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Cement and Concrete Research 34 (2004) 1275–1296

CEMENT AND CONCRETE RESEARCH

Review article

The confused world of sulfate attack on concrete

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Received 23 March 2004; accepted 8 April 2004

Abstract

External sulfate attack is not completely understood. Part I identifies the issues involved, pointing out disagreements, and distinguishes between the mere occurrence of chemical reactions of sulfates with hydrated cement paste and the damage or deterioration of concrete; only the latter are taken to represent sulfate attack. Furthermore, sulfate attack is defined as deleterious action involving sulfate ions; if the reaction is physical, then, it is physical sulfate attack that takes place. The discussion of the two forms of sulfate attack leads to a recommendation for distinct nomenclature. Sulfate attack on concrete structures in service is not widespread, and the amount of laboratory-based research seems to be disproportionately large. The mechanisms of attack by different sulfates—sodium, calcium, and magnesium—are discussed, including the issue of topochemical and through-solution reactions. The specific aspects of the action of magnesium sulfate are discussed, and the differences between laboratory conditions and field exposure are pointed out.

Part II discusses the progress of sulfate attack and its manifestations. This is followed by a discussion of making sulfate-resisting concrete. One of the measures is to use Type V cement, and this topic is extensively discussed. Likewise, the influence of w/c on sulfate resistance is considered. The two parameters are not independent of one another. Moreover, the cation in the sulfate salt has a strong bearing on the efficiency of the Type V cement. Recent interpretations of the Bureau of Reclamation tests, both long term and accelerated, are evaluated, and it appears that they need reworking.

Part III reviews the standards and guides for the classification of the severity of exposure of structures to sulfates and points out the lack of calibration of the various classes of exposure. A particular problem is the classification of soils because much depends on the extraction ratio of sulfate in the soil: there is a need for a standardized approach. Taking soil samples is discussed, with particular reference to interpreting highly variable contents of sulfates. The consequences of disturbed drainage of the soil adjacent to foundations and of excessive irrigation, coupled with the use of fertilizer, are described. Whether concrete has undergone sulfate attack can be established by determining the change in the compressive strength since the time of placing the concrete. The rejection of this method and the reliance on determining the tensile strength of concrete because of "layered damage" are erroneous. Scanning electron microscopy (SEM) should not be the primary, and certainly not the first, method of determining whether sulfate attack has occurred. Mathematical modeling will be of help in the future but, at present, cannot provide guidance on the sulfate resistance of concrete in structures.

Part IV presents conclusions and an overview of the situation, with consideration of future improvements. Appendix A contains the classification of exposure to sulfate given by various codes and guides.

Keywords: C Sulfate; Attack; Soil; Groundwater; Type V

This paper is in four parts. Part I establishes what is meant by sulfate attack. Part II discusses the progress and consequences of sulfate attack. Part III reviews the testing of aggressive soils and waters, and also testing for the purpose of establishing whether sulfate attack of concrete in the field has occurred. And Part IV presents an overview.

1. Part I: What is meant by sulfate attack?

1.1. Introduction

I have toyed with using the word "topsy-turvy" instead of "confused" because topsy-turvy is defined in the Shorter Oxford Dictionary as "utterly confused". This is how the situation with respect to sulfate attack seems to me, but perhaps, topsy-turvy is not a proper adjective for a research journal. It is not that our knowledge of the various phenomena and the actions involved have never been clarified;

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doi:10.1016/j.cemconres.2004.04.004

they are understood, at least at the engineering level, but the disputes in the last 10 years or so have resulted in many assertions. These, each taken separately, are not necessarily wrong, but taken together, result in a thoroughly confused situation.

I suppose that at the outset, I should justify my attempt to find some general strands in the issue of sulfate attack of actual structures: I am an engineer and not a scientist, and my view is that the behavior of structures in the field is the professional concern of an engineer.

I am not alone in emphasizing the need for engineering judgment and, therefore, for an engineer to be prominently involved in studies of sulfate attack. DePuy [1] of the Bureau of Reclamation wrote that, in certain circumstances, "it becomes increasingly important that the engineers have a good understanding of the chemical reactions, factors governing the rate of reaction, and mechanisms causing deterioration in concrete".

Nor am I alone in pointing out that laboratory studies to date are inadequate to translate into an understanding of field behavior. DePuy [1] wrote: "Most of the knowledge of sulfate attack has been developed from laboratory studies involving relatively simple chemical systems of pure materials, yet in actual practice the situation is more complicated...". And, like me, DePuy [1] feels that "although sulfate attack has been extensively investigated, it is still not completely understood".

1.2. Scope of the paper

I do not claim that the present paper will make the situation crystal clear. I am unable to achieve this, in part, because I am a civil engineer, and understanding sulfate attack involves not only civil engineering and construction practices, but also chemistry, soil engineering, and field and laboratory testing. It is not easy to get people from all these disciplines to work together. Worse still, there is sometimes a tendency for any one specialist to opine on phenomena outside his or her specialism. Unfortunately, some expert witnesses are tempted to express opinions outside their own field of expertise, fearing that admitting ignorance might detract from their standing, or else, they are inveigled into opining in alien fields.

Of course, I, too, must try not to fall into that trap, and yet, I am writing on the broad issue of external sulfate attack. So let me reassure readers that I intend to limit myself to identifying the issues involved and to pointing out the disagreements. However, of course, this will not prevent me from expressing my views, where I have some confidence in doing so.

"Chemists Should be Studying Chemical Attack on Concrete" is the title of an article by Hime [2], published in *Concrete International* in April 2003. And yet I, an engineer, am writing on a topic that concerns chemical action on concrete. Why?

First of all, Hime [2] himself says that chemists have not been "doing the chemistry" of chemical attack.

Second, I am not expressing any views on chemical reactions, although I shall need to refer to some of them.

Third, the *real* significance of chemical reactions between sulfates and concrete is in the damage to concrete. Mere chemical changes that do not affect the health, performance, or durability of concrete are of very limited interest to those concerned with real structures in the field, as distinct from laboratory specimens under artificial conditions. I hasten to add that laboratory research is important and essential to advance our knowledge, but the practical significance of that knowledge needs to be examined in engineering terms.

This brings me to the fourth issue: How widespread is sulfate attack? And also, how significant are the consequences of the reactions of hydrated cement paste with sulfates?

The present paper is not concerned with internal sulfate attack or with thaumasite attack, which is a separate form of sulfate attack [3]. Nor does the paper specifically deal with sulfate attack on concrete in consequence of oxidation of iron sulfide, such as pyrite, in the soil, which is largely an acid attack because sulfuric acid is formed. This can have very serious consequences, but allowing concrete to come into contact with soil containing pyrite is simply bad practice and can be avoided or prevented.

1.3. Definition of "attack"

At this juncture, it may be appropriate to define the meaning of the term attack. Usually, I find the New Shorter Oxford Dictionary, published in 1993, to be a good starting point. The Dictionary says, "a destructive action by a physical agency, corrosion, eating away, dissolution". I see the adjective "destructive" as being crucial; in other words, an action *by itself* does not necessarily represent attack. From an engineer's point of view, what matters is what has happened to the concrete: an action that does not result in deterioration or in a loss of durability is not an attack.

My view is supported by some researchers in the field of thaumasite attack. Bensted [4] says, "It is important that thaumasite formation and thaumasite sulfate attack are properly differentiated". This distinction is of vital importance. The mere fact of a given chemical reaction occurring is not evidence of damage and of consequential loss to the owner of the given concrete. The distinction of Bensted [4] is equally applicable to sulfate attack that does not result in the formation of thaumasite.

Further support to my views is given by Harrison [5], who says, "When the analysis of concrete reveals a high sulphate content this does not necessarily indicate any deterioration although conversely, loss of strength or visible deterioration accompanied by a high sulphate content would be evidence of sulphate attack".

In addition, Skalny et al. [6] emphasize that "the presence of ettringite per se is not a sign of sulfate attack". On the other hand, they refer to efflorescence as "virtually observable damage" and describe efflorescence as being "predominantly sodium sulfate; occasionally also sodium chloride, magnesium sulfate, other salts" [6]. They say that efflorescence represents severe *chemical* attack, the word chemical being italicized in their book.

My view that efflorescence per se is not a proof of *damage* has been expressed earlier [7]. Mehta [8] also says that efflorescence "should not cause any damage", except under certain circumstances.

1.4. Definition of sulfate attack

I have already expressed the view that attack on concrete occurs only if concrete experiences deterioration or damage. This still leaves open the question of what kind of mechanism needs to be involved for the action to be described as sulfate attack. There are two schools of thought.

One school considers sulfate attack to have taken place if sulfates are involved, regardless of the mechanisms acting. The other school limits the concept of sulfate attack to the consequences of chemical reactions between sulfate ions and hydrated cement paste, so that chemical changes in the paste take place. However, if sulfates interact with cement and cause damage to it, but the action is physical, and a similar action can occur with salts other than sulfates, then the damage is considered to be physical attack or physical sulfate attack.

I am aware of the fact that chemical changes are accompanied by physical changes, and I hesitate to enter into the niceties of science. Why then am I raising the issue? Indeed, it could be argued that nomenclature is of little significance. However, in my opinion, in a large and complex field, it is helpful if everybody uses the same terminology when referring to a given phenomenon.

Furthermore, I believe that there is a difference between chemical and physical attack in that the chemical attack involves *necessarily* the sulfate ion. On the other hand, physical attack involves crystallization of salts, of which one example is sulfate, but it is a topic of wider interest with respect to concrete and, also, rocks. In consequence, in this paper, the term sulfate attack will be limited to chemical attack, but I shall also consider briefly the physical sulfate attack.

I am far from being alone in holding the abovementioned views. For example, the Concrete Society Technical Report on Diagnosis of Deterioration of Concrete Structures [9] recognizes "physical salt weathering" as a phenomenon separate from sulfate attack, regardless of whether the salts are sulfates or not.

I would also like to quote Collepardi [10] who, in a state-of-the-art review of delayed ettringite attack on concrete, considers sulfate both of internal and external origin but explicitly excludes "damage which is specifically attributed to the physical sulfate attack such as crystallization of water-soluble sulfate salts". Mehta [8], in a paper subtitled "Separating Myths from Reality", says: "Surface scaling of concrete due to the physical salt-weathering attack is being confused with the chemical sulfate attack. Salt weathering is purely a physical phenomenon that occurs under certain environmental conditions when any porous solid, such as brick, stone, or poor-quality concrete, is exposed to alkali salt solutions including sulfates (but not necessarily limited to sulfates)". I am not sure that the qualification "poor quality" applied to concrete is appropriate; rather, the openness of the surface texture is relevant, and this could exist with some types of finishes of any concrete. Mehta [8] reports that "the physical attack associated with salt crystallization was not limited to alkali–sulfate solutions; for example, it occurs with alkali carbonate solution...".

I have to record that opposite views are also held. For example, Skalny et al. [11] say that "to draw a distinction between 'physical' and 'chemical' processes does not serve a useful purpose and will only serve to further confuse engineers". Being an engineer, I find this solicitude touching, but I do not believe that we, engineers, are already confused and have to be saved from being further confused!

I would like to emphasize that the issue of chemical or physical attack is not just semantic because the consequences of physical attack manifest themselves in a different way from chemical attack. Moreover, prevention of the two types of attack is likely to be different.

