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A review of the experience of thaumasite sulfate attack by the UK Highways Agency

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Abstract

The paper summarises and reviews the UK Highways Agency experience of thaumasite sulfate attack.

Thaumasite sulfate attack was found in February 1998 in a number of bridge foundations and buried columns on the M5 Motorway in Gloucestershire. The paper will highlight the investigation of these structures, and assess the implications of the results of the extensive testing undertaken at these sites, for other structures.

Subsequent to the discovery of thaumasite in Gloucestershire the Highways Agency participated in the Thaumasite Expert Group set up by the Minister for Construction. The report produced by the group influenced the development of the Agencies own guidance. Investigations were undertaken nationally using risk based criteria, to determine whether the occurrence of thaumasite was a local phenomenon, or of more widespread concern. Concurrently guidance was also issued for managing and minimising the risks of thaumasite in new construction, and this culminated in the development of a new specification for buried concrete. There are also implications for ground investigations, and these will be discussed.

The paper will also highlight the case study of the A1 Mally Gill Bridge in County Durham, where a markedly different set of circumstances gave rise to thaumasite sulfate attack in a foundation.

The Highways Agency has been involved with the development of improved guidance, as a result of the Expert Group Report, to ensure that that there is a consistency of approach across the construction industry. The paper will acknowledge that there are still many unknowns, particularly the mechanism governing the occurrence of thaumasite and the speed of thaumasite production.

A particular aspect of concern to the Highways Agency is the ongoing management of structures that are known to be or may be affected by thaumasite.

What are the methods for investigation and testing and are there suitable methods for remote detection?

Do we need to introduce new inspection regimes?

What are the requirements for the repair of thaumasite affected structures?

Mention will be made of some of the research in this area, particularly the trial of repaired concrete at Moreton Valence.

The paper will summarise the lessons learnt so far from the thaumasite experience, the implications for the future management of structures in potentially higher risk areas, and identify research needs.

Keywords: Thaumasite; Structures; Highways Agency

1. Background

In early 1998, in the course of other maintenance and bridge strengthening works, unusual concrete deterioration was found to have occurred in the foundations and buried columns on a couple of bridges on the M5 Motorway in Gloucestershire. Subsequent investigations proved that the observed defects were the result of thaumasite sulfate attack, and the Highways Agency were faced with a number of immediate questions.

How serious was the attack?

Were there structural implications?

How many bridges were affected?

Was it a local problem, or national?

What were the costs?

How do we undertake repairs or other remedial action?

Were there any faults in the original design and construction?

Were there implications for new construction?

What were the implications beyond the Highways Agency interests?

Do we need to carry out any research?

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This paper covers the responses to some of these questions, and summarises the current situation, and identifies other issues for the future.

2. Tredington-Ashchurch Bridge

Thaumasite sulfate attack was first observed in early 1998 on a Highways Agency structure in the substructure of the Tredington-Ashchurch Bridge, an overbridge carrying a local road over the M5 Motorway situated between Junctions 9 and 10 in Gloucestershire. At about the same time similar, but less severe defects, were also found in Grove Lane Bridge foundations, also on the M5, but further south, between Junctions 12 and 13.

Tredington-Ashchurch is a four span overbridge with a reinforced concrete deck. Supporting columns are sited in the central reserve and verges, and extend through placed fill for about 5 m to reinforced concrete spread footings. The bridge was built about 30 years ago, to the applicable contemporary Ministry of Transport standards and specifications. Regular structural inspections and testing of the concrete elements above ground have not indicated any observable signs of distress to the bridge in the intervening period.

Planned strengthening work to the columns of the bridge necessitated excavation of some of the backfill surrounding the concrete supports, and in the course of this work site staff observed some unusual deterioration in the exposed concrete. This indicated that some of the concrete surfaces had turned to a 'mushy' consistency, and of 'warty' appearance with evidence of expansion of the residual material. This was unexpected to the say the least, and potentially extremely serious. Diagnosis was first made by our Maintenance Agents, Gloucestershire County Council/Halcrow and later confirmed by the Building Research Establishment (BRE) as thaumasite sulfate attack, after initial concrete samples had been analysed.

