DWER CONSULTING

Historic Defects in Buildings

Introduction

What do you need to know before you say ‘yes’ to your Client’s request for a running track on the roof?

The purpose of buildings and how we use them is changing. A trend accelerated by the coronavirus pandemic. Buildings are being refitted, refurbished and repurposed to meet the demands of hybrid working, new retail/leisure concepts and change of use to accommodate hotels, build to rent residential, logistics and bio/medical sciences.

Seven storey office block repurposed to 150 room Malmaison Boutique Hotel with roof-top bar

Former Co-Op Department Store, Sheffield – retail to hybrid working

In addition these changes have to satisfy the criteria for sustainability, zero net carbon and other green requirements from BREEAM, LEEED and WELL in order to attract the ethical/green investment. As part of the move to reduce carbon emissions the retention and re-use of existing buildings is an essential element.

So how are we to address the viability of that running track on the roof?

It is essential to establish the age and method of construction of the building to be reconfigured. Whilst 'state-of-the-art' at the time many methods or components of construction in the past 30/60 years have not aged well or developed serious flaws or have latent defects.

So can your building safely support a running track on the roof? Similarly could it withstand hacking the large floor plates for that 'must have' full height atrium, cascade stairs, or create internal space for a vertical go-kart circuit?

The go-kart track in an ex-Debenhams store

An important feature of achieving this is to check and verify that the existing structure and fabric of the building can be utilised for the new role and is safe to occupy, fit for purpose and can meet the standards required.

Whilst the checking for faults and latent defects will reflect current technical experience and codes of practice, we need to be aware that for the refurbishment of buildings it is necessary to check that the structure does not contain one (or more) of any historic defects that may manifest itself as part of the 'upgrade' or 'change of use' works. The historic defect may well be 'dormant' and hidden within the corporate archive but the new use may change the building's dynamic and trigger a deterioration.

Some examples of historic defects are considered in the following guidance notes (this is not a complete list but serves to illustrate the potential for the newly refurbished structure to contain a latent defect). This list does not replace the usual due diligence required when assessing an existing building for a new use.

Some examples of historic defects include –

- Carbonation of Concrete Cover
- High Alumina Cement (HAC)
- Reinforced Autoclaved Aerated Concrete (RAAC)
- Alkali Silica Reaction (ASR)
- Regent Street Disease
- Woodwool Formwork

Articles on these topics are written only to alert the reader to the defect with some broad guidance on investigation and repair. The reader will need to consult more widely to gain a working knowledge of how to deal with these defects.

Carbonation of concrete cover

Description and effects

Contrary to what many believe, embedded steel in concrete is protected primarily by the slightly alkaline chemistry of the concrete that surrounds it. When carbon dioxide in the air combines with free water in the concrete pores, it forms carbonic acid. This reduces the alkalinity of the protective concrete cover to the reinforcing steel. The process is known as 'carbonation' and gradually progresses into the concrete, the depth at which it has extended being known as the "depth of carbonation". Once the depth of carbonation reaches the embedded reinforcement, then if moisture and oxygen are present, the reinforcement will corrode. The rate at which carbonation proceeds from the surface is generally slow but is accelerated by a number of factors, such as porosity, low concrete cover, type of cement, high water-to-cement ratio and low cement content. Carbonation induced corrosion often occurs in areas of buildings exposed to rainfall, shaded from direct sunlight, and where the concrete cover to the reinforcement is low.

Corrosion product (rust) is around 4 to 11 times larger in volume than the steel from which it was derived, so the corroding steel will develop tensile stresses in the concrete cover. As a consequence the concrete will crack and with continuing steel corrosion will spall away from the reinforcement. Invariably this leads to a need for extensive repairs and in extreme cases, carbonation may ultimately lead to structural failure.

Carbonation of the concrete cover allows water and oxygen to attack and corrode the reinforcing steel. This results in the expansion of the corroding steel which will develop tensile stresses in the concrete cover. As a consequence the concrete will crack and with continuing steel corrosion will spall away from the reinforcement. In extreme cases, carbonation may ultimately lead to structural failure.