1.5. Physical sulfate attack

A prevalent form of physical attack is the reversible change of anhydrous sodium sulfate (thenardite) into decahydrate (mirabilite). If crystallization takes place in the pores at or near the surface of concrete, large pressure may develop, with consequent deleterious action. Hime and Mather [12] say that "precipitation from supersaturated solution may be required". The term "may" shows that the phenomena involved are not yet fully understood.

The problem of physical salt attack has been studied for a very long time. In 1929, Lafuma [13], in France, reported his experiments on the transformation of sodium sulfate decahydrate into anhydrous form of that salt and pointed out the significance of the temperature of 33 °C, above which the anhydrous salt is formed in a solution with a low apparent volume. While the minutiae of the papers of Lafuma [13] may, or may not, be correct—and they are not within my field of expertise—I have studied them because they recognize clearly that the actions involved are physical and that the chemical action of sulfate ions does not enter the picture.

In 1939, the crystallization of salts in porous materials was studied by Bonnell and Nottage [14] in England. Their tests were performed on a material with a very low tensile strength, saturated with a sodium sulfate solution. They showed that "when hydration takes place within the pores, stresses sufficiently high to overcome the tensile strength of normal porous building materials may be developed'' and the salt may ''exert a sufficient force to bring about disintegration of the material'' [14].

These were experiments involving thenardite and mirabilite (although these names were not mentioned), although it was not concrete that was tested. The experiments are highly relevant to the consideration of physical sulfate attack on concrete, but the paper by Bonnell and Nottage [14] is probably not well known because it was published shortly before the outbreak of World War II.

In 1949, Lea and Nurse [15] studied the crystallization of solids in aqueous systems, using both sodium and calcium sulfates. They identified a lack of knowledge of the growth of crystals under stress, but, with respect to ettringite, they favored the notion of topochemical reaction.

Consideration of through-solution as against topochemical reactions is a matter for chemists. The proposition of Lafuma [13] of topochemical formation is criticized by Brown and Taylor [16] and also by Mehta [17].

The specific behavior of sodium sulfate salts has continued to be a subject of study. Thenardite has a much higher solubility than does mirabilite so that thenardite can produce a supersaturated solution with respect to mirabilite. In 2002, Flatt [18] expressed the view that at 20 °C, a tensile hoop stress of 10 to 20 MPa develops by the crystallization of mirabilite (decahydrate) from a saturated solution of thenardite (anhydrite). Tensile stress of such magnitude would inevitably disrupt concrete, but the pore size influences the ease with which the crystals can grow [18].

According to Flatt [18], ''the development of crystallization pressure requires supersaturation in the liquid film between the crystals and the pore wall'', but he notes that in concrete, ''unfilled large pores tend to consume supersaturation in harmless growth''. Flatt [18] expresses the view that ''sodium sulfate can cause more damage than just about any other salt''.

In a 2002 paper, Brown [19] recognizes the distinction between what he calls ''classic form of sulfate attack associated with ettringite and/or gypsum formation'' and ''physical sulfate attack associated with crystallization of sulfate''. He also acknowledges the fact that the involvement of a sulfate is almost incidental to what is essentially a physical attack by saying: ''Physical sulfate attack can be regarded a specific type of salt damage'' [19].

The various papers that I have just discussed are concerned with physical actions, the fact that sodium sulfate has sulfate ions being incidental, so that they point toward the concept of physical attack.

Overall then, I think it is useful to distinguish attack that involves sulfate ions, i.e., sulfate attack, from a situation where damage is caused *solely* by physical forces, which is physical sulfate attack. I venture to recommend such nomenclature.

1.6. How widespread is sulfate attack?

In a paper reviewing the progress in the practical field of concrete in the last 40 years [20], I commented that in some cases, the volume of laboratory research is disproportionate to the practical extent of the problem. I cited the alkali–aggregate reaction, but now, I wonder whether this is not also the case with sulfate attack.

The opinion that sulfate attack is not a widespread problem in concrete structures is expressed even by those who have published extensively on the topic. Specifically, a book titled *Sulfate Attack on Concrete* [6] says ''that neither external nor internal forms of sulfate attack are major causes of degradation of concrete structures,'' and, also, that ''sulfate-related deterioration is globally minute'' compared with damage by corrosion of steel or by freezing and thawing. The same book says—and I agree—that owners of particular structures that have suffered sulfate-induced damage are justified in being concerned. On the other hand, the book contains a number of sweeping statements, elevating the mere presence of sulfates to damage [6], supported by global references such as *Deposition Transcripts 1996–2000*. I am aware of some of these transcripts, and I find in them also diametrically opposed views, opinions, and interpretation.

Moreover, despite numerous allegations about damaged foundations in California, not a single collapse has been reported, nor has any house or building been evacuated.

In 1993, Mehta [21], who has repeatedly reviewed the problems of sulfate attack, expressed the view ''that sulfate attack is seldom the sole phenomenon responsible for concrete deterioration''. Seven years later, he wrote that ''the threat of structural failures due to sulfate attack...seems to be even less of a threat than that caused by alkali–silica reaction'' [8].

At the 1998 Seminar on Sulfate Attack Mechanisms held in Quebec City, Pierce [22], who was head of the U.S. Bureau of Reclamation, said that he echoed Haynes' words, ''we do not see problems in the field'', and ascribed this situation to the fact that ''we have taken the necessary precautions''. The precautions are incorporated in codes of practice. Literature search indicates that in temperate climates, there have been very few, if any, actual failures.

The view that there are very few reported cases of structures in service damaged by sulfates in the soil or in groundwater is supported by Tobin [23]. In a technical information note dated May 22, 2002, he refers to his 66 years' experience with residential and commercial construction using concrete, and says, ''Surface damages have been observed, not unlike those that occur due to freeze–thaw weather conditions on exposed concrete, but not a single instance of a progressive attack or a complete failure due to sulfate attack in the true meaning of the word'' [23]. Those are the words of a structural engineer.

These views contrast, to a large extent, with the opinions of laboratory scientists who use accelerated test methods. Often, their objective is to study sulfate attack, so that they have little interest in concrete that performs well. I am not blaming them, but those dealing with real concrete in service should not be swayed by tales of doom.

There are, nevertheless, some parts of the world where sulfates are problematic. In South Australia, especially in the city of Adelaide, there is an endemic problem known as salt damp. Essentially, the ground contains sulfate-laden salt; this rises through the concrete, or other building material such as limestone or rubble, in house foundations during cool, wet winters. When the water evaporates during hot, dry summers, salt is deposited on the surface of the concrete. In consequence, concrete may be damaged. Prevention in existing buildings made of porous materials is generally uneconomic, and, usually, a sacrificial render is applied and renewed periodically.

Parts of the Canadian Prairies abound in sulfates, and so do some other areas in several countries. In the U.K., sulfates are found in some clayey soils and on so-called brownfield sites, i.e., locations of former factories involving chemical processes; these are not natural deposits.

1.7. Mechanism of sulfate attack

First of all, it is useful to list the principal reactions of sulfates with hydrated cement paste. Those of main interest are as follows.

Sodium sulfate reacts with calcium hydroxide to form calcium sulfate (gypsum). This reaction proceeds to a greater or lesser extent, depending on the conditions. In flowing water, with a constant supply of sodium sulfate and removal of calcium hydroxide, the reaction may eventually continue to completion, i.e., leaching of all calcium hydroxide (which, on a volume basis, is a major product of hydration of portland cement). Otherwise, equilibrium is reached.

Calcium sulfate formed as described above can subsequently react with C_3A, usually via the formation of monosulfoaluminate, to form ettringite.

Sodium sulfate is the predominant salt involved in reactions with concrete in California.

Calcium sulfate reacts with C_3A to form ettringite and reacts also with sodium and potassium hydroxides. It is to minimize the reaction with C_3A that Type V cement was developed.

Calcium sulfate is the predominant salt involved in reactions with concrete in England.

Magnesium sulfate reacts with all products of hydration of cement; the important resulting compounds are calcium sulfate and magnesia. Calcium sulfate can proceed to react with C_3A.

The reactions of sulfates are well known so that there is no need to write here the relevant equations in stoichiometric form. However, it is important to recognize that the end products of the various reactions, if they occur so as to damage the concrete, result in different types of damage. In consequence, different preventive measures are required.

Specifically, in the case of sodium sulfate, the use of cement with a low C_3A content (which becomes calcium aluminate hydrate) minimizes the extent of reaction with sodium sulfate and, therefore, of the formation of ettringite. This may lead to expansion, but, as pointed out by Taylor [24], "seeing ettringite in a concrete does not necessarily mean that ettringite has caused the stress".

As reported by Santhanam et al. [25], gypsum is the primary product of sulfate attack at high concentrations of the sulfate ion. When the pH of the pore water in hydrated cement paste falls below about 11.5, ettringite is not stable and decomposes to gypsum.

The formation of gypsum and its effects are still far from clear. As recently as 2000, tests on pure C_3S paste (i.e., in the absence of C_3A) showed that gypsum formation "may be a cause leading to expansion and subsequent cracking" [26], which occurred after about one year in a 5% sodium sulfate solution. The words "may be" are important. The paper concluded that "it is not clear that gypsum formation follows either the topochemical reaction mechanism or the through-solution mechanism" [26]. The final words "more research is needed in this area" [26] have a familiar ring.

Indeed, Mather [27] said, "I have seen no evidence that the formation of gypsum during sulfate attack on cement paste causes expansion". He favors the notion of a through-solution formation of gypsum [27]. Harrison [5] expresses a similar view.

In tests by Rasheeduzzafar et al. [28] on neat cement paste and mortar specimens immersed in a solution of sodium and magnesium sulfates, damage manifested itself primarily by scaling, spalling, and softening, rather than by expansion or cracking; there was a large reduction in compressive strength [28]. Because magnesium hydroxide has a very low solubility and its saturated solution has a pH of about 10.5, C-S-H decomposes, liberating lime. This lime reacts with magnesium sulfate and forms further magnesium hydroxide and gypsum. This reaction continues until gypsum is crystallized out [28]. Magnesium hydroxide reacts also with silicate hydrate arising from the decomposition of C-S-H, and this results in the formation of magnesium silicate hydrate, which lacks cohesive properties [28]. These reactions take place even when the C_3A content in the cement is very low [28].

Thus, it can be seen that magnesium sulfate is more aggressive than sodium sulfate due to the lowering of pH of the pore water in the hydrated cement paste. It follows that a laboratory test using magnesium sulfate is not valid for field conditions where the pH is not lowered during the sulfate attack [21].

In this connection, I have to admit that my own laboratory tests [29] on sulfate attack on concrete were performed using magnesium sulfate because, when I started the tests in 1965, I did not realize the peculiar consequences of that salt. I also used a very high sulfate cement in the attacking solution (50,000 ppm) as against several thousand parts per million encountered in the field. The error of my ways continues to be repeated because, as Hime [2] says, the reaction is faster, which suits PhD students, and the fact that it is different from that of calcium sulfate seems to elude many investigators.

A further complication should be mentioned. Magnesium hydroxide, called brucite, forms a protective layer on concrete, unless this is damaged mechanically [30]. This explains the good record of concrete in seawater, which has a high magnesium sulfate content.

It might be thought by some readers that the preceding apparent literature review is too academic for a paper purporting to deal with sulfate attack in service. My defense is that the seeming lack of clarity allows one-sided, and therefore biased, views on the lines that "if gypsum is present, sulfate attack has occurred" or "if no ettringite has been found, there is no sulfate attack". Moreover, often, experience with, say, magnesium sulfate is directly transferred to a situation involving sodium sulfate. Conversely, laboratory test results on a single type of sulfate are applied to field situations, in which a mixture of sulfates is present.