Further excavation of the backfill ensued to completely expose the buried columns and the top surface of the foundations, entailing extensive temporary works to provide the necessary support. A large programme of investigation was initiated, including extensive concrete sampling, and soil and groundwater testing, backed up by a thorough laboratory testing regime, and analytical work to correlate soil conditions with concrete defects. The objective was to determine the precise causes of the deterioration, and to see if parameters could be found that would assist future identification of affected structures and their investigation.

Other papers at the conference will deal with the Tredington-Ashchurch case study in much more detail, however suffice to say that it transpired that a number of critical factors in combination had occurred (listed below), which were significant in terms of the deterioration that occurred, and particularly in relation to the severity of the thaumasite sulfate attack:

(a) use of limestone aggregates in the concrete;
(b) use of sulfate and sulfide bearing materials for backfilling around the foundations and buried columns (the soil excavated to construct the foundations contained iron pyrites (sulfides) which started to oxidise after exposure to the atmosphere, and added to the reservoir of available sulfates);
(c) groundwater movements;
(d) physical disposition of the structure (deep foundations and slender concrete elements);
(e) construction regime, particularly the excavation of a large hole through undisturbed ground which was subsequently backfilled with the excavated materials and created a 'sump' around the buried columns;
(f) leaking motorway drainage;
(g) relatively cold conditions.

These factors are illustrated in Fig. 1.

When the deterioration was first observed, a decision was taken to close the local road carried by the bridge, on safety grounds, until such time as the extent and nature of the problem could be determined. Subsequently the defects were found to be surface effects, with a sound central core of concrete remaining. Assessment of the structure showed that the road could be safely reopened whilst the investigations continued.

Based on the information available at the time, and the need to undertake the planned strengthening work on the columns against vehicular impact, it was decided that the columns should be removed. This decision was reached after considerable deliberation, and assessment of costed options, but was influenced by the lack of available information on how to repair structural elements affected by thaumasite. There was also uncertainty as to whether the concrete deterioration had 'stabilised' or was continuing. In the event the most effective strategy was the complete removal of the bridge columns. A system of temporary propping was introduced to allow the columns to be cut up and removed, and a new foundation and supports cast on top of the existing foundation.

Alongside the continuing site investigation work, records of the structure were inspected, and also available geotechnical information. It was evident that the design of 30 years ago had been undertaken in accordance with the standards and specifications of the time, based on the contemporary soil survey. This had duly taken account of the prevailing soil conditions in regard to the occurrence of sulfates. However at that time there was no requirement to consider sulfides, and so in comparison to the rules developed in 1999 in response to the discovery of thaumasite, may have underestimated the influence of sulfates by 2–3 classes (based on BRE Di-

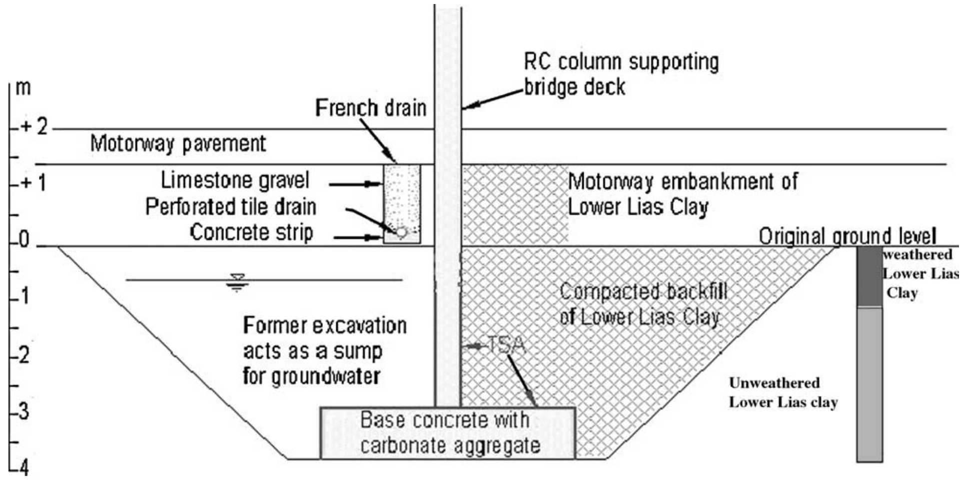

Fig. 1. Diagrammatic representation of Tredington-Ashchurch Overbridge.

gest 363 [1]). Clearly this was very significant, but no fault could be attached to the design or construction process of 30 years ago.