For example, carbonation of the concrete cover to the steel reinforcement, leading to corrosion, was identified as one of the contributing factors to the collapse of the Pipers Row Multi-Storey Car Park in Wolverhampton. On the night of 20 March 1997, a 120 tonne section of the top floor of the car park, built in 1965, collapsed as a result of an initial punching shear failure which developed into a progressive collapse.

Pipers Row car park after the collapse

Identification

An indication of the presence of the depth of carbonation extending to the depth of the embedded reinforcement could be the presence of rust stains on the surface of the concrete element, or cracking of the concrete cover (often in line with the reinforcement), spalling and sometimes exposure of the reinforcement beneath.

Once the presence of carbonation is suspected an easy test to establish this is to spray a phenolphthalein solution onto a freshly broken concrete surface. The solution indicates alkaline zones by a purple red colouration. In the event that a freshly broken surface is not possible to achieve then incremental drilling can be used. The drilling dust will remain colourless when sprayed with phenolphthalein solution if it is from a carbonated zone. The test is straightforward to undertake and only creates minor surface damage.

Mitigation/remedial options

Repair techniques will depend on the presence and severity of any corrosion. If there is no corrosion present then preventative measures can be taken – such as, amongst others, the application (and then maintenance) of anti-carbonation coatings to restrict the ingress of carbon dioxide and moisture.

If corrosion has started then it is necessary to restore the original alkaline environment around the reinforcement. This will entail the removal of the carbonated concrete from around the reinforcement, cleaning and/or augmenting the reinforcement and then reinstating the cover with a suitable cementitious material. An alternative would be to introduce a Cathodic Protection system to the structure.

Further guidance

BS EN 14630: 2006: Products and systems for the protection and repair of concrete structures.

Building Research Establishment. Carbonation of concrete made with dense material aggregates. BRE Information Paper IP6/81 (withdrawn 2016)

Pipers Row Car Park, Wolverhampton - Quantitative study of the causes of the partial collapse on 20 March 1997 https://www.hse.gov.uk/research/misc/index.htm

Appraisal of Existing Structures (Third Edition) October 2010. The Institution of Structural Engineers.

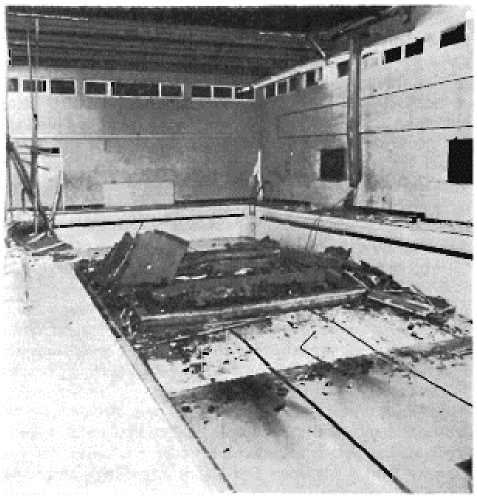
G. Somerville: 'The Design Life of Concrete Structures'. The Structural Engineer, Vol 64 (1986) Issue 2

High Alumina Cement

Description and effects

Concrete made using high alumina cement (HAC) was popular from around 1950 to 1970. The reason being that it gave a considerable advantage to precast concrete manufacturers because it gained high early strength. Thus enabling formwork to be struck early and immediately re-used.
However, in certain conditions, the HAC concrete suffers from a phenomenon called conversion, resulting in a change in the structure of the hydrated cement. In some circumstances this may be accompanied by a substantial reduction in concrete strength, down to as low as 15% of the original strength.

On 13 June 1973 the roof of the assembly hall at the Camden (London) School for Girls collapsed. On 8 February 1974 a similar collapse occurred to the roof over the swimming pool at Sir John Cass's Foundation and Redcoat Church of England Secondary School in Stepney, East London.