With reference to exposure conditions, it is worth noting that the carbonation of a concrete surface prior to exposure to sulfates "reduces the build-up of sulfate within concrete" [5].

2. Part II: Progress of sulfate attack and preventive measures

This part of the four-part paper discusses the progress and consequences of sulfate attack, mainly under field conditions, and also some preventive measures.

2.1. Progress of attack

It is obvious that sulfate attack can occur only when sulfates are present in contact with concrete. But how much sulfate needs to be present for the reactions between the sulfates and the hydrated cement paste to result in damage to concrete, i.e., to constitute sulfate attack? We should also ask the question whether the concentration of sulfate in the water in contact with concrete affects the extent of the attack; the extent comprises the intensity and the rate. These depend on the solubility of the given sulfate and on the continuity, or otherwise, of the supply, i.e., on whether the water is static or is flowing.

The preceding paragraph could be interpreted to refer first to sulfates in the soil, but then to continue with consideration of sulfates in water. The explanation of this apparent inconsistency is that dry salts do not react with concrete so that it is the concentration of sulfates in water in contact with concrete that is relevant. In other words, sulfates can move into concrete only in solution.

The rate of attack by sulfates is affected by the strength of the sulfate solution, but the effect becomes small beyond about 1% of sodium sulfate and about 0.5% for magnesium sulfate [31]. This effect is of significance in the classification of aggressivity of exposure, given in the various codes, and is discussed in a later section.

Taylor [32] lists the following as consequences of sulfate attack: strength loss, expansion, cracking, and, ultimately, disintegration. He further points out that whereas laboratory studies have concentrated on "expansion and cracking, field experience shows that loss of adhesion and strength are usually more important" [32]. This accords with my criticism of excessive reliance on individual, and often disconnected, laboratory studies coupled with an absence of in-depth (no pun intended) evaluation of field experience. Similarly, Brown and Taylor [16] say, "Further experimental work should take into account the conditions existing in the field and be related to field observations".

As for changes in concrete resulting from the action of sulfates, Skalny et al. [6] list nine chemical changes and nine physical changes, but say that "by themselves, neither (sic) of the above chemical, physical, and microstructural changes are necessarily an adequate sign of sulfate attack". They say further: "However, in combination, there can be little doubt" [6]. This is a very sweeping statement because much depends on which combination is involved.

References to the action of sulfates in Southern California should not be generalized because, as stated by Skalny et al. [6], soils there contain "high levels of sulfates, often in the form of gypsum". As I have already pointed out, the action of calcium sulfate and its consequences are different from the action of sodium and magnesium sulfates. Thus, unqualified statements, such as "one of the characteristic features of severe external sulfate attack is formation of gypsum" [6], are too vague and may be misleading to engineers without specialized knowledge of chemistry.

2.2. How to make sulfate-resisting concrete

It would be contrary to the tenor of this paper if I were to make a categorical statement of the "one-size-fits-all" type about how to ensure sulfate resistance of concrete. However, I have come across forceful assertions that for concrete to be resistant to sulfates, all that matters is a low w/c. An experienced engineer knows that unless concrete is well compacted and dense, a low w/c is useless. DePuy [1] gave as a first requirement for good resistance, "a high-quality impermeable concrete. This requires good workmanship (workable mixes, good consolidation, a hard finish, and good curing), and the use of a relatively rich mix with a low w/c." Most engineers would subscribe to this view, but some laboratory scientists might have little experience of these site-related factors.

I shall deal with w/c in a later section but, by way of introduction to the concept of sulfate-resisting concrete, I have to mention also the use of Type V, i.e., sulfate-resisting cement. This will be considered in the next section.

At this stage, I would suggest that there is no single answer to the question often posed to me: Which is more important, w/c or the type of cement? The main reason for the absence of a unique answer is that the mechanism of sulfate attack depends on the cation in the sulfate: sodium, calcium, or magnesium. Of course, more than one of these may be present in a single location. Alas, in disputes, an expert may be expected to present a single answer.

Parenthetically, I would like to refer to another problem occasionally faced by an expert. He or she is asked whether it is certain that, under some circumstances, damage cannot occur. Alas, lawyers cannot, or do not want to, accept that a certainty of impossibility of the occurrence of an event does not exist in engineering.

Apropos of making a categorical statement that is universally right, Northcote Parkinson, a 20th century English satirical writer, commented that no one is always right, but that in every organization, there is one person who is invariably wrong. That person is very useful as a sounding board for a new idea claimed to be a winner: if that person thinks so too, then, the idea is wrong!

2.3. Use of sulfate-resisting cement

This type of cement (known as Type V) has existed in the United States since 1940, although since then, ASTM has introduced some modifications in the standard requirements for its chemical composition.

The essential feature of Type V cement is that it limits the content of C_3A, as calculated by the Bogue method. However, as pointed out by Mehta [21], Type V cement "addresses only the problem of sulfate expansion associated with the ettringite formation". I would expect, therefore, Type V cement to be particularly efficacious when calcium sulfate is the attacking medium, although it could be beneficial with respect to the prevention of the formation of gypsum owing to the action of sodium sulfate.

Thus, Type V cement is of no avail in the attack of calcium hydroxide and C-S-H and the subsequent loss of strength [21]. This situation is relevant to tests on sulfate resistance: do we determine expansion or loss of strength? These tests are discussed in Part III of this paper.

We should note that for exposure to modest amounts of sulfates, codes allow the use of Type II cement with pozzolans as an alternative to Type V cement.

Nevertheless, the importance of using Type V cement should not be underestimated. The *Bureau of Reclamation Concrete Manual* stated, in 1985, that "concrete containing cement with a low content of the vulnerable calcium aluminate is highly resistant to attack by sulfate-laden soils and water" [33]. Even today, the Bureau of Reclamation is reported to consider "the C_3A content to be the greatest single factor influencing the resistance of portland cement concrete to sulfate attack, with cement content second" [31]. Some specific values of the C_3A content in cement and of the cement content in concrete are quoted, but I suspect that it is the density of concrete and not the cement content as such that is the real factor. The view that cement content has no effect on sulfate resistance was expressed also by The Concrete Society [34] in 1999.

Recent interpretations of long-term tests at the Bureau of Reclamation will be discussed in a subsequent section.

Although dated, the views of Lea [35] are of importance. He stated, "The resistance of Portland cements to attack by sulphate solutions is known to be related in a general way to their calculated C_3A content, but there are many anomalies in this relationship" [35]. One reason is that the rate of cooling the clinker influences the morphology of the aluminate: if it is in glass form (amorphous), it is much less susceptible to attack by sodium or magnesium sulfate [35].

Also somewhat dated, but of interest, are the views of Mather [36]. He said that when the Bureau of Reclamation recommendations are observed, i.e., Type V cement is used, "no significant deterioration of concrete due to sulphate attack has been encountered" [36].

An enormous contribution in the field of sulfate attack on concrete was made by Thorvaldson in the 1950s [37]. (In 1962, I had the privilege of knowing him, and I profited from his wealth of knowledge of cement.) He confirmed the influence of the type of cement on the resistance to sulfate attack of concrete with a high w/c. As usual, the studies were comparative with respect to Type I cement. However, Type I cement has changed considerably since then, mainly by way of an increase in the ratio of C_3S to C_2S. In consequence, the products of hydration contain more calcium hydroxide than is generated by C_2S. This makes the cement more vulnerable to sulfate attack, with the consequence of the formation of gypsum. Al-Amoudi [38] observed that in the case of magnesium sulfate, a lower content of calcium hydroxide in hydrated cement is undesirable because it encourages the reaction of sulfate with C-S-H, leading to the softening of the matrix, mass loss, and a reduction in strength.

The positive influence of a low C_3S-to-C_2S ratio was reported also by Irassar et al. [39]. In my view, their paper is an example of an investigation involving a single set of conditions, and great care is required before generalizations can be made. At least on evidence to date, we should refrain from saying that a low C_3S-to-C_2S ratio is a significant positive factor in the choice of cement for good sulfate resistance.

Furthermore, consideration of the ratio of C_3S to C_2S is often not included in the interpretation of laboratory tests. In the case of concrete in situ, the ratio is usually unknown.

Nowadays, in addition to portland cement, there are commonly used various cementitious materials, such as fly ash and ground granulated blastfurnace slag (slag). They inevitably affect the chemical reactions involving sulfates. I am not considering these cementitious materials because the situation when only portland cement is used should be disentangled first. With additional cementitious materials, the complexity of sulfate attack becomes even greater. For example, Taylor [24] pointed out that if slag has a low alumina content, it improves the sulfate resistance, but with a high content of alumina, the reverse is the case. On the other hand, if calcium hydroxide becomes bound by, say, fly ash, the sulfate resistance may improve.

A further complication arises from a possible interaction between the type of cement and the w/c. This makes it difficult to interpret test results in which one parameter at a time is varied. To illustrate the situation, I shall refer to the works of Stark. He conducted long-term studies and reported his findings in 1989 [40] and again in 2002 [41].

According to the first report of Stark [40], visual assessment of concrete specimens half-submerged in a sodium-sulfate-rich soil, with periodic wetting and drying, showed that Type V cement performed better than did Type I cement at values of w/c between 0.75 and 0.45. At w/c = 0.36, the two cements were equally good. To me, these results show a superior performance of Type V cement and not a predominant influence of w/c. A generalization is, however, not possible. It is worth noting that Stark [40] commented that "wetting and drying with crystallization of salts may have contributed to deterioration".

The second report of Stark [41], dated 2002, also relies on visual assessment of deterioration. He found that at a w/c of 0.40, concrete, partly immersed in sulfate-laden soil and alternately wetted and dried, performed significantly worse when Type I cement was used than with Type V or Type II cement [41]. The w/c had a significant effect on the performance above a w/c of 0.50. At a w/c of 0.65, all cements led to a poor performance but, at intermediate values of w/c, Stark [41] found the cement composition to be "of some importance". Interestingly, laboratory concrete immersed continuously in a solution of sodium sulfate of the same concentration as in the field tests (65,000 ppm of sulfate) showed uniformly excellent performance regardless of the type of cement, w/c, or additional cementitious materials and surface treatments [41]. The conclusion of Stark [41] is that "the traditional explanation of expansion of concrete due to chemical reaction of sulfate ion with aluminate-bearing cement hydration products was of relatively minor significance". He concluded that a major mechanism of deterioration in the field tests (but absent in the laboratory) is cooling and heating, and wetting and drying (by natural variation) with cyclic crystallization of sodium sulfate salts [41].

According to the classification that I have used in this paper, the above mechanism should be considered to be physical attack. Much more importantly, the tests of Stark [41] show that predicting the behavior in the field on the basis of laboratory tests under singular, uniform, and strictly controlled conditions is likely to be unreliable. This explains why various laboratory tests lead to different conclusions. Hence, my plea for a new approach to the study of sulfate attack is by way of *field* performance.

Actually, varying one parameter at a time in a concrete mix is not possible. For example, at a given workability, a change in the w/c entails a change in the cement content.