Whilst work was taking place at Tredington-Ashchurch Bridge, a further maintenance contract at Grove Lane Bridge further south on the M5 Motorway, revealed similar signs of thaumasite deterioration in buried concrete, although evidently not as severe or as widespread. In this case after initial investigation, conventional concrete repairs were conducted, after removal of the contaminated concrete.

3. DETR Expert Group

When the concrete deterioration was first discovered in the motorway bridges, it was immediately apparent that the thaumasite attack was very serious, and there were potential implications for all new construction as well as existing buildings and civil engineering structures. The Highways Agency briefed the Department of the Environment Transport and the Regions (DETR) and Government Ministers. It also transpired that BRE, through Dr. Norah Crammond and other colleagues, had been investigating thaumasite related concrete deterioration for nearly 10 years, though the results of this research had not been published, and the current edition of BRE Digest 363 [1], made only passing reference.

A decision was taken at Ministerial level to set up a National Expert Group under the chairmanship of Professor Les Clarke of University of Birmingham, with a remit to investigate thaumasite and report back within six months. This was a very tight constraint, but it was decided that it was essential to provide authoritative guidance at the earliest opportunity to allay public and industry concerns. The Expert Group was derived from a wide cross section of industry and the author was also seconded to represent the Highways Agency.

After considerable discussion and deliberation a report entitled "The Thaumasite Form of Sulfate Attack: Risks, Diagnosis, Remedial Works and Guidance on New Construction" [2] was produced and published in January 1999. As such, it was a significant achievement to publish a very detailed report in such a short timescale, and represented a collaborative and very constructive approach by all the participants, although it was apparent that there were differing views on many aspects, and especially the detailed and complex chemistry involved in thaumasite. It was also apparent that many of the construction industry representatives, had understandable concerns about the commercial implications for their own sector of the market.

The report dealt with the nature and risk of thaumasite and sulfate attack, inspection and testing requirements, structural assessment, remedial works, and a specification for new works, and it is particularly with this last section I was involved. However the report as a whole provided authoritative guidance and recommendations for both new works, and for clients and property owners managing structures and buildings.

The report itself set out 'guidance' in areas where only limited research and case studies had been undertaken, but 'recommendations' where more reliable and well documented information was available. It was acknowledged that not all the answers were known. In particular there was much debate surrounding the mechanisms for occurrence of thaumasite, and the timescales over which it occurred, and in this area further research was essential. Consequently some caution had to be exercised in the detailed recommendations. Overall the report acknowledged that there had been relatively limited occurrence of thaumasite in practice, although laboratory work indicated that conditions for thaumasite could be recreated relatively easily.

One aspect of major importance, particularly as regards new construction, was the need to strike the correct balance between technical issues and commercial interests. To do this the Report had to deal authoritatively with the technical concerns without unnecessarily placing restrictions on the use of the constituent materials to produce concrete. At the time it was published the Report acknowledged that the information was of an interim nature and would need to be updated as more evidence concerning thaumasite become available. It also sought to 'minimise' the risk of future occurrence, rather than the introduction of draconian measures to completely eliminate the risks.

Key facets to the Report were the identification of a number of primary and secondary factors governing the occurrence of sulfate (these are referred to later in the paper) and the classification of thaumasite in affected structures:

(a) 'TSA' for thaumasite sulfate attack where there is significant damage to the matrix of the concrete or
(b) 'TF' for thaumasite formation where thaumasite is present in pre-existing voids in the concrete, but there is no deterioration evident (a latent stage in development of TSA).

The Report also contained practical information on the requirements and methods for identification and testing of concrete and soils in existing structures, to determine if thaumasite is present. Particularly important was the strong message to clients and designers of new structures to undertake a thorough soil survey as part of the design process. This has always been undertaken on road building projects and major civil engineering contracts, but less so on smaller works, and in the domestic property market.

