5H2O$. In some places, we report field studies that note that the sulfate content may exceed 10% by mass. This is particularly true in the provinces of Basra, Thi-Qar, Muthanna, and Salah al-Din [11, 12].

2.1.2 Classification Systems

Sulfate content is classified according to the categories in Table 1, which are based on international standards and adapted to local Iraqi conditions. Many Iraqi sites are at a severe level, which in turn requires us to take special precautions in concrete mix design and foundation protection.

Table 1: Sulfate Severity Classification for Iraqi Soils

Typical Iraqi Regions	Severity Class	Sulfate Concentration (mg/kg soil)
Northern uplands	Mild	< 500
Central Iraq (Baghdad area)	Moderate	500 – 2000
Parts of Diyala, Wasit	Severe	2000 – 5000
Basra, Thi-Qar, Muthanna	Very severe	> 5000

2.2.1 Geographical Variation and Cartography

In recent years, GIS-based research has produced preliminary maps that identify hot spots. In Figure 1, we present a schematic map of sulfate distribution in Iraq, which also highlights which regions require special foundation design. That map is a compilation of data from over 200 boreholes and groundwater analysis [13].

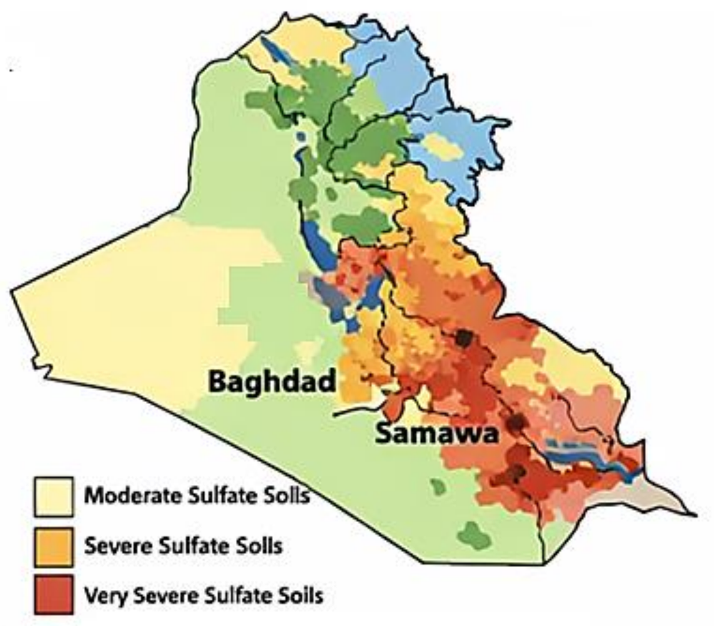

Figure 1: Schematic map of the sulfate concentration zones in Iraq, with the southern provinces' severe portions highlighted

2.2. Soil-Concrete Evolution Mechanisms

2.2.1 Chemical Attack Mechanisms

In sulfate-containing soils, concrete foundation deterioration occurs due to chemical and mechanical processes. In external sulfate attack, $SO4^{2-}$ penetrates concrete pores and reacts with tricalcium aluminate (C_3A) and calcium hydroxide (CH), in turn forming ettringite ($3CaO·Al_2O_3·3CaSO_4·32H_2O$) and gypsum (CaSO4•2H2O). These issues cause concrete to expand in volume, develop internal stress, and crack. The degree of which depends on the level of sulfate present, the temperature, and the porosity of the concrete.

Ettringite formation:

$$C_3A+3CaSO_4+32H_2O \rightarrow C_6AS3H32$$

Gypsum formation:

$$Ca(OH)_2+SO_4^{2-}+2H_2O \rightarrow CaSO_4\,.\,2H_2O$$

These reactions create large crystalline structures which in turn put stress on the concrete matrix, in the end causing it to crack and deteriorate.

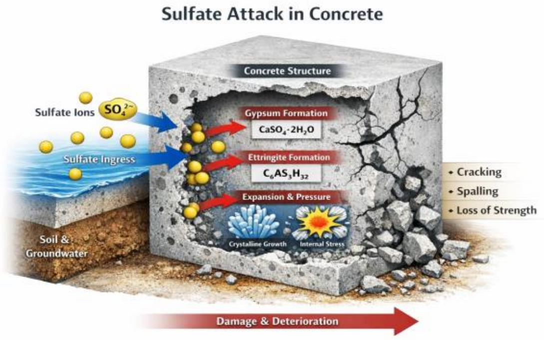

Figure 2: Mechanism of sulfate attack and deterioration process in concrete structures

Illustration of sulfate ion penetration from soil and groundwater into the concrete pore system. The sulfate ions react with hydration products such as calcium hydroxide and tricalcium aluminate, leading to the formation of gypsum and ettringite. These expansive products generate internal stresses that cause cracking, spalling, and gradual deterioration of the concrete structure.