2.4. Importance of w/c

Occasionally, especially in disputes, strong emphasis is placed on the low value of w/c being the essential requirement for sulfate resistance, the type of cement being considered irrelevant or, at best, secondary. Other people express the contrary view. Each proponent adduces evidence supporting his or her opinion. Such a situation is highly conducive to the continuation of the present confusion, but it is not surprising.

It is not surprising because much depends on the cation in the attacking sulfate, as shown earlier in this paper. There are other important factors at play as well.

There is, however, an overriding requirement, necessary but not sufficient, for good sulfate resistance of concrete, and that is its density in the sense of a very low permeability. This is achieved by good proportioning of the mix ingredients, such that full compaction can be obtained, by actual achievement of full compaction, and by effective curing to maximize the degree of hydration of the cement paste. These requirements are obvious to an engineer, but often not fully considered by laboratory experimenters. Hence, my repeated plea for consideration of field concrete.

Building Research Establishment (BRE) Special Digest 1 states: "Poorly compacted concrete will be particularly vulnerable to chemical attack" [42]. Taylor [32] says that "the effects (of sulfate) are minimized in a dense concrete of low permeability and by using a sulphate-resisting cement, in which there is little or no aluminate phase...".

Consideration of low permeability to ensure durability is included in British Standard BS 5328, which says that permeability is "governed by the constituents, their proportions and the procedures used in making concrete" [43]. Eight factors influencing durability are listed, of which one is the type of cement, and another the cement content and free w/c taken together [43].

Permeability was also considered in the tests of Khatri et al. [44], who found that the expansion of mortar specimens immersed in a 5% sodium sulfate solution was affected both by the type of binder and by permeability.

With reference to the influence of w/c on the resistance of concrete to external attack in general, it is useful to quote Shah et al. [45]: "a relatively low *w/c* in cement paste does not necessarily mean a reduced permeability because of the significant influence of aggregates". Specifically, they consider early-age cracking to be a factor in ensuring durability. The relevance to the theme of this paper is that absolutist statements about w/c being the governing factor ensuring resistance to sulfate attack are not correct.

Young et al. [46] say that sulfate attack can be prevented by any one of three factors: a low w/c, a low calcium hydroxide content, or a low C_3A content. If their claim is valid, then adequate protection of concrete should be ensured by the use of a low w/c alone or by the use of Type V cement alone. In my opinion, these solutions are too sweeping and not valid under all circumstances.

Somewhat surprisingly, it has been found in several investigations, as reported by Al-Amoudi [38], that lowering w/c has a deleterious effect on the resistance of concrete exposed to magnesium sulfate, the use of Type V cement being of no avail. A likely explanation is that at low values of w/c, there is limited pore space to accommodate the products of reactions with sulfate, namely, magnesium silicate hydrate (which has no adhesive properties) and gypsum. Care is required in translating these observations into practical recommendations about mix selection. My purpose in reporting the above findings is to show, once again, that a systematic review of the entire problem of reactions of sulfates with hydrated cement, for the purpose of guidance about making durable concrete, is still to come. Specifically, we often fail to differentiate between the cations in guidance documents or codes, or when applying such documents.

2.5. Bureau of Reclamation tests

The Bureau has played a preeminent early role in studying sulfate attack on concrete and in developing sulfate-resisting concrete. An extensive and independent long-term investigation of the behavior of concrete exposed to sodium sulfate was started by the Bureau of Reclamation in the 1950s. The specimens were continuously exposed to sulfate over a period of more than 40 years. In addition, the Bureau conducted accelerated tests. Unfortunately, because of funding changes, the Bureau did not analyze and report the long-term test results.

The spate of litigation involving alleged sulfate attack on concrete led several people to visit the Bureau test results and to publish their interpretations. The steady-exposure, i.e., nonaccelerated tests, were analyzed by Kurtis et al. [47]. It is not my intention to comment in detail on their analysis, but I believe the following observations are in order. First, the extensive development of what they call "empirical model to predict concrete expansion" in their paper was revoked by an erratum published eight months later [47], and equations with new shapes were introduced. This is a great pity. Less hurried research would serve us better.

Another aspect of the interpretation by Kurtis et al. [47] of the test data of the Bureau of Reclamation deserves mention. The interpretation distinguishes cements with a low C_3A content (described as $< 8\%$) and cements with a high C_3A content (described as $> 10\%$). This gives the impression that the Bureau tested cements with quite a range of C_3A contents. It is true that the range was wide, but the distribution of C_3A contents was uneven, and the division at 10% is fortuitous: there were no cements with a C_3A content between 8.0 and 10.0. Moreover, the distribution of values was not uniform: 81 cements with less than 8.0% and 33 with more than 10.0%; of these 33 cements, 16 had a C_3A content of between 16.01% and 17%. In addition, of the 81 cements with the C_3A content of less than 8.0%, 43 had a content higher than 6.01% and 53 higher than 5.01%. The relevance of the value of 5.01% will be mentioned in the next paragraph.

My remarks are not meant to criticize the findings of Kurtis et al. [47] because it was not they who chose the cements (and the Bureau of Reclamation had its own objectives), but their interpretation in qualitative terms, such as "low C_3A content" and "high C_3A content", may not be justified. Even more importantly, we should note that ASTM C 150-2002 limits the C_3A content of Type V cement to 5% and also restricts the sum of the content of C_4AF plus twice the C_3A content to 25%. Thus, as I see it, conclusions in terms of high- and low-C_3A contents need careful qualification.

I have a similar reservation with respect to the use of w/c as a parameter. Whereas the value of w/c used by the Bureau ranged from 0.35 to 0.75, of the 114 mixes used, 85 had w/c between 0.46 and 0.55. Thus, the real spread of w/c was minimal. This is relevant to the conclusions about the significance of w/c with respect to the sulfate resistance of concrete.

Monteiro and Kurtis [48] (who were the coauthors of Ref. [47]) wrote another paper discussing the same test results. Although they emphasize the importance of the influence of w/c on the sulfate resistance of concrete, this is not entirely borne out by the test results. Their conclusion that the "time to failure, as measured by expansion, decreases with increasing *w/c* and C_3A content" is correct, but it is far too broad for practical application. At one extreme, they report that the concrete that failed first (after 3½ years) had a w/c of 0.48 [48]. This concrete was made with a cement that contained as much as 73.7% of C_3S; hence, the C_3S content may be significant. At the other extreme, of the nine concretes that failed in less than 25 years and had a w/c >0.55, seven had a C_3A content above 6%. Moreover, a graphical interpretation of the tests, reported by Monteiro and Kurtis [48], shows that for values of w/c between 0.45 and 0.55, the time to failure ranged from 3½ years (but mostly >12 years) up to more than 40 years. My view of their analysis is that it does not enable us to draw any practical conclusions, especially because only the expansion of specimens was used as a measure of sulfate attack and only exposure to sodium sulfate was tested.

In view of this, it is surprising that they report [48] a reliability analysis (of which they were coauthors) that is said to have shown "that the effect of *w/c* on expansion was one order of magnitude higher than the effect of C_3A content for cements with a C_3A content of less than 8%" [49]. That phrase is followed by the following parenthetical qualification: "for cements with low C_3A". They mean less than 8% and not a Type V cement, whose upper limit is 5%. Strangely enough, I cannot find the exact wording attributed to Corr et al. in Ref. [49].

It could be thought that a person who uses (or misuses) the Bureau of Reclamation test data to prove that w/c is the sole factor governing the sulfate resistance of concrete "doth protest too much".

The test results of the accelerated tests conducted by the Bureau of Reclamation, starting in the early 1950s over a period of 18 years, were analyzed by Ficcadenti [50]. The tests used soaking the concrete specimens alternately in a sodium sulfate solution and drying in hot air; the expansion of the specimens was measured. What is significant is his finding that the expansion does not progress linearly but slows down or ceases when C_3A has been used up. Ficcadenti [50], therefore, concluded that the C_3A content of the cement is the crucial factor, and w/c has little influence on expansion over long periods.

I do not have enough information to try to reconcile the findings of Ficcadenti [50] with those of Kurtis et al. [47] or, alternatively, to deduce the correct interpretation of the Bureau of Reclamation tests, nor is such a resolution of conflicting conclusions within the ambit of this paper. My purpose in mentioning the varying interpretations of the work of the Bureau of Reclamation is to illustrate the confused and confusing state of our knowledge of sulfate attack on concrete. Possibly, someone will undertake an independent retrospective study of all of the Bureau test results.

3. Part III: Assessment of sulfate attack

In this part, I discuss the approach of various codes to the classification of the severity of exposure conditions prior to construction. This is followed by consideration of tests to determine the damage to concrete in situ. Appendix A of this paper contains selected tables from various sources giving a classification of exposure to sulfates.

3.1. Severity of exposure to sulfates

The preceding discussion of sulfate attack was in qualitative terms, but for practical purposes, we need to relate the degree of severity of field exposure to the extent of the attack on concrete. In the American and British standards (until 2003), there exist two methods of characterization of the exposure: sulfate content in the ground water that is likely to be in contact with the concrete, and the sulfate content in the soil that will be in contact with concrete. Two general comments are pertinent.

First, how comparable are the severities of exposure when determined on water and on soil? This question will be dealt with in a later section, and so will the related issue of the extraction ratio from the soil.

Second, in all cases, the quality of sulfate is expressed in parts of SO_4 in milligrams per kilogram of water, i.e., in ppm (parts per million), generally without consideration of the type of cation in the sulfate. And yet, we have seen that different cations may result in different forms of attack. Incidentally, some earlier standards expressed the sulfate as SO_3. While it is easy to convert the amount of SO_3 into SO_4, care is required when using different documents.

The British Code of Practice for structural use of concrete, BS 8110, 1985 [51], recognizes four classes of exposure, plus a class (less that 300 ppm in groundwater or 1000 ppm in a 2:1 water–soil extract) that has no requirements with respect to the concrete mix. In 1997, there was published British Standard BS 5328 on the selection of mix proportions [43]. This standard recognizes magnesium sulfate as a separate criterion of severity of exposure.

BS 5328 has now been withdrawn, and the current British standard is the European Standard EN 206-1 [52]. With respect to sulfates, expressed as SO_4, three classes of severity are recognized (the harmless condition not being considered). It is interesting to note that the classification by exposure classes and the limiting values in EN 206-1 are not recommended for use in the U.K. Instead, a complementary British Standard to EN 206-1, known as BS 8500-1, has been published. One shortcoming of EN 206-1 is that it uses the total sulfate in the soil (obtained by hydrochloric acid extraction) but allows water extraction if local experience is available. In the U.K., between 1939 and 1968, the sulfate content in the soil used to be determined by acid extraction (although this was not explicitly stated), and this greatly overestimated the severity of exposure.

In the United States, ACI Building Code 318 [53] recognizes three classes of exposure in terms of SO_4 (plus the harmless condition) and prescribes a maximum value of the water/cementitious material ratio, the minimum compressive strength, and the type of cement. The latter is selected on the basis of the C_3A content. The Commentary on ACI 318 lists "other requirements for durable concrete exposed to concentrations of sulfate"; these include adequate compaction, uniformity, and sufficient moist curing [53]. The importance of compaction and curing was emphasized earlier in this paper.

In addition to design codes and standards, in the U.K., there exist so-called Digests, which are nonmandatory guidance documents, perhaps like the ACI guides. Guides relating to the sulfate resistance of concrete have existed for many years, but were revised from time to time. A selection of extracts from various American, British, European, and Canadian sources giving a classification of the severity of exposure to sulfates is given in Appendix A.