Cass School pool after roof collapse

In the case of the Cass School, failure occurred 18 years after construction.
Extensive investigations into these incidents revealed that the conversion, leading to a much reduced strength, of the high alumina cement (HAC) in the precast prestressed concrete beams to these roof structures was the principal cause of collapse.

Investigations by BRE also revealed that HAC concrete is often carbonated to the depth of the reinforcement, therefore heralding the onset of reinforcement corrosion.

HAC concrete was effectively banned for use in new structural concrete in the UK following the collapses in the 1970s. Time and experience have shown that the primary causes of these collapses was the loss of strength following conversion of the HAC often allied with poor construction details or chemical attack requiring the presence of moisture.

Most HAC concrete in the UK went into precast beams. Several thousand buildings with similar beams continue to remain in service today in the UK. The beams can be found in older public and industrial buildings such as schools, flats and business units. The beams were not limited to use in roofs but may be present in internal floors as well.

Identification

An indication of the presence of HAC would be the dark grey or brown colour of the precast beams. This can then be confirmed by testing a sample of the concrete. The residual strength of the concrete can be assessed using a 'pull-out' test.

The degree of conversion is, however, complex and depends on the quality of the concrete and the temperatures to which it is subjected to throughout its life. Chemical attack and the presence of moisture are also factors in the degree of conversion and subsequent loss of strength, with a high risk location being in a warm moist atmosphere over a swimming pool.

Mitigation/remedial options

In severe cases of deterioration it will be necessary to replace parts or all of the structure. Alternatively a secondary support system could be introduced to respond to the reduced strength and thus design span of the existing precast beams.
In other cases, especially where beams made from HAC concrete act compositely with in-situ Ordinary Portland Cement (OPC) concrete, the structure may continue to perform satisfactorily but need regular monitoring to check for any further deterioration.

Further guidance

Appraisal of Existing Structures (Third Edition) October 2010. The Institution of Structural Engineers.

Are Old HAC Roofs Still a Problem – ISE Dec 1997 - https://www.istructe.org/journal/volumes/volume-75-(published-in-1997)/issue-23/are-old-high-aluminia-cement-concrete-(hacc)-roof/

Report of Working Party on HAC – ISE 1976 - https://www.istructe.org/journal/volumes/volume-54-(published-in-1976)/issue-9/report-of-working-party-on-high-aluminia-cement-co/

Reinforced Autoclaved Aerated Concrete (RAAC)

Description and Effects

Autoclaved aerated concrete (AAC) is different from normal dense concrete. It has no coarse aggregate, and is made in factories using fine aggregate, chemicals to create gas bubbles, and heat to cure the compound. It is relatively weak with a low capacity for developing bond with embedded reinforcement.

AAC

It was used in two main forms of structural elements: lightweight masonry blocks and structural units. When reinforced (Reinforced AAC: RAAC) to form structural units, the protection of the reinforcement against corrosion is usually provided by a cement latex slurry coating, which is applied to the reinforcement prior to casting the planks. The reinforcement mesh is then introduced into the formwork and the liquid AAC mix added.

RAAC is a lightweight form of concrete that was commonly used in school and other buildings (including hospitals and offices) from the mid-1960s to the mid-1980s. RAAC is mainly found in roofs, although occasionally in floor and wall panels.

The limited durability of RAAC roofs has long been recognised; however recent experience (which includes two roof failures with little or no warning) suggests the problem may be more serious than previously appreciated and that many building owners are not aware that it is present in their property. RAAC appears to have been used by some municipal architects in a wide range of public sector buildings, not all of which are still in the public sector.

Although called “concrete”, it is very different from traditional concrete and, because of the way in which it was made, much weaker. Pre-1990 RAAC planks are now past their expected service life.