Table 2: Mechanisms of Sulfate Attack on Concrete

Factor	Chemical reaction	Effect on concrete	Impact index
$SO_4^{2-} + C_3A$	Ettringite formation	Expansion within pores and cracking	High
$SO_4^{2-} + Ca(OH)^2$	Gypsum formation	Structural weakness	Medium
Impurities	Crystals salt crystallization in pores	Internal stress/cracking	High
Salt crystallization	Thenardite/mirabilite formation	Internal stress, spalling	High
Thaumasite formation	Carbonate-sulfate reaction	Mushy consistency, strength loss	Very high

2.2.2 Physical Attack Mechanisms

In addition to chemical reactions, in some cases, salt crystallization from a cycle of wetting and drying out, which is very common in Iraq, may cause physical sulfate attack. This process pressure from the crystals causes surface scaling and microcracking, which in turn accelerates weathering.

2.2.3. Combined Sulfate–Chloride Effects

In saline groundwater, sulfates coexist, which in turn influence the degradation process. Chlorides, by competing with alumina, delay ettringite formation, but at the same time, they reinforce corrosion. The interaction is complex, which in turn requires careful study in the mixed design [14].

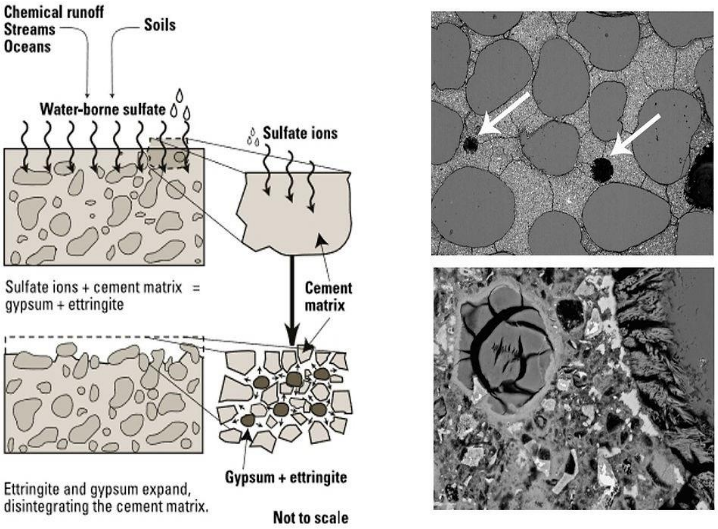

Figure 3: illustrates the microstructural evolution of concrete under combined sulfate–chloride attack.

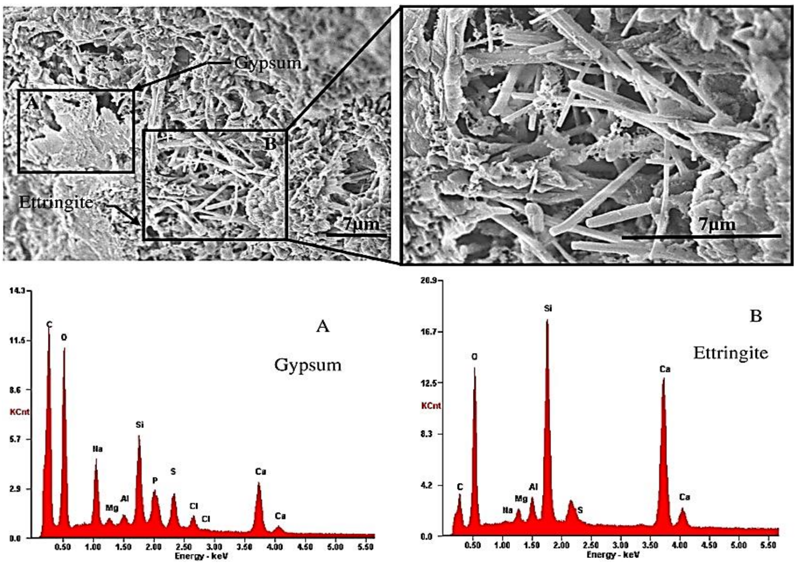

Figure 4: SEM micrographs showing ettringite needles and gypsum crystals in concrete pores after 12 months of exposure to sulfate-rich soil