In 2002, there was published a new BRE Special Digest 1 [42], dealing with concrete in aggressive ground. It is a long and complex four-part document, which provides design guidance for various types of buildings. Part 1 introduces six classes of aggressive chemical environment in terms of soluble sulfate, magnesium, potential sulfate from oxidation of pyrite (not considered in the present paper), pH, and mobility of ground water [54].

The class of aggressive chemical environment is combined with the ‘‘structural performance level’’, which is categorized according to the service life, criticality of use, and structural details. This useful innovation distinguishes three levels: (i) structures expected to have a life of less than 30 years and unreinforced house foundations; (ii) structures with an expected life of 30 to 100 years; and (iii) structures expected to have a life in excess of 100 years and critical parts of structures, such as slender elements and hinges. This approach represents a great improvement on the traditional approach in existing codes, which uses a one-size-fits-all approach.

The combination of the class of aggressive chemical environment with the structural performance level determines the so-called design class. There are 13 design classes, each of which can be combined with three structural performance levels, and three cross-section thicknesses. Hence, the number of ‘‘additional protective measures’’ required is obtained; these include surface protection, a sacrificial layer, and use of controlled permeability formwork. Finally, this information leads to mixes specified in terms of type of cement (or cement group, in European parlance), minimum cement content, and maximum w/c.

It is useful to note that the size of the cross-section of the concrete member is taken into consideration in determining the structural performance level. This means that this approach implicitly accepts that some attack on the surface of concrete can be tolerated in thicker sections [54]. However, fine-tuning according to the thickness of individual members on a single site is, in my opinion, impractical in terms of mix delivery on site.

Consideration of mobility of ground water in an explicit manner, rather than casually, and advice on the determination of mobility of the water, introduced in Special Digest 1 [42], are a very useful innovation.

As I mentioned earlier, BRE Special Digest 1 [42] is not a mandatory document but is intended to serve as a guide. It is thus a competent source of advice for a competent engineer, but it should not be used as a rulebook to be followed, more or less, blindly.

Those concerned with investigations of allegedly damaged concrete should note that the design of structures using Part 3 of the Special Digest 1 ‘‘is not intended as a basis for assessing the risk of sulfate attack to existing properties’’ [42].

The system devised in the BRE Special Digest 1 [42] is sound and admirable. Alas, in my view, it looks like a product of an extensive desk study, with little consideration of the realities on site, where, often, there does not exist a single set of physical conditions. I shall discuss the variability of site conditions in a later section.

I realize that it is not easy to write a comprehensive alternative set of recommendations for the choice of the concrete mixes to ensure resistance to sulfates, but I suspect that what is proposed in BRE Special Digest 1 is unlikely to find favor with designers. The choice of a mix is on the basis of 16 classes of aggressive environment, for three structural performance levels, and three thicknesses of the concrete member, compounded by ‘‘additional protective measures’’ that raise or lower the quality of the concrete mix. All this is a true *embarras de richesse*. Giving a choice of all the 124 single malt whiskies at the same time might be too much for a regular drinker.

What should be of greater concern are the class boundaries of the various exposure conditions. In a sense, they are arbitrary because they have not been calibrated by the measurement of recorded incidence of damage to concrete caused by sulfate attack. This, of course, would not be easy because of the variability of conditions in the field. Hence, although we are not sure about the exact position of class boundaries, the approach currently used is qualitatively satisfactory. However, notice should be taken of the predominant cation in the sulfate because this is relevant to the efficacy of using a Type V cement.

3.2. Extraction of sulfate from soil

The various codes classify the degree of exposure of concrete to sulfates according to the sulfate content in ground water or in an extract from the soil. Presumably, it is intended that either of these determinations should result in the same class of severity of exposure for the purpose of mix selection.

The reason for the dual approach is that where a borehole does not contain static or flowing ground water, it is necessary to resort to testing the soil. Where there is a choice, it is water that should be tested; this is explicitly recommended by BRE Special Digest 1 [42].

Why then am I discussing the two test methods? Whereas determining the sulfate content in water is a matter of a simple chemical procedure, in the case of an extract, the outcome of the same procedure will be affected by the method of obtaining the extract. The method is by no means standardized or uniform in various codes.

I should like to add that I am discussing the determination of the content of water-soluble, and not of acid-soluble, sulfates. The latter method is used in some codes for certain purposes, but I view it as inappropriate because the attack of concrete, if any, occurs by water in contact with its surface penetrating into the interior of the concrete. On the other hand, acids may dissolve sulfates that have only a low solubility in water.

The extract should be described by mass of water per unit mass of soil; this varies from 1:1 to 20:1. I understand that the California Department of Transportation [55] uses an extraction ratio of 3:1, and the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers use 5:1. The significance of the extraction is that, under some circumstances, a high extraction ratio will give a higher sulfate content, and this will lead the designer to choose a concrete mix with superior properties than otherwise would be the case.

Many earlier standards were silent on the extraction ratio. In consequence, and not surprisingly, when a party interested in demonstrating a high sulfate content was in control, it used a high ratio, sometimes as high as 20:1, whereas the opposing party would use a very low ratio, possibly down to 1:1. The recent Special Digest 1 prescribes a 2:1 extraction ratio [42]. This has been used in the U.K. since 1975 and replaces the 1:1 ratio used between 1968 and 1975. The change was made because, with the 1:1 ratio, some clays yielded an insufficient amount of extract water for chemical tests; this problem, however, could be remedied by taking a larger sample of soil.

The significance of the extraction ratio depends on the type of sulfate prevalent in a given situation. Specifically, if sodium and magnesium sulfates are dominant, and calcium sulfate is a minor component, then a low extraction ratio may be appropriate because both sodium and magnesium sulfate have a high solubility, so that even a small amount of water will result in an appropriate measure of sulfate exposure. On the other hand, with calcium sulfate, a low extraction ratio may lead to a measured value of sulfate content corresponding to the maximum solubility of calcium sulfate, whereas the actual sulfate content may be much higher. This situation obtains when the sulfate content is expressed in milligram of sulfate per kilogram of soil.

To give an example, assume that the content of calcium sulfate in the soil is such that there are 10,000 mg of sulfate per 1 kg of soil. Now, the low solubility of calcium sulfate means that a maximum of 1440 of sulfate (SO_4) can be dissolved in 1 kg of water. Thus, a 1:1 extract would indicate 1440 ppm, which would be reported as 1440 mg/kg of soil, although the actual content is 10,000 mg/kg. Now, using an extraction ratio of 20:1, the amount of calcium sulfate would be 10,000 ppm or 10,000 mg/kg, which is the actual value in the soil because all the sulfate in the soil would be dissolved without reaching saturation of the water.

I hesitate to offer an opinion on the choice of an appropriate extraction ratio or on the class of boundaries for the severity of exposure to sulfates. However, I find the argument for expressing the limits in terms of sulfate in an extract solution, and not as sulfate in the soil, to be compelling. Thus, the European approach is preferable to the ACI method.

I believe ACI is considering a change in the method of expressing the sulfate content in soil. One proposal is to use the term "sulfate activity index". This term is uninformative. Another proposal is to use the term "sulfate in pore water of saturated soil". This is cumbersome and may mislead some people who associate the term pore water with water in the hydrated cement paste. Moreover, the soil tested may not always have pores in it saturated, and the extract may contain more water than could fill the pores in the soil in situ. My support, for whatever it is worth, is for "sulfate in extract solution", with the extraction ratio uniquely defined.

The difficulty of establishing the sulfate content of the soil is illustrated by the data of Marchand et al. [56] who compared the values obtained by extraction using the California Transportation Procedure 417 (Method A; [55]) with tests on centrifuged liquid from the soil, followed by ion chromatography, to yield the value of sulfate (Method B). Marchand et al. [56] present a plot relating these two sets of test results but make no statement about confidence limits. By eye, there seems to be a large scatter; for example, here are four pairs of results (in ppm of SO_4):

Method A	7000	7000	10,000	9000
Method B	5000	11,000	8000	11,000

Unless a statistically sound explanation of these results is available, we should beware of making definite claims about relationships. Rather, we should establish a reliable and universally acceptable method of determining the sulfate content of the soil.

Finally, there exist some newer chemical methods, such as inductively coupled plasma atomic spectroscopy, and they may not yield the same results as other methods, but this is for chemists to say.

3.3. Taking soil samples

At the beginning of this paper, I admitted that even though I am not a chemist, I felt justified in writing about chemical attack on concrete. At this stage, I would like to write about some soil aspects of sulfate attack on concrete, even though I am not a geotechnical engineer. (Of course, these topics were included in my civil engineering curriculum.) Why? The answer is that both chemical and geotechnical considerations are provided for engineering purposes: construction is preeminently an engineering matter.

In documents dealing with sulfate attack on concrete, there is generally no guidance on taking soil samples. There is a recent exception to this, namely, the BRE Special Digest 1 [42], which gives advice on taking samples and on the interpretation of the test results on sulfates in water and in the soil. Generally, the distribution of sulfates in soil varies both horizontally and vertically. In the U.K., often, the top meter or so of soil is relatively free from sulfates because of leaching by groundwater [35]. On the other hand, in dry regions, where the rate of evaporation is high, there may be a higher concentration near the surface [35].

In my, admittedly limited, experience of large sites for multiple buildings construction, I learned that there may be a considerable variability in the different factors involved. For example, if the site is sloping, the conditions of groundwater may vary from place to place. They will vary also depending on whether sampling was done just after a heavy rainfall or after a prolonged period of drought. The conditions can also vary on a given site in consequence of excavation elsewhere. The combinations are numerous. And yet, for practical purposes, the foundations for a number of, say, houses cannot be finely tuned to the conditions established at every individual site. Moreover, the measurements may well be taken prior to exact siting of every individual house.

At the same time, it would be prohibitively expensive to go on testing until the worst spot has been found and to make the conditions there govern the entire site. Nevertheless, such an extreme approach has been taken: it was said that if one part of the land has a high sulfate content and the rest only a low or even negligible content, then the high content governs. The opinion expressed was: "take enough results and you'll find that it (high sulfate content) exists throughout". In other words, all the foundations have to be designed for the most severe condition encountered. Accepting such reasoning leads to demonstrably nonsensical consequences.

Let us say that we propose to construct 100 individual homes. Let us assume that there is an adjacent existing development on a soil in which a high sulfate content was established some time ago. Given that the soil and sulfates are not aware of ownership boundaries, a high sulfate content in the soil on an adjacent property means, according to the logic quoted above, that all 100 proposed homes need to have foundations that will resist the high sulfate content on the adjacent property. It follows further that no testing for sulfate is necessary. This saves money that would otherwise be used for testing, but a great deal of money *may* be wasted by an unnecessary provision for resistance to a high sulfate content in the soil. Indulging in *reductio ad absurdum*, the conditions on a single site could be extrapolated to be valid further and further away.

Some help in solving this dilemma is offered by Special Digest 1 [42], which recommends calculating a characteristic value, rather than taking the maximum value, except when only a small number of soil samples has been taken. When there are five to nine results, the mean of the two highest values is taken as the characteristic value. And when there are more than 10 results, the mean of the highest 20% is used [42].

This advice is helpful, but it is less clear what to do on very large sites, such as those for, say, 100 individual houses. Much depends on the uniformity of soil in geological terms and on the extent of disturbance and grading that the soil has been subjected to. I am not proffering advice because this problem is more within the province of soil or geotechnical engineers.