As reported in the SCOSS alert of May 2019 there were instances of failure in the 1980’s of RAAC roof planks installed during the mid-1960s. Several case studies revealed some primary deficiencies e.g. incorrect cover to the tension steel, high span-to depth ratio, insufficient provision of crossbars for providing anchorage for the longitudinal steel, and rapid worsening of corrosion of steel. It is known that RAAC was used for walls and that there are RAAC floor planks.

In late 2018, there was a failure at a school involving a flat roof constructed using RAAC planks. There was evidence of shear cracking adjacent to a support and possible indications of tension reinforcement stopping short of the support. There was little warning of the sudden collapse.

Identification

When inspecting flat roofs the potential presence of RAAC planks could be indicated by excessive deflection leading to rainwater ponding and thence dead load increases and/or water penetration. The water ingress would lead to corrosion of the plank reinforcement.
An inspection of the planks from the underside should note any visible cracks (particularly near the end supports), signs of water ingress, rust staining or spalling. Where possible a small intrusive drill sample would assist the confirmation of RAAC being present, although the inherent softness of the RAAC may allow it to be identified by surface testing only. Refer to the recent publication from the Department for Education – Reinforced Autoclaved Aerated Concrete: Lightweight Concrete Roofs – dated February 2021 - for guidance on identifying the presence of RAAC planks.

Mitigation/remedial options

Following the establishment of the presence of RAAC roof planks a survey is required to ensure that the building is safe to continue to be used. Once it has been confirmed that it is safe to continue to be occupied an inspection routine should be put in place to monitor the possibility of defects occurring as part of a management strategy. These inspections should initially establish the reinforcement provision in the planks (cover meter survey for main reinforcement), the support conditions, signs of corrosion, deflections, any cracks and signs of water penetration. Subsequent regular inspections should check the deflections, ensure that water can drain freely from the roof with no ponding, check for visual signs of cracks and any signs of water penetration.

Further advice is available in the SCOSS Alert – Failure of RACC Planks May 2019 and the Institution of Structural Engineers paper published in February 2022

Recent reports (August 2021) indicate the type of temporary emergency measures that can be implemented where RAAC planks within walls and ceilings have deteriorated or have structural weaknesses.

In one case 27 metal supports have been placed under the planks, and the entire roof has been fitted with monitoring equipment to catch any further deterioration or weakness in the planks.

In other instances, more than 200 supports have been put in place whilst another has set a weight limit on the floors due to concerns about the condition of the building's RAAC planks.
The main remedial options are either replace the roof planks with new structural roofs or introduce intermediate supports to the existing spans depending on the condition of the RAAC planks to be supported.

Further guidance

RAAC panels Investigation and Assessment – Institution of Structural Engineers - February 2022

CROSS theme page: Structural safety of reinforced autoclaved aerated concrete (RAAC) planks

IStructE RAAC Study Group

Local Government Association, Information on Reinforced Autoclaved Aerated Concrete (RAAC)

CROSS Safety Report 908 - Failure of RAAC planks in schools

Appraisal of Existing Structures (Third Edition) October 2010. The Institution of Structural Engineers.

SCOSS Alert May 2019 - Alert on Failure of RAAC Planks

Department of Education – RAAC: Lightweight Concrete Roofs. A guide for identification and initial action – February 2021

Alkali Silica Reaction

Description and effects

ASR is one example of a more general problem known as Alkali Aggregate Reaction (AAR). ASR is a chemical process in which alkalis, usually predominantly from the cement or external contaminants (e.g. de-icing salts) combine with certain types of silica in the aggregate when moisture is present. This reaction produces an alkali-silica gel that can absorb water and expand to cause cracking and disruption of the concrete.

For a damaging reaction to take place the following need to be present:
• High alkali cement
• Reactive aggregate (e.g. crushed greywacke type sandstone, microcrystalline quartz or chalcedony found in flints and cherts)
• Moisture

The problem is known to exist in at least 46 countries. In relation to total construction volume, the incidence of significant damage due to ASR in the UK is small. The following have been affected by ASR –

- Keybridge House, South Lambeth Road, Vauxhall, London.
- Millennium Stadium North Stand (part of the old National Stadium) Cardiff.
- Merafield Bridge, A38, England. Demolished manually in 2016.
- Pebble Mill Studios, Birmingham. Demolished in 2005
- Royal Devon and Exeter Hospital, Wonford. Demolished and replaced in the mid-1990s.