3- Impact on Foundation Performance

3.1. Shallow Foundations

Isolated and strip foundations, which are what we term shallow foundations, are affected by proximity to near-surface sulfate soils. In severe cases, we see a reduction in compressive strength – in some cases, we've seen a 40% drop in 5 years [15]. Also, we are seeing edges crack and corners lift due to unequal expansion. What we also see is differential settlement, which is a result of non-uniform sulfate distribution.

3.2. Raft Foundations

Raft foundations have issues with surface scaling, reduced stiffness, and pressure redistribution. In the end, a drop in bearing capacity and an increase in rotation.

3.3. Pile Foundations

In the top zone, the highest sulfate levels, deep foundations like piles experience surface deterioration. Also, we see that friction is greatly reduced and steel reinforcement corrosion is accelerated when both sulfates and chlorides are present.

3.4. Iraqi case Studies

In some cities in Iraq, we have reported on what appears to be premature failure of structures due to sulfate attack. In a case of concrete at the Thi-Qar bridges, the strength had diminished by 50% in only 7 years, which in turn has required extensive rehabilitation [16].

4- Evaluation and Testing Methods

4.1. Soil Assessment

In terms of standard soil tests for sulfate attack potential, we have:

- Chemical sulfate analysis, which may be gravimetric or turbidimetric (ASTM C1580).
- pH, which reports on soil acidity that, in turn, may worsen attack.
- Electrical conductivity, which in fact is a measure of total dissolved salts.
- Water soluble vs total sulfate – it is the water soluble fraction which is more relevant for attack.

4.2. Concrete Durability Tests

Laboratory tests for concrete durability:

- Compressive strength (ASTM C39) at various ages;
- Linear expansion (ASTM C1012) of mortar bars, which are put in a sulfate solution;
- Rapid chloride permeability (ASTM C1202), which is an indicator of pore structure;
- Sulfate immersion testing, which we do at regular intervals, and we also take note of mass and strength changes.

4.3. Field Non-Destructive Techniques (NDT)

In the field we use:

- Ultrasonic Pulse Velocity (UPV) for identifying internal cracks.
- Surface resistivity (as per AASHTO T 358), which is for evaluation of permeability and corrosion risk.
- Half-cell potential (based on ASTM C876) for assessment of reinforcement corrosion activity.
- Ground Penetrating Radar (GPR) for mapping subsurface damage

Table 3: Evaluation and Diagnostic Techniques
provides an overview of the benefits and drawbacks of primary diagnostic techniques

Method	Type	Purpose	Advantages	Limitations
Soil sulfate content analysis	Chemical	Determine$SO4^2$ concentration	Accurate	Requires laboratory equipment
Concrete sulfate resistance test	Laboratory	Measure expansion	Design standard	Design standard costly
UPV (ultrasonic pulse velocity)	Field NDT	Detect changes	fast	Cannot measure $SO4^2$ concentration
UPV	Field NDT	Detect internal damage	Fast, portable	Cannot quantify sulfate level
Half-cell potential	Field NDT	Corrosion activity	Direct corrosion indication	requires electrical contact
Surface resistivity	Field NDT	Permeability/corrosion risk	Rapid, repeatable	Affected by moisture/temp

5. Mitigation and Stabilization Techniques

5.1. Material-Based Solutions

In the case of cement (Type V), we see that it has a C3A content of less than 5% also, which also means lower ettringite formation. Also, we have cementitious materials (SCMs), such as fly ash, silica fume, and slag, which improve the structure of the pores and, at the same time, consume CH, thus bettering the sulfate resistance. Also, we note water-to-cement ratio ($w/c < 0.45$) does very well in reducing permeability and, in turn, also slows down ion entry. Also of note is the use of Limestone calcined clay cement (LC3), which is a growing solution that has been doing very well in regard to sulfate resistance in hot climates.