Chapter 9 of the Report provided detailed specification requirements for new construction to minimise the risk of thaumasite sulfate attack, based on the approach already adopted in BRE Digest 363 [1], namely by classifying the sulfate conditions in the soil adjacent to the designed concrete, and by setting a series of restrictions and options for the concrete mixes for each classification. However this approach was extended to adopt a "package" of measures to deal with all ground classifications. It sought to leave as many options open to designers, and particularly to the contracting and concrete supply industries, and all such options were deemed to be equally effective. There was also a desire to keep all guidance and recommendations as simple as possible, and user friendly.

The Report recommendations consisted of detailed materials requirements for concrete mixes and this was allied to a risk based strategy based on different structural performance levels, depending on the required service life and usage of the structure. There was an overarching assumption that the soil/ground water classification had been correctly assessed, and the recommendations in chapter 6 of the Report had been followed, and so consequently the concrete requirements were appropriate to the existing and anticipated future ground conditions. The recommended concrete options followed on from this correct sulfate classification of the soils, with due allowance for any sulfides present. Other related guidance involved consideration of the construction operations and the need, where appropriate, to provide additional drainage around structures, to avoid creating sumps, and where possible not to use reworked sulfate/sulfide bearing backfills.

The concrete materials requirements embodied various controls on cement content, and free water/cement ratios, but adopted a new classification of aggregates by defining different carbonate ranges depending on the amount of carbonate present in the fine and coarse aggregate fractions. In terms of the structural performance level the philosophy adopted was one based on banding of structures into high, normal and low performance, representing a range from long service life structures to low performance for short service life structures, and structures with massive buried concrete foundations or those with slender or critical buried elements. This recognised that thaumasite attack in reality was assumed to be a relatively slow process, and may be insignificant for structures with only a short design life. More restrictive measures would be required when dealing with longer service lives for structures and critical/sensitive buried elements, and conversely less severe requirements imposed where structures had short anticipated service lives.

Since there were a number of areas where the dearth of research data prevented authoritative recommendations for materials, it was agreed that it would be prudent to adopt a 'multi-layered' protection approach, whereby a number of additional protective measures would be instigated, in addition to the material requirements, in appropriate situations. They would represent an important first line of defence and consisted of the adoption of surface protection and drainage requirements, as well as the choice of lower carbonate range aggregates in certain circumstances.

Overall the Expert Group Report provided a number of important messages. The number of structures potentially at risk was not thought to be large, and the structural consequences not generally serious. The deterioration would generally provide early warning signs above ground where significant thaumasite sulfate attack was occurring below ground. There was also not thought to be any significant problem for domestic properties. The Report, if followed would minimise the risk of thaumasite sulfate attack, but also pointed out that not all the answers were known and that further research was needed. It also acknowledged that there was a need to update various documents and in particular BS 5328 [3] and BRE Digest 363 [1].

4. Highways Agency guidance for new construction

In parallel with the work of the Thaumasite Expert Group the Highways Agency set down its own advice for new construction, based on the Expert Group requirements. Interim Advice Note 25 [4] was issued, which laid down requirements to be adopted for highway structures, to minimise the risk of thaumasite sulfate attack in new construction. In particular it assumed that in most cases highway structures would be deemed to be high performance level, as befitting the required 120 year service life. The Advice Note also provided some more specific guidance on drainage around structural foundations and the type of protective coatings appropriate for application to buried concrete in highway structures.

5. Highways Agency strategy for existing structures

However as well as dealing with new construction, the Highways Agency also needed to address the issues of the occurrence of thaumasite in existing structures and particularly whether it was confined to the existing area of Gloucestershire or more widespread. A decision was taken to embark on a national investigation. The Expert Group had identified a number of primary and secondary factors that must coexist or would influence the occurrence or severity of the attack.

Primary factors
(a) presence of sulfates and/or sulfides in the ground;
(b) presence of mobile groundwater;
(c) presence of carbonate generally in coarse and/or fine concrete aggregates;
(d) low temperatures.
Secondary factors
(a) type and quantity of cement used;
(b) quality of concrete mix and compaction;
(c) changes to ground chemistry and water regime resulting from construction;
(d) type, depth and geometry of buried concrete.