Because water is essential for sulfates to interact with concrete, the possible movement of water should be considered in the construction of foundations. When these are shallow, the isolation of concrete from the ambient material is possible. Alternatively, or additionally, drainage around the foundations can be provided. Similarly, a means of carrying rainwater from the roof away from the foundations should always be provided, even if the climate is thought to be dry.

I am sure I am not alone in having observed a drainage system vitiated by the house owner who extended the garden right up to the house wall and then provided continual watering so as to make the concrete almost permanently wet. The situation can be aggravated by the use of fertilizers for plants in close proximity to foundations.

Many fertilizers contain potassium and magnesium sulfate. I understand that the so-called greening agents, which impart a vivid green color to a lawn, contain ammonium sulfate. This salt is known to be particularly aggressive to concrete. The relevance of the above statement is that gardening procedures, including lawn and garden irrigation, can greatly alter the sulfate conditions that existed at the time of construction. Now, changes in the conditions in service are beyond the scope of those involved in construction. Even if instruction handbooks and injunctions given to homeowners do not allow the irrigation water to run off onto foundations, such an approach is usually ineffective. Either a complete moisture barrier around the foundations needs to be provided (and this is not cheap or easy) or the homeowner has to bear the consequences of his or her actions.

At the other extreme, once the soil has been compacted, there may be limited availability of water, so that some sulfates in the soil will not be available for reaction with hydrated cement paste. According to Pye and Harrison [57], "a dry site where the depth of the water table is difficult to find in any season is unlikely to give rise to significant chemical attack on concrete placed on it".

3.4. My tests

I am not a newcomer to the study of sulfate attack on concrete. In 1969, I published a paper about my tests on the behavior of concrete in saturated and weak solutions of magnesium sulfate [29]; the period of exposure was 1000 days. What is relevant to this paper is the type of tests that I performed to assess the deterioration of concrete. These were: a change in the weight of the specimen, a change in the dynamic modulus of elasticity, and a change in the length of the specimen. I did not use a determination of the compressive strength of concrete because this is a destructive test so that, at each age, a different specimen would have been tested, and having many dozen specimens for a single mix would have been impractical. Compressive strength can be determined on cores when the health of a structure at a particular moment is at issue.

In my 1969 paper, I noted that "the changes in length, weight, and frequency do not all show the same tendency, as the influence of reactions of corrosion (sulfate attack) on the three properties of concrete varies" [29]. This begs the question: which test is the most appropriate?

The answer is that much depends on the mechanism involved in the attack, which, in turn, depends on the cation of the attacking sulfate. Calcium sulfate can result in the formation of ettringite, which may (but not necessarily so) lead to expansion. This can occur with sodium sulfate as well, but sodium sulfate also leaches calcium hydroxide, and this would result in a decrease in the dynamic modulus of elasticity and, possibly, also in a decrease in weight.

I have couched the last paragraph in rather tentative terms because, in a sulfate solution, just as much as in water, cement continues to hydrate, and this initially improves the properties of the specimen. It is only in the longer term that the sulfate reactions dominate over the consequence of continuing hydration.

Now, magnesium sulfate has a deleterious effect on various properties of concrete and, specifically, on compressive strength, in consequence of the decomposition of C-S-H. However, if magnesium hydroxide (brucite) is allowed to remain undisturbed on the surface of the concrete specimen, a protective layer will be formed, and the sulfate attack will be self-limiting.

In view of the above statements, I have to admit that my tests were not structured as well as I would do now, but then, hindsight has a 20/20 vision. The difference in the action of various sulfates should be borne in mind; however, on site, it is also possible for more than one type of sulfate to be involved at the same time.

3.5. Change in compressive strength

If there is a dispute about whether concrete in a structure has suffered damage due to sulfate attack, testing may be necessary. It is well known that the presence of voids in concrete decreases its compressive strength, the rule of thumb being that 1% voids decrease the strength by about 5.5%. It is therefore logical to expect leaching of products of hydration or the formation of cracks to cause a reduction in the compressive strength. Thus, if cores taken from an existing structure have a lower strength than the 28-day strength at the time of placing the concrete, then it is reasonable to conclude that the concrete has suffered damage, possibly owing to sulfate attack.

This approach has been used on a number of occasions. A few examples should suffice. Ibrahim et al. [58] wrote, ‘‘the effectiveness of these materials (surface treatment) in decreasing the sulfate attack was evaluated by measuring the reduction in compressive strength’’. Harrison [5] determined the changes in compressive strength to establish whether sulfate attack had taken place in 15-year long field exposure tests. These findings were cited with approval by Figg [59]. In his laboratory studies, Brown [60] also used the loss of compressive strength of mortar specimens to assess the damage by sulfates. Al-Amoudi et al. [61] have also used the change in compressive strength in their study of the performance of blended cements exposed to magnesium and sodium sulfates.

I would like to emphasize that what was measured in the references reviewed above is the change in the compressive strength consequent upon sulfate attack (or only exposure to sulfates) and not the level of strength as such, which depends on the mix used. I subscribe to the view that determining the *change* in compressive strength is one means of detecting sulfate attack; the absence of a reduction in strength indicates that there has been no attack, even if some reactions have taken place. It is unfortunate that I have been wrongly listed as a reference in support of the view that the determination of the compressive strength of cores is irrelevant to proving that sulfate attack has or has not taken place [62]. I am also misrepresented in the quotation from my paper on high-alumina cement concrete by the words: ‘‘strength, especially compressive strength, is an inappropriate measure of durability’’ [6]. The common first author of these two references is Skalny.

I am citing the above spurious reliance on my publications because the difference between the level of strength and the change in strength is vital. What is significant with reference to sulfate attack is that an increase in strength (except at very early ages) is inconsistent with such an attack, i.e., with deterioration of concrete by the action of sulfates.

Laboratory tests on concrete exposed to sulfates are generally performed on unstressed specimens, whereas, in some service situations, stress may act concurrently with sulfate attack. Laboratory tests on concrete under stress have shown that ‘‘the durability of concrete under sodium sulfate attack is affected by the state and level of sustained stress’’ [63]. However, the stress–strength ratio applied was generally higher than would be the case in practice. Nevertheless, the effect of stress on damage during exposure to sulfates represents an additional complication in the study of sulfate attack.

3.6. ‘‘Layered damage’’ and tensile strength

In the absence of documents and clear-cut procedures for the assessment of damage caused by sulfate attack, there is a danger of one-off methods, sometimes quite fanciful, being used to prove one’s point. Two of these may be worth mentioning: the use of tensile strength (to the exclusion of compressive strength) and the demonstration (real or alleged) of so-called layered damage.

It is to be expected that when an attack on concrete takes place from one face of a concrete element, the extent of damage will be progressive with the distance from the exposed surface. This, for example, is observed in the case of carbonation.

A much more complex situation has, however, been proposed by some investigators who have introduced the concept of layered damage, which implies that concrete consists of a number of layers parallel to the exposed surface, these layers having distinct properties. In consequence, if a tensile force is applied at right angles to the layers, failure will occur at a low tensile strength, while a compressive force in the same direction would not be affected by the layered nature of the damaged concrete.

A ‘‘proof’’ of the existence of layered damage was provided by Ju et al. [64] by their measurement of ultrasonic pulse velocity in different layers of cores taken from a concrete slab. I have reviewed that work in a book [7] so that only a brief mention here should suffice. The pulse velocity measurements were taken at levels 15 mm apart on four equally spaced diameters, and the average values of velocity at each level were reported. On applying a statistical analysis, I found that the mean value of *all* eight levels lay within 95% confidence limits for *one* level, so that the differences between the mean values at the different levels were not statistically significant. Thus, the presence of layers was not proved. Ju has not challenged my views.

Another "proof" of layer damage was proffered by an expert by the use of the term "layers" by Taylor [32]. On a closer study of his book [32], I found that by the words "surface layers may be progressively removed", he meant laboratory preparation of successive surfaces for examination by X-ray diffractometry.

The assumption of layered damage has led to the proposition that compressive strength tests are incapable of detecting sulfate damage, but that the determination of direct tensile strength does do so. I should make it clear where I stand on this issue because my studies of concretes suspected of having been subject to sulfate attack have shown that the ratio of the splitting tensile strength to the compressive strength of such concretes is the same as for concrete stored under normal conditions [7]. I should point out that I am referring to the splitting tensile strength, and not to the direct tensile strength, because the latter is not standardized by ASTM or by a British Standard, so that a reliable test method is not available. For that matter, testing concrete in direct tension is very difficult because of the danger of eccentricity and of complex end stresses.

The suggestion that the compressive strength is unaffected by sulfate attack, while the splitting tension strength is lowered, is founded upon a 1982 report by Harboe [65]. His tests were performed on cores from the spillway of a dam in Wyoming, built in the mid-1930s, the cores being tested in 1967. Harboe [65] found the compressive strength to be 40 MPa (5900 psi) while the tensile strength was only 2.2% of that value. Normally, the tensile strength would be expected to be about 10% of the compressive strength.

I have no explanation for those results, but they have not been independently confirmed on any other concrete in the succeeding 35 years. Harboe himself did not offer an explanation for what appears to be an anomalous ratio of splitting tensile strength to compressive strength. I find it difficult to accept this anomaly because, if concrete has developed cracks and contains damaged and soft hydrated cement paste, how can its compressive strength remain unimpaired? Proponents of selective influence of alleged sulfate attack upon mechanical properties of concrete have offered no answer to my question about tensile and compressive strengths; my view is that both compressive and tensile strengths must be affected by damage in the same manner.

In addition to quoting Harboe [65], proponents of testing concrete in direct tension also rely on Ju et al. [64], who say, "the uniaxial compression test is *not* indicative or suitable for layer-damaged concrete cylinders" [64]; italics are in the original text. Because the compression test is, according to them, not suitable, they proceed to use direct tension testing, basing themselves on ASTM D 2936-95, which is a test for "intact rock core specimens". Using standardized tests for one material on a different material is a dubious practice.

Further work on tensile testing was done by Boyd and Mindess [66], who interpreted their tests on concrete exposed to sulfates to show that the splitting-tensile strength is less sensitive to damage by sulfate. My interpretation of their results is that they simply conform to the general pattern of variation in the ratio of the tensile strength to compressive strength: this ratio decreases with an increase in strength. Thus, I do not see their tests as supporting the hypothesis of the level of tensile strength being an indicator of sulfate damage.

Moreover, Boyd and Mindess [66] introduced what they describe as a "novel tensile strength test", actually developed in England in 1978, in which gas pressure is applied to the curved surface of a cylinder. Unfortunately, as stated by the inventor of the test, Clayton [67], the value of strength so determined varies according to the choice of loading medium. Perhaps this is why the new method died, and resurrecting it 20 years later does not seem to be profitable.

Locher [68] is cited as having used, as far back as 1966, the tensile strength to determine sulfate resistance of mixes containing slag. This is correct in that he tested 10 × 10 × 60 mm mortar prisms exposed to various conditions [68]. However, given the shape and size of his specimens, the determination of compressive strength was impossible. There is no indication in his paper that he considered the measurement of flexural strength preferable or superior to the compressive strength: this was simply a necessity. Thus, I see reliance on Locher [68] as a proponent of testing mortar (and presumably concrete) in tension, as against testing in compression, to be unfounded.