Pebble Mill Studios

Structures most at risk are bridges, hydraulic structures, exposed frames (e.g. open multi-storey car parks) and foundations.

Identification
The expansion caused by the reaction of the silica and alkali content in the concrete can lead to 'map cracking' on the surface of the concrete member. Damage is usually located within 100-200mm of the surface of the concrete. In heavily loaded sections the cracking will probably follow the line of the main reinforcement.

The damage occurs in concretes that are permanently damp or exposed to the weather. The resultant gel is colourless, opaque (or white) and located in the aggregate particles, voids, and cracks. The gel can appear as a discharge on the concrete surface and when dried is white in colour.

Typical surface crack pattern for ASR

Mitigation/remedial options

Mitigation measures at the design stage include limiting the alkali in the cement, use of non-reactive aggregates, shielding the structure from moisture and the use of blends of cements by introducing various dosages of pfa, ggbs and silica fume. Most of these recommendations approximate to UK practice.

Generally there are no remedies for ASR affected structures and whilst repair of damaged sections is possible the reaction will continue. In thin structural sections (walls, slabs etc.) mild cases of ASR may be managed by using a combination of external coatings; restriction of the supply of moisture and regular monitoring of the structure. More severe cases may require the introduction of secondary supports or demolition and member replacement.

Further guidance

Appraisal of Existing Structures (Third Edition) October 2010. The Institution of Structural Engineers.

The Appraisal and Maintenance of structures with ASR – ISE 1993 https://www.istructe.org/journal/volumes/volume-71-(published-in-1993)/issue-2/the-appraisal-and-maintenance-of-structures-with-a/

Expansion of Concrete due to ASR – ISE 1984 https://www.istructe.org/journal/volumes/volume-62-(published-in-1984)/issue-1/expansion-of-concrete-due-to-alkali-silica-reactio/

Expansion of concrete due to ASR – ISSE 1984 https://www.istructe.org/journal/volumes/volume-62-(published-in-1984)/issue-1/expansion-of-concrete-due-to-alkali-silica-reactio/

Regent Street Disease

Description and effects

In the first half of the 20th Century masonry clad steel framed buildings were constructed with thick masonry or stone units placed tightly against the structural steel frame with no cavities. The masonry or stone and any in-fill materials are often porous and permit moisture to reach the embedded steelwork. Together with other entry routes for water (open joints, cracks or faulty or ill-maintained rainwater details) there can be sufficient moisture ingress to promote corrosion of the structural steel.

At the time of construction it was usual for the steel to receive one coat of 'red lead' paint or none at all. The adopted construction detail will keep any ingress of water in contact with the steel sections and thus eventually break down the single coat of paint protection. The steel will then start to corrode and expand outwards. The corrosion products are much greater than the original steel volume and will apply significant pressure if constrained.

The situation applies to many of the buildings in Regent Street (hence the name). However, It is not just confined to Regent Street but is also prevalent elsewhere in London and other large cities, such as Bristol and Manchester, in buildings of a similar age.

It was not until 1957 that it was a requirement to protect steel placed within an external wall with concrete or other durable and impervious material

Identification

The presence of corroding steelwork will become apparent with the appearance of vertical cracking at column locations and displacement of stonework along beams at floor levels. By the time that the cracks become evident the corrosion is likely to be well established. The stonework local to the column or beam will be displaced outwards as the corrosion products expand. In extreme cases the stonework of façade material may be dislodged and fall away.

Mitigation/remedial options

One repair option comprises the removal of the external masonry/stonework and then repair the steelwork as needed. This permits access to the steelwork to remove any corrosion and thence apply waterproof barriers or a paint treatment to protect against further corrosion.