Instructions were issued to all the Maintenance Agents in England to commence an investigation. This was divided into two parts, initially based on a risk based desk study, and followed up where necessary with site investigation work. The aim of the desk study was to determine the coexistent presence of the primary factors, and particularly whether carbonate bearing aggregates had been used in buried concrete, and whether structural backfill or adjacent ground included sulfate/sulfides. The assessment was also related to structural significance and network needs, such as planned maintenance work. Of particular interest were structures such as those exhibiting signs of distress above ground, such as settlement or other ground movements or unexplained cracking. This desk study required the critical examination of structures records and soil survey information. In some cases there was insufficient information available, and limited confirmatory material testing was required.

As part of the desktop assessment, structures were prioritised on the basis of risk. Follow up investigations were then conducted on a limited number of the higher priority structures in each area (if necessary), and with judgement made on the ease of access to buried concrete, so as to minimise the amount of temporary works and traffic management required. The aim of the investigation was to determine whether there were any visible signs of thaumasite attack present. If there was, then detailed sampling of the backfill/soils, and concrete coring was undertaken, backed up by laboratory testing. It was important to confirm for the highest priority structures that record information was correct. If all the critical factors were present, both positive and negative results were important. The absence of thaumasite, where carbonate in the aggregates and sulfates/sulfides in the soils was present, was just as important as if thaumasite was found. Significant results of the investigation were passed back to BRE to assist with their future research.

The results of this investigation were very much as expected, and confirmed the findings of the Expert Group Report, and particularly the perceived areas of greatest risk. Apart from the Gloucestershire/Avon area where further cases emerged, the only significant positive result was from County Durham, and is reported later in this paper. However the investigation was invaluable, as it also confirmed that no thaumasite was present in the lower risk areas. Some words of caution about areas of risk are required, in particular about the presence of carbonates in aggregates. Aggregates can and often were transported substantial distances from their quarry source to their eventual place of use and assumptions cannot be made just on the basis of quarry locations.

Although the Expert Group recommendations for concrete and related measures were very detailed, they were not in the form that had been used by the Highways Agency for its published Specification for Highway Works and the related Notes for Guidance in relation to concrete. Consequently, and with the assistance of BRE, a specification for concrete was drawn up to be integrated with the existing requirements for structural concrete, and was included in the republished Specification in June 2001 [5].

6. A1 Mally Gill Bridge County Durham

Other than in the Gloucestershire/Avon area, where further cases of thaumasite were expected and emerged, the only other positive result from the national investigation occurred in County Durham on the Mally Gill Bridge on the A1 in County Durham. Initial desk study assessment had indicated that this bridge and others in the area were at relatively low risk from thaumasite sulfate attack, as there appeared to be no known source of sulfates in the ground. However site investigations in advance of other planned works revealed concrete deterioration on the foundation. This was observed in flanking concrete acting as protection to a concrete hinge detail at the bottom of a deck support column, and was clearly a critical area for the structure. Fortunately the hinge itself and the adjacent concrete appeared to be unaffected. After further investigation and testing by our Maintenance Agents, and also by BRE, the concrete deterioration was confirmed as thaumasite sulfate attack, although the extent and severity was less than that observed at the Tredington-Ashchurch Bridge.

Tests confirmed carbonates in the concrete aggregates, however the source of the sulfate was not so readily apparent. Further work determined that the sulfates originated from a red burnt colliery shale, an industrial waste product, which had been widely used in the 1960s and 1970s. In this instance it had been utilised as an economic road sub-base material, and some was also present in the backfill around the bridge foundations. This produced a significant 'reservoir' of sulfates, and lead to the accumulation of critical levels in the backfill to the bridge foundation. Once again this fitted the pattern identified in the Expert Group Report, which had specifically identified burnt colliery shale as a potential source of sulfates.

Concrete repairs were subsequently undertaken as part of the planned maintenance works. As a result of this discovery it was also necessary to review the findings of the desk study and investigate other structures in proximity to known areas where burnt colliery shale has been used. Further cases have now come to light in this area.

7. Gloucestershire/Avon area

Special investigations were made in the area where thaumasite was initially discovered. The aim was to anticipate the severity of deterioration, in advance of other planned work, so that decisions on the required remedial work could be taken. Further cases were expected, and indeed came to light. About thirty structures are known to be affected, though others are expected in the future. None have deterioration as severe as Tredington-Ashchurch.