3.7. Use of scanning electron microscopy

This paper is not concerned with advanced testing techniques, but a brief comment on the use of scanning electron microscopy (SEM) may be in order. In some cases, SEM has been used to establish that sulfate attack had occurred by demonstrating the presence of ettringite. As I understand the situation, SEM does not show the presence of compounds but only of chemical elements, so that compounds are inferred from the quantities of elements that would be present in the given compound. Hence, the presence of, say, ettringite cannot be unequivocally proven.

Moreover, the mere presence of ettringite is not a proof of damage because much depends on whether the ettringite is located in preexisting voids or cracks, or whether the cracks were the consequence of expansion by ettringite formation. Furthermore, Detwiler et al. [69] say that "ettringite is not a sign of sulfate attack unless its concentration is greater than would be expected from hydration of cement''. It is not easy to establish how much ettringite originates from the hydration of cement because, generally, the composition of the cement is not known at the time of the investigation, which is usually several years after construction. Moreover, Detwiler et al. [69] point out that ''in concrete exposed to conditions of wetting and drying, it is possible that sulfate concentration would be higher just below the surface than immediately at the surface due to washing out of ions''. This is highly relevant to the fact that SEM looks at an exceedingly small surface. Typically, using a 1000-fold magnification, the area whose elemental analysis is determined would be $10^{-6} \times 10^{-6}$ m and about 2×10^{-6} m deep. For comparison, human hair has a typical diameter of about 80×10^{-6} m (but there is a decreasing availability of hirsute men).

Because of the small size of the SEM picture, Detwiler et al. [69] recommend the following procedure in the investigation of suspected sulfate attack: ''Step-by-step progression from large scale (tens of meters) to submicroscopic scale (tens of nanometers) gave context to the testing, allowing for selection of specimens that suitably represented the concrete as a whole and for appropriate interpretation of results''. I find this to be a logical approach.

There is also an important influence of relative humidity to which the test specimen is exposed in SEM (except in the latest generation of instruments). This problem has been very clearly considered by Kurtis et al. [70]. They point out that ''characterization techniques that require high vacuum or drying...are not particularly appropriate as artifacts are introduced'' and go on to say that ''methods, such as scanning electron microscopy...have given limited and misleading information about expansion reactions in concrete...'' [70]. Accordingly, they recommend the use of soft X-ray transmission microscopy, which does not require drying or application of pressure [70]. Enthusiasts of SEM might like to take note.

The danger of artifacts created by a high vacuum in the sample chamber is pointed out also by Zelić et al. [71].

3.8. Mathematical modeling

A totally different approach to assessing the damage by sulfates is by the use of mathematical models. They are likely to become a valuable tool but, until they have been calibrated and confirmed by field behavior—and we are not there yet—they will not provide an understanding of the physical phenomena involved. In addition, the boundary conditions applied in a model may be arbitrary and conveniently simplistic.

This can happen with laboratory testing as well. Idorn [72] criticizes laboratory procedures that confine the energy conversion to occur at a constant temperature for reasons of convenience, thus violating the true kinetics of the reactions instead of modeling the reality of concrete.

It is pertinent to quote a statement made in the *Magazine of Concrete Research* about site tests (for a different purpose): ''Conditions on site are not controlled in the same way as in the laboratory, but the benefits of assessing real effects at full scale are obvious, and allow greater confidence in modeling and prediction procedures derived from data presented and, by extrapolation, from data obtained by others'' [73]. It is also said about site data that ''the benefits of being able to confirm predictions made on the basis of short-term or small-scale experiments are evident [73].

What I find highly surprising are mathematical models that ''predict'' that failure has already occurred [64] and, sometimes, even at a date preceding the construction of a building. And yet, the building is still in use and has neither been condemned nor recommended for urgent repairs. As an engineer, I find a theory that is flatly contradicted by reality too difficult to accept.

A problem with models is the choice of boundary conditions, which sometimes may distort the output of a model. For example, one theoretical analysis concluded that ''numerical simulations indicate that the exposure to weak sodium sulfate solutions may yield (sic) to a significant reorganization of the internal microstructure of concrete'' [74], This may be true, but it does not necessarily mean sulfate *attack* and damage to concrete. Support for my statement is given by DePuy [1] (referred to in the same paper): ''Chemical reactions per se in concrete are not necessarily harmful''.

Sometimes, the authors developing theoretical analyses cite numerous references to support their assumptions, but such support is diminished when the references are to tests on concrete mixes of a bygone era, which used cements significantly different from those used nowadays. To give one example, the statement that ''there is overwhelming evidence to show that the degradation also contributes to a significant reduction in the mechanical properties of concrete'' [74] cites: a paper from the 1920s, another from the 1940s, two papers on laboratory tests, including neat cement paste specimens, and a book by the proponent of the theoretical analysis in question. I expect that the use of ''self-support'' is not all that uncommon; after all, every one of us has confidence in our own publications. However, there is the danger that a statement about ''overwhelming evidence'' is likely to be cited again and may well become embedded in the received wisdom, but is it really correct?

Another example of a sweeping generalization is a statement that ''none of them (building codes) contains any specific limit concerning the maximum *w/c* that should be selected for the production of concrete elements to be exposed to negligible levels of sulfate. This is unfortunate since, as emphasized by many authors, potentially destructive conditions may exist although analyses indicate the ground water or soil to have a low sulfate content'' [74]. The references supporting the preceding statement include a paper published in 1968, another published in 1982, and one published in 1994.

I sometimes wonder whether some of the papers discussing concrete in Southern California alleged to have been attacked by sulfates have not been written to establish the damage of those concretes. The models then developed are premised on sulfate attack that had not been physically established in an independent manner. I am not imputing ill will because we can all be subject to what Bertrand Russell, a great philosopher, called "the delusive support of subjective certainty".

There is a more frivolous, but nonetheless valid, support of my view that an opinion repeated often enough, even if incorrect, acquires currency. Lewis Carroll (a Cambridge mathematician, best known as the author of *Alice in Wonderland*) wrote in *The Hunting of the Snark*, published in 1876: "What I tell you three times is true".

4. Part IV: An overview

4.1. Conclusions

Amid the plethora of confusing information and opinion, some general conclusions can be drawn.

The term *attack* should be used only to describe damage to concrete, and not just the fact that reactions have taken place. Furthermore, the term *sulfate attack* should be applied only to the consequences of chemical reactions involving the sulfate ion, recognizing that all reactions have physical consequences. Damage by sulfates where the action is purely physical and which can also be produced by other salts should be termed *physical attack*.

Sulfate attack on concrete structures in service is not widespread except in some areas, and the amount of laboratory-based research seems to be disproportionately large. On the other hand, our knowledge and understanding of sulfate attack in the *field* remains inadequate.

The efficacy of Type V cement as against the use of a low w/c in reducing sulfate attack on concrete is still unresolved, but there is no doubt that dense concrete, well compacted, and well cured is essential.

The significance of the cation in the sulfate is often not appreciated, and yet, this influences the chemical reactions and, thus, the consequences of sulfate attack.

The classification of the severity of exposure of concrete to sulfates is not firmly established and has not been calibrated by the determination of actual damage to concrete under different conditions. A review of classifications used in the past is given in Ref. [75].

The classification of exposure conditions should be clear but also simple. It is not sensible to make elaborate and complex recommendations for the selection of the concrete mix when this classification is predicated on largely uncertain and variable measurements of sulfate in the ground. We are not dealing with an industrial product whose property can be measured precisely, but rather with a variable natural material—soil—that is furthermore disturbed by human operations during construction and by the user of the structure, who may change the drainage or introduce salts while beautifying or maintaining the land around the building.

Drainage of soil around the foundations is important because dry salts do not attack the concrete.

The classification of severity by the determination of the sulfate content in the soil is still a matter of debate. The determination of the sulfate content in the soil should be standardized in terms of the extraction ratio, so that the outcome of the test cannot be varied according to the whim or objectives of the tester. The amount of sulfate should be expressed in milligrams of SO_4 per kilogram of extract water.

The assessment of the extent of damage by the determination of the *change* in compressive strength appears to be reliable. On the other hand, the argument that only tensile strength testing should be used seems to be unfounded.

Mathematical models will be of help in understanding sulfate attack, but so far, they have not been verified.

The use of SEM is not a primary evidence of sulfate attack but should be preceded by tests on a large scale.

4.2. What next?

I would also like to draw some broader inferences. Alas, I believe that the title of this paper is correct: Our knowledge of sulfate attack is confused, and the practitioners in construction lack a clear picture that would enable them to achieve sulfate-resisting structures. Individual researchers know much about specific actions and materials, but the ensemble of their knowledge does not hold together. Unfortunately, a reconciliation of these various opinions is not possible at the present state of our knowledge. What this paper has tried to achieve is to point out the conflicting views, with reasons for the divergences in opinion where these could be ascertained. Thus, we know at least *why* the world of sulfate attack is confused.

The purpose of this paper was to present, as objectively as I could, the problems in assessing the sulfate attack on concrete and to point out the ramifications of generalized statements about damage to concrete. To resolve the various issues, much needs to be done. In other words, we need research.

But what research? Limiting oneself to laboratory tests is not enough. It is not particularly helpful to use accelerated tests on miniscule specimens of neat cement paste or mortar. Realistic conditions of exposure need to be achieved.

I would like to think that this paper will be of use in showing where *practical* research is needed and is likely to pay off. But this research has to be related to *field* conditions of exposure to sulfates.

To say that researchers should be objective is to state the obvious. But with large-scale litigation being the driving force, all too often, research is undertaken to "prove a point" for one party or another, or to secure a "victory". Once a researcher has become bound to his or her paymaster, even if he or she wishes to remain objective, the researcher moves towards a goal and narrows the horizon of his or her work. Moreover, even if this is not the case, he or she is perceived to be biased, and this prompts others working on the topic to prove the researcher wrong. And so it goes on.

I am not saying the above to criticize anybody because we are all fallible "sinners". What we have to beware of, however, is that sweeping assertions that are advanced, without objective and verifiable documentation available for all to see, are not good science. These assertions should not become a part of the body of knowledge upon which all concrete specialists in the world at large can rely.

I am not recommending a mammoth experimental investigation. I believe that much can be gleaned from revisiting published information, both on laboratory test results and on-site observations, as well as from tests on field concrete. This needs to be done by a team of chemists, petrographers, and structural engineers, all working together.

Thomas Macaulay, an early 19th century historian, wrote in *How Horatius Kept the Bridge*:

> "Now who will stand on either hand and keep the bridge with me"

The leader of the team should be a *new* person versed in matters structural, and he or she should be flanked by someone (on the right hand) versed in chemistry of concrete, not just cement, and by someone (on the left hand) experienced in optical microscopy of field concrete.

If eyebrows are raised at the inclusion of structural engineers, my answer is that the objective of establishing facts about sulfate attack and, hence, providing guidance on achieving sulfate-resisting *structures*, is to build structures that will be durable for the required service life under the expected conditions of exposure.

I have used the term "sulfate-resisting structures" rather than sulfate-resisting concrete because, all too often, the field of vision of researchers is limited to the material, whereas the purpose of studying concrete is to build good and durable structures. If we do not succeed in this, competitors to concrete structures—and we must not delude ourselves by thinking that concrete is irreplaceable—will gain the ascendancy. But then, I am a structural engineer and not a backroom researcher; I offer no apology for this.