This approach may prove difficult where removal of the cladding is not viable and in these circumstances cathodic protection may be used to halt the corrosion of embedded ferrous metals, including structural steel. Cathodic protection will not remove the previous corrosion but will prevent the process from continuing.

Further guidance

Appraisal of Existing Structures (Third Edition) October 2010. The Institution of Structural Engineers.

Corrosion of steel frames behind masonry elevations part1 -
https://www.istructe.org/journal/volumes/volume-93-(2015)/issue-8/technical-conservation-compendium-part-9-corrosion/

Corrosion of steel frames behind masonry elevations part 2 -
https://www.istructe.org/journal/volumes/volume-93-(2015)/issue-9/technical-conservation-compendium-part-10-corrosio/

Regent Street Disease assessment and treatment options
https://www.researchgate.net/publication/281294955_Regent_Street_Disease_Assesment_and_Treatment_Options

Woodwool Formwork

Description and effects

Woodwool is a man-made board material about 50 to 75mm thick comprising shredded timber bound together in a cement paste. It was often used as a load-bearing sheet material (mainly at roof level) during the 1960s and 1970's. It also provided a degree of insulation. Greater spans were achieved by the addition of steel channel reinforcement incorporated along long edges making what was referred to as "channel reinforced woodwool slabs". in addition to this it became useful as permanent formwork to in-situ reinforced concrete slabs and as a void former for concrete ribs

The woodwool slabs could not always sustain localised loads from reinforcement spacers and a degree of skill and care was required when placing concrete against them. Variable concrete compaction could occur adjacent to the woodwool slabs. This lack of compaction resulted in voids and honeycombing on the soffit of the slab leading to the possibility of no cover to the reinforcing steel. As well as this the wet concrete could 'bleed' into the woodwool leaving as a result a layer of no-fines concrete. In other instances the reinforcement spacers have sunk into the woodwool leaving reduced cover to the steel reinforcement.

As the woodwool boards were permanent formwork and left in place, any defects remained undetected.

The impact of the woodwool formwork is mitigated when the woodwool boards are placed between the insitu concrete ribs. In this instance the concrete rib (the key structural element) is visible and any construction defect therein can be identified immediately. This may be limited to variations in the width of the ribs caused by excessive vibration dislodging the woodwool former during placement of the concrete. However the soffit of the slab between the ribs would not be visible unless some part of the woodwool slab was removed as part of any inspection.

In 1972 it was reported in 'The Structural Engineer' (January 1972 Volume 50) that a failure had occurred where woodwool slabs had been used as permanent formwork over a car park area. The building was in Northern Ireland and the formwork had been loosened as a result of an IRA bomb. Upon inspection of an area of slab it was noted that almost all of the bottom reinforcement was exposed and had no concrete bond. The plastic spacers had sunk into the woodwool and grout from the concrete when vibrated had soaked down into the woodwool leaving a 50mm layer of no-fines concrete.

In 1975 at New Malden House some floor sections cast on woodwool formers failed as a result of using this type of permanent formwork.

Identification

The presence of woodwool formwork can be established from a visual survey of the structural soffit of the floor slabs. It should be noted that in some instances the woodwool slab may have had a slurry or mortar coat applied to its surface.

Woodwool Board

Exposed reinforcement with woodwool formwork

Having established that woodwool formwork is present in the building some intrusive investigation should be conducted to establish whether any of the attendant defects are present. Tests should check for lack of concrete cover to the bottom reinforcement, evidence of any reinforcement deterioration and any loose reinforcement.

Mitigation/remedial options

In extreme cases it will be necessary to replace the affected structure; in less severe cases it should be possible to strip out the woodwool and replace the concrete cover using sprayed concrete or other techniques.

Further guidance

- Failure of wood-wool slabs used as permanent shuttering – TSE January 1972 Volume 50
- Appraisal of existing structures – Institution of Structural Engineers (2010)
- Refurbishment and Repair in Construction – Doran, Douglas and Pratley