8. Updating of Bre Digest 363 [1], BS 5328 [3]

One year on from the original publication of the Expert Group Report, a review was carried out by Professor Les Clarke for the DETR. This confirmed that the originally issued guidance was still fundamentally sound, although it was apparent that a number of documents required urgent updating to achieve consistency. There were also a number of issues that had emerged requiring clarification, as a result of the issued guidance. In particular the requirements in the Report in relation to precast concrete products, the Additional Protective Measures, especially the 'design drainage' recommendation, and Structural Performance Levels needed further explanation and interpretation.

A small committee was set up, under the auspices of BRE, to update BRE Digest 363 [1], which up to the publication of the Expert Group Report, represented the authoritative guidance on sulfate attack. There was a need to ensure that all the issued guidance remained compatible and so this committee retained strong links with the BSI committee updating BS 5328 [3] for concrete, to ensure that there was good coordination and consistency was achieved. The opportunity was taken to update the guidance for concrete requirements based on the experience with the Expert Group Report, and the latest available research information. The replacement Digest was drafted to include Design Guides to assist designers and concrete suppliers. It also included a revised classification of soil conditions based on their aggressive nature (ACEC Class) (for definition refer to [6]).

The work has been completed and is now published as BRE Special Digest 1 [6]. As a result the Highways Agency needed to update its own technical advice and specification to align with this latest industry documentation, and this is now in hand.

9. M5 Moreton Valence site trial

The Expert Group Report made a great deal of use of the available research on thaumasite. This had been conducted largely by BRE, but also by other academic researchers and by various groups in the construction industry. However as has already been indicated, there were many areas where further work was identified. One particular aspect concerned the suitability of repair techniques, where the Expert Group does not make definitive recommendations, although guidance is provided. In particular information is needed on the amount of defective concrete to be removed, the suitability of concrete removal techniques and materials for repair. Also a concern is the effectiveness of the different concrete protective coatings recommended in the Expert Group Report.

Fortuitously an opportunity to undertake the necessary research work was presented. The removal of the damaged columns from the M5 Tredington-Ashchurch Bridge provided ideal specimens to carry out repair works under controlled conditions. The Highways

Agency funded a small contract with BRE for removal of the columns to BRE's facilities at the Cardington airship hanger. There they were subjected to a range of repair treatments, on each column face, to be compared with untreated control samples.

The Highways Agency has also made available a site alongside the M5 at Moreton Valence in Gloucestershire, to allow these repaired column specimens to be buried in a longer term (10 year) trial to assess whether the various repair techniques are viable. A geotechnical survey was carried out to ensure that the soil and groundwater conditions were appropriate to instigate thaumasite. The monitoring and final analysis of the specimens is being undertaken by BRE as part of a contract funded by DETR. Also buried on the same site are a number of precast concrete pipes, as part of a project conducted by BRE in collaboration with the Concrete Pipe Association, and partially funded by the DETR.

10. Other research

A separate research project funded by the Highways Agency looking at the potential for sulfate attack on buried steel structures has also produced a benefit in relation to thaumasite. This has developed new sulfate tests, that can be utilised to determine total sulfate in the ground, and should be helpful to assist site investigation work where buried concrete structures are proposed. The research was undertaken by TRL, with the assistance of Sheffield University, and subsequently published [7].

Much other research work is also being undertaken, not directly involving the Highways Agency, and will ensure that the knowledge on thaumasite is increased as time progresses.

11. Lessons learnt

Overall the author believes that the experience of dealing with thaumasite should be read as being quite positive. From the time of the initial discovery of the concrete deterioration in Gloucestershire, in February 1998, less than one year elapsed before authoritative guidance was issued. The guidance was produced by a very positive, collaborative process involving many parts of the construction industry. The publication of the Expert Group Report and its attendant publicity, together with a series of presentations around the country by members of the Expert Group quickly dispelled some of the initial fears and 'scare' stories about thaumasite. This kept the anticipated problems in proportion, and showed that they could be handled by responsible management of structures and adoption of measures to minimise risks in new construction. Furthermore national investigations have also been undertaken, and allowed the Highways Agency to identify the higher risk areas for occurrence, and to discount the lower risk locations.