At the outset of this paper, I said that sulfate has generally not caused significant damage to structures in service. So why this major discussion and recommendations for an independent review and study? The answer is that a lack of clarity permits some people to claim sulfate attack, and, at present, there is no reliable and coherent body of knowledge that would make it easy to distinguish real damage from spurious allegations. The reaction of some designers has already been to overprovide protective measures so as to avoid potential (even if unjustified) claims in the future. This costs the client money and reduces the competitiveness of concrete.

It would be unsatisfactory for this paper to end by observing simply that our knowledge of sulfate attack on structures in service is confusing. On the other hand, we are not yet in a position to present a coherent and complete picture on the basis of which we could select suitable concrete mixes and design durable structures, as well as assess objectively the state and probable future of existing structures. To achieve this, we need to review all the available information and to pull it together, clearly distinguishing laboratory results and field observations. It is the latter—structural behavior—that is of paramount importance, but scientific knowledge is also necessary.

Finally, I would like to make a very general remark: There is an incompatibility between the breadth of specified limits on the properties of cement on the one hand, and on the other, the more demanding expectations of concrete, which can be achieved by the use of cementitious materials with specific properties. Now, portland cement needs to comply only with very broad limits on strength, fineness, and chemical compounds. At the same time, requirements such as compatibility with superplasticizers or ensuring sulfate resistance need close and narrow controls. Whenever this issue is raised, cement manufacturers reply that you cannot have a high-tech material for the price of a low-tech one. Which do we want? Consideration of this dilemma requires a separate study.

An essential part of sulfate is sulfur, and the element sulfur has long been known to contribute to damage. In *King Lear*, Shakespeare says:

> "There's hell, there's darkness,
>   there is the sulphurous pit,
> Burning, scalding, stench, consumption;
>   fie, fie, fie!"

and also

> "Singe my white head!"

which, given my white head, is an appropriate ending to this paper.

Appendix A. Classification of exposure to sulfates

This Appendix contains a selection of tables from American, Canadian, British, and European sources giving a classification of exposure to sulfates (Tables 1–15).

Table 1
ACI 201.2R (1997) Guide to durable concrete. ACI 332R (1984, reapproved 1997) Guide to Residential Concrete

Class of exposure	Concentration of sulfates as SO_4	
	In ground water (ppm)	Water soluble in soil (%)
Mild	< 150	< 0.10
Moderate	150–1500	0.10–0.20
Severe	1500–10,000	0.20–2.00
Very severe	>10,000	>2.00

Table 2
ACI 318 (1983 through 2002) Building Code

Class of exposure	Concentration of sulfates as SO$_4$	
	In water (ppm)	Water soluble in soil (percent by weight)
Negligible	< 150	< 0.10
Moderate	150–1500	0.10–0.20
Severe	1500–10,000	0.20–2.00
Very severe	>10,000	>2.00

Table 3
U.S Bureau of Reclamation *Concrete Manual* (1966)

Class of exposure	Concentration of sulfates as SO$_4$	
	In water (ppm)	Water soluble in soil (%)
Negligible	0–150	< 1000
Positive	150–1000	1000–2000
Considerable	1000–2000	2000–5000
Severe	>2000	>5000

Table 4
Uniform Building Code (1991)

Class of exposure	Concentration of sulfates as SO$_4$	
	In ground water (ppm)	Water soluble in soil (percent by weight)
Negligible	< 150	< 0.10
Moderate	150–1500	0.10–0.20
Severe	1500–10,000	0.20–2.00
Very severe	>10,000	>2.00

Table 5
Canadian Standard A23.1.94

Class of exposure	Concentration of sulfates as SO$_4$	
	In ground water (ppm)	Water soluble in soil (%)
S-3 moderate	150–1500	0.10–0.20
S-2 severe	1500–10,000	0.20–2.0
S-1 very severe	>10,000	>2.0

Table 6
European Standard EN206-1:2000

Class of exposure (chemical environment)	Concentration of sulfates as SO$_4$		Concentration of magnesium in ground water (ppm)
	In ground water (ppm)	In soil (ppm total)	
Slightly aggressive	200–600	2000–3000	300–1000
Moderately aggressive	600–3000	3000–12,000	1000–3000
Highly aggressive	3000–6000	12,000–24,000	3000 to saturation

The extraction of SO$_4$ from soil is by hydrochloric acid. However, water extraction may be used if experience is available in the place of use of the concrete.
Clay soils with a permeability below 10^{-5} m/s may be moved into a lower class.

Table 7
British Building Research Station: notes on concrete in sulfate-bearing clays and ground waters, *The Builder*, July 7, 1939, p.29. This table was incorporated into British BRE Digest 31 (1951)

Class of exposure	Concentration of sulfates as SO$_3$	
	In water (ppm)	In clay (percent by weight)
1	< 300	< 0.2
2	300–1000	0.2–0.5
3	>1000	>0.5

Analysis of ground water is preferred to that of clay.
In some cases, it may be found that the results of the ground water and clay analyses lead to different classifications; the more severe classification should be adopted.

Table 8
British Code of Practice CP 110:1972

Class of exposure	Concentration of sulfates as SO$_3$		
	In ground water (ppm)	In 2:1 water–soil extract (g/l)	Total in soil (ppm)
1	< 300	–	< 2000
2	300–1200	–	2000–5000
3	1200–2500	1.9–3.1	5000–10,000
4	2500–5000	3.1–5.6	10,000–20,000
5	>5000	>5.6	>20,000

For classes 3 to 5, if calcium sulfate is predominant, the water–soil extract may give a lower class of exposure than the total SO$_3$.
To convert SO$_3$ to SO$_4$, multiply by 1.2.

These tables show that it is not only the sulfate content boundaries of the various exposure classes that vary, but also the water–soil extraction ratios (sometimes unspecified), as well as the method of determining the sulfate content: acid or water soluble. Furthermore, the concentration of the sulfate in the soil is sometimes expressed per unit mass of soil; in other cases, per unit mass of extraction water. The rationale of these various approaches is not self-evident.

Even a quick look at the ensemble of the classifications of exposure conditions and at the class boundaries shows substantial differences. However, their full significance can

Table 9
British Code of Practice CP 8110:1985

Class of exposure	Concentration of sulfates as SO$_3$		
	In ground water (g/l)	In 2:1 water–soil extract (g/l)	Total (ppm)
1	< 0.3	< 1.0	< 2000
2	0.3–1.2	1.0–1.9	2000–5000
3	1.2–2.5	1.9–3.1	5000–10,000
4	2.5–5.0	3.1–5.6	10,000–20,000
5	>5.0	>5.6	>20,000

If calcium sulfate is predominant the water–soil extract may give a lower class than total SO$_3$.
To convert SO$_3$ to SO$_4$, multiply by 1.2.

Table 10
British Standard BS 5328:1997 Guide to specifying concrete

Class of exposure	Concentration of sulfate as SO_4			Concentration of magnesium	
	In ground water (ppm)	In soil		In ground water (ppm)	In soil (g/l)
		By acid extraction (%)	By 2:1 water–soil extract (g/l)		
1	< 400	< 0.24	< 1.2	–	–
2	400–1400	*	1.2–2.3	–	–
3	1500–3000	*	2.4–3.7	–	–
4A	3100–6000	*	3.8–6.7	≤ 1000	≤ 1.2
4B	3100–6000	*	3.8–6.7	>1000	>1.2
5A	>6000	*	>6.7	≤ 1000	≤ 1.2
5B	>6000	*	>6.7	>1000	>1.2

Consider both SO_4 and magnesium.
Classification on the basis of groundwater is preferred.
Higher values are given for the water–soil extract in recognition of the difficulty of obtaining representative samples and of achieving a comparable extraction rate to that from ground water.
* Classify on the basis of 2:1 water–soil extract.

be assessed only by a consideration of the properties of the concrete mixes corresponding to the various exposure classes.

Such a consideration is not possible because the properties of the various cements were not the same in the different countries. Moreover, the actual properties of cements varied over time, and the standard requirements for cements were also not immutable.

I am not saying that such a study is impossible, but it would be a very major undertaking. Moreover, the study would be meaningful only if we had a record of long-term performance of the various concretes under the actual exposure conditions. Alas, with very few exceptions of long-term field studies, one in California and one in England, no such information is available.

The preceding discussion exemplifies our dilemma: we do not know whether the exposure class boundaries are "correct" because they have not been calibrated or verified. This then is the reason for the paper titled, "The confused

Table 11
British BRE Digest 90 (1968)

Class of exposure	Concentration of sulfates as SO_3		
	In ground water (ppm)	In 2:1 water–soil extract (g/l)	Total (ppm)
1	< 300	–	< 2000
2	300–1200	–	2000–5000
3	1200–2500	2.5–5.0	5000–10,000
4	2500–5000	5.0–10.0	10,000–20,000
5	>5000	>10.0	>20,000

To convert SO_3 to SO_4, multiply by 1.2.

Table 12
British BRE Digest 174 (1975)

Class of exposure	Concentration of sulfates as SO_3		
	In ground water (ppm)	In 2:1 water–soil extract (g/l)	Total (ppm)
1	< 300	–	< 2000
2	300–1200	–	2000–5000
3	1200–2500	1.9–3.1	5000–10,000
4	2500–5000	3.1–5.6	10,000–20,000
5	>5000	>5.6	>20,000

To convert SO_3 to SO_4, multiply by 1.2.

Table 13
British BRE Digest 250 (1981)

Class of exposure	Concentration of sulfates as SO_3		
	In ground water (ppm)	In 2:1 water–soil extract (g/l)	Total (ppm)
1	< 300	< 1.0	< 2000
2	300–1200	1.0–1.9	2000–5000
3	1200–2500	1.9–3.1	5000–10,000
4	2500–5000	3.1–5.6	10,000–20,000
5	>5000	>5.6	>20,000

To convert SO_3 to SO_4, multiply by 1.2.

Table 14
British BRE Digest 363 (1991)

Class of exposure	Concentration of sulfate as SO_4			Concentration of magnesium	
	In ground water (ppm)	In soil		In ground water (ppm)	In soil (g/l)
		By acid extraction (%)	By 2:1 water–soil extract (g/l)		
1	< 400	< 0.24	< 1.2		
2	400–1400	*	1.2–2.3		
3	1400–3000	*	2.3–3.7		
4a	3000–6000	*	3.7–6.7	< 1.0	< 1.2
4b	3000–6000	*	3.7–6.7	>1.0	>1.2
5a	>6000	*	>6.7	< 1.0	< 1.2
5b	>6000	*	>6.7	>1.0	>1.2

* If >0.24, classify on the basis of 2:1 water–soil extract.

Table 15
British BRE Special Digest 1 (2002). British Standard BS 8500:2000

Class of exposure	Concentration of sulfate as SO_4		Concentration of magnesium	
	In ground water (ppm)	In 2:1 water–soil extract (g/l)	In ground water (ppm)	In 2:1 water–soil extract (ppm)
DS-1	< 400	< 1200		
DS-2	400–1400	1200–2300		
DS-3	1500–3000	2400–3700		
DS-4a	3100–6000	3800–6700	≤ 1000	≤ 1200
DS-4b	3100–6000	3800–6700	>1000	>1200
DS-5a	>6000	>6700	≤ 1000	≤ 1200
DS-5b	>6000	>6700	>1000	>1200

Consider both SO_4 and magnesium.
Static and mobile water are distinguished.
The value of pH of the water is also considered.

world of sulfate attack" and this is why the entire arena of sulfate attack in *the field* needs to be studied.

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