ASSESSMENT OF CONCRETE IN SERVICE IN THE UK - REMEMBERING THE VALUE OF PRACTICAL PETROGRAPHY

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Abstract

Between 2002 and 2004, the usually reliable alkali content data from a large UK cement plant were compromised by the illegal activity of some individuals; cement was supplied as having ‘moderate' alkali content when in fact it had 'high' alkali content. This led to concerns that potentially expansive concrete may have been used in structures.

This paper presents actual cases that the authors assessed. The structures, suppliers and clients must be anonymous, but all the data and observations are from real investigations. When concrete alkali contents were recalculated, using reliable data, many mixes containing nominally ‘normal’ reactivity aggregate combinations were found to be at theoretical risk of damaging ASR. However, by quantitative petrographic examination of core samples, it proved possible in many cases to establish that the aggregate combinations exhibited only 'low' reactivity and that the concrete was not vulnerable to ASR damage in service.

Keywords: Alkali Silica reactivity, petrography, high alkali cement, aggregate reactivity

1 INTRODUCTION

It is well established that the risk of expansion caused by alkali-silica reaction (ASR) can be minimised in new concrete work by removing at least one of the three critical factors: moisture, sufficient alkalis or a potentially reactive aggregate combination [1]. Preferred precautionary measures to achieve such control vary around the world, dependent upon local conditions, materials and construction practice. In the United Kingdom (UK), where moist conditions are ubiquitous for externally exposed concrete, also owing to the detailed investigation required to establish the reactivity of the commonest aggregate materials and the comparative abundance of binder options, authoritative and standardised guidance has mainly relied upon alkali control since the late 1990s. This appears largely to have been successful and is facilitated by the operation by UK-based cement manufacturers of quality assurance schemes in relation to alkali analysis and continuous monitoring.

As a result of illegal activity by individuals during the period September 2002 to December 2004, which the manufacturer publicised as soon as it was discovered, a cement works in the UK was producing cement of ‘high’ alkali content (>0.75% Na_2O equivalent) labelled and declared as being of ‘moderate’ alkali content (≤ 0.75% Na_2O equivalent). Consequently, some concrete mixes produced with these cements did not comply with Standard guidance for the maximum permitted alkali concentrations[4] [5].

The authors have subsequently been involved in re-assessing the potential for ASR in a number of structures, variously commercial, residential and industrial buildings, bridges, water treatment tanks and roads, based on the correct reported alkali levels for the cement used. Generally, these structures are within the south-central to south-western regions of the UK.

The assessment of potential reactivity was based on recalculation of the alkali levels, followed by an assessment of the reactivity potential of the aggregate or aggregate combination used; this was sometimes based on previous petrographic examination of the aggregates from known sources or from specific quantitative petrographic analysis of concrete samples taken from site. This assessed aggregate reactivity potential was compared with previously published [2] [3] and unpublished results of laboratory expansion testing at BRE for similar aggregates and aggregate combinations, to determine the likely risk of ASR for these high alkali concrete mixes.

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2 BACKGROUND

Alkali-Aggregate Reactivity (AAR) can develop in concrete when the following criteria are met:

1. Sufficient levels of moisture
2. A critical amount of reactive material, usually silica, within the aggregate or aggregate combination
3. Sufficient levels of alkali within the concrete mix. The principal source of these is the cement, with some also possibly from additions, admixtures or from the aggregate.

In the UK case, Alkali-Silica Reactivity (ASR) is the most prevalent form of AAR, and can lead to damaging expansive reactions, that typically manifest themselves years to decades after construction.

In the UK, all externally exposed concrete and some buried concrete are assumed to be in potentially moist settings. The evaluation of aggregate reactivity requires extensive investigation, and direct project-specific testing becomes practically impossible, given the range of aggregate combinations available and the current absence of an adequately rapid test. Furthermore, the wide variety of available binder materials would complicate the assessment of risk based on aggregate composition. Therefore, British Standard and other guidance (Concrete Society Technical Report CSTR30 [4] BRE Digest 330 [5]) is based principally on controlling total levels of alkalis within the concrete mix. Generally, such an approach has proved to be successful, and is facilitated by the operation by UK-based cement manufacturers of approved quality assurance schemes that requires continual re-assessment of the alkali levels in produced cement. In this case, the failure of the system reportedly (Price 2005, *pers comm.*) related to deliberate and wilful manipulation of the system by individuals rather than a failure of the system to operate correctly.

3 STANDARDS AND OTHER PUBLISHED GUIDANCE

During the period when the mis-labelled cement was being produced, the applicable British Standard code of practice changed from BS 5328-2: 1997 [6] to BS EN 206-1: 2000 [7], with the latter European standard being supported by a complementary British Standard BS 8500-2: 2002 [8]. Specification documents for the specific construction projects consequently referred to either of these standards, depending on when these specifications were developed.

Alkali level determinations

There was a notable change between the approach of these standard documents to the determination of alkali content and consequently evaluation of ASR risk to the building. The older BS 5328 document refers to the alkali level calculations and limits given in BRE Digest 330, with the additional option of agreement between the producer and purchaser based on previous service record.

The later European Standard and complementary British Standard BS 8500-2 (which includes specific guidance on resistance to alkali-silica reactivity) provide tabulations of maximum permitted cement contents based on levels of alkali in the cement and other contributors. It was advised by the compilers of BS 8500-2 that the intention had been to develop a tabulation consistent with BRE Digest 330 calculations but to allow a more user-friendly format. However during these investigations it became apparent to us that the tabulation provided was not consistent with the calculations, generally permitting slightly higher alkali levels than intended owing to an error in the standard. This was reported to the relevant British Standards Committee and a subsequent (2006) revision of BS 8500-2 has removed the tabulations of cement content and instead simply refers to the guidance given in BRE Digest 330.

Aggregate Classification

The natural aggregates and aggregate combinations in concrete are classified by CSTR 30 into low, normal and high reactivity, and the permitted total alkali levels in concrete are modified based on these aggregate classifications (Table 1