More recent work has seen further collaboration to ensure compatibility between documentation, and to ensure consistency across the industry. However the situation is not one that should engender complacency. There is still more work to be completed.

On more detailed points there are a number of lessons to be learnt:

- Geotechnical investigation—essential to undertake, and interpret correctly, not just by major clients such as the Highways Agency.
- Design—important to follow the recommendations of the Expert Group Report, but there are lessons about the need to think about detailing subsurface concrete elements, such as avoiding sensitive details and slender elements where possible.
- Detailing—water management is essential, including catering for subsurface groundwater movements, and location of drains close to foundations pits is to be avoided.
- Construction—avoid sumps, avoid use of sulfate/sulfide backfills where possible.
- Management of structures—need to periodically inspect some foundations and buried elements where there are higher risks, the Highways Agency currently only inspects above ground elements, unless there is evidence of distress above ground.
- Developing guidance—need to issue authoritative consistent guidance, and important to work with industry. Must act quickly, even if not all the answers are known it is important to issue guidance as soon as possible. Recognition of the commercial interests, as there is no point issuing guidance that would mean that nothing can be built, and achieving a careful balance of the technical requirements and commercial concerns.
- Publicity—need for awareness of media and public interest, and to keep press well briefed.

12. The future

A few thoughts are also offered on the future direction.

As already noted, there are a number of research projects under way, and as the results from them become available, this will add to the bank of knowledge regarding thaumasite. The key areas are to gain a better understanding of the mechanism of thaumasite sulfate attack, and particularly the timescale for its occurrence. There has also been a continuing debate about whether thaumasite can occur in other conditions where not all the primary factors, previously identified, are present. In particular there are views held by some researchers as to whether it can occur in aggregates other than carbonates, whether the sources of both the sulfates and carbonates can occur outside the concrete, and effects in above ground concrete, and in other cement based materials.

One particular area where there is a need for further development is in the area of managing existing structures. Most clients would not as a general rule expose foundations to assess their condition. However the occurrence of thaumasite has promoted the need to review this practice, and where risks are perceived to be higher, then it would be prudent to undertake periodic exposure of foundations and other buried concrete elements. An alternative approach would be the development of remote sensing and testing methods and equipment to determine if thaumasite is present below ground. Some thought has already been given to the possibilities of utilising probes, and this must remain an area for possible future developments.

Reference has already been made to the trial of repaired thaumasite affected concrete at Moreton Valence. Although this is long term research work, designers and clients require more information on suitable techniques.

As a result of the work currently underway, it is anticipated that there will be a need to adapt and update present documentation where the thaumasite issues impinge. This is true for the Highways Agency, and it is clear that the concrete specification and other documentation must be amended periodically to reflect the latest authoritative thinking, and ensure industry consistency.

One other area which requires addressing is over the dissemination of information concerning thaumasite. Although much work was undertaken at the time of the publication of the Expert Group Report and subsequently, it is apparent that some designers and clients are still not recognising the issues involved. However, this will gradually be resolved as changes to standards filter through. This conference also seeks to address this problem, and also to widen the perspective to the international arena.

Overall one can say that thaumasite is a serious issue, not only for designers of new structures, but also for managers of existing stock. However the construction/research industry has demonstrated that the issue can be handled sensitively and responsibly. Sufficient research and information has already been compiled and interpreted into practical guidance and recommendations to ensure that there are minimal risks in the future of thaumasite causing serious or significant structural problems. The industry must continue to build on this, and the Highways Agency is determined to play its part in the process.

Acknowledgements

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References

[1] BRE—Digest 363 Sulfate and acid resistance of concrete in the ground, 1996.
[2] DETR—The thaumasite form of sulfate attack: risks, diagnosis, remedial works and guidance on new construction, January 1999.
[3] BSI BS5328—Methods of specifying concrete, including ready mixed concrete, 1997.
[4] Highways Agency—IA25 Measures to minimise the risk of sulfate attack (including thaumasite)—New construction and structures under construction, 1999.
[5] Highways Agency—Specification for highway works, May 2001.
[6] BRE—Special Digest 1 Concrete in aggressive ground, 2001.
[7] TRL—Research Report 447 Sulfate specification for structural backfills, 2001.