5.2. Geotechnical Solutions

In some cases, we remove the sulfate-rich soil via excavation and use non-reactive material. Also, we have lime stabilization, which may reduce sulfate solubility; however, that is a fine line – too little or too much can cause issues like sulfate-induced heave. Preloading with drainage: Consolidates soil and reduces groundwater contact.

5.3. Protective Systems

· Waterproof membranes: Bituminous or polymeric sheets placed under foundations.

· Epoxy coatings: Applied to concrete surfaces to seal pores.

· Cathodic protection: For reinforced concrete in extremely aggressive environments.

Table 4: Mitigation and Protection Strategies provides a comparative overview of mitigation strategies.

Strategy	Type	Mechanism	Effectiveness
SCMs (fly ash, slag)	Material	Reduce C3A and CH, refine pores	High
Sulfate-resistant cement	material	lower C3A content	High
Low w/c ratio	Mix design	Reduce permeability	High
Protective coatings	Surface protection	Prevent water/ion ingress	Medium
Soil replacement	Geotechnical	Remove sulfate source	High
Membrane systems	Barrier	Isolate concrete from soil	Medium–High

6. Critical Evaluation of Iraqi Engineering Practice

6.1. Current Practice

In the present engineering culture in Iraq, design for durability is a secondary issue to structural strength. Most of our designs use standard concrete mix proportions, which we do not play around with for sulfate exposure unless the client requests it. We use sulfate-resistant cements in only high-profile projects, which also tend to have large budgets. Also, we don’t see much use for SCMs in our market due to issues with availability and cost.

6*.2. Code Compliance and Gaps*

In Iraq, building codes, which include (for instance, IQS 5/2019), put forth some of what is related to concrete in aggressive environments, but we do not see in them a great deal of performance-based details. Also, we do not have enough reports that report the results of long-term exposure under our local conditions, and quality control during the construction process is a moving target, whichresults in variable concrete permeability and cover thickness.

6.3. Research–Practice Gap

Although we have many academic studies that look at sulfate attack, what has been translated into practice is weak. Only some projects present monitoring programs or durability models; also, we do not have a central database of foundation performance in sulfate soils.

7. Research Gaps and Future Directions

7.1. Long-Term Field Monitoring

Instrumented test sites are a requirement for the collection of real-time info on concrete wear and tear, environmental conditions, and soil chemistry over decades. That data, in turn, will enable us to calibrate predictive models.

7.2. Iraq-Specific Durability Guidelines

We must develop a national durability design guide that will use local soil and climate data and materials. The guide will present sulfate exposure classes, put forth recommended mix proportions, and provide construction practices.

7.3. Coupled Chemo-Mechanical Modeling

Advanced models that put together ion transport, chemical reactions, and mechanical damage are able to predict service life and also to optimize repair strategies. Also, these models should be validated with Iraqi soil conditions.

7.4. Smart Sensing Systems

In the field of smart sensing, technologies that include fiber optics, MEMS, and other types of embedded sensors are able to detect the early signs of an attack, thus enabling a proactive maintenance approach. Also, we may see very affordable wireless networks that can be put in place in our critical infrastructure.

7.5. Life-Cycle Cost Analysis

Economic evaluations that compare initial investment in mitigation with the repair costs in the long term, which in turn will support our investment in durability. Also, we should include in these models elements of probability, which will account for wear and tear.

7.6. Evaluation of advanced materials in the Iraqi construction field

The fact that technologies like Limestone Calcined Clay Cement (LC3) and smart sensing systems have great promise for improving sulfate resistance, in Iraq, we see that their wide-scale use is hampered by issues of cost and material availability.

Table 5: practical design recommendations for sulphate resistant concrete in Iraq

Recommended value	Parameter
≤0.45	Water-cement ratio
Sulfate resistant cement	Cement type
15-25%	Fly ash replacement
30-50%	Slag replacement
≥35 PMa	Minimum compressive strength
≥50mm	Concrete cover

8. Conclusions

In Iraq, that sulfate containing soils present a large issue. We see chemical reaction along with geotech effects, which in turn cause structure decline, reduced service life, and high maintenance costs. At present, our engineering practices are, to a great degree, which is out of date in what we put forward as solutions and also in terms of what we have in terms of long term performance data. What is essential for sustainable infrastructure growth is the implementation of durability-based design, soil – structure interaction analysis, and the use of modern sensing technologies. Also included must be the update of national codes, promotion of their use, and the putting in place of field monitoring program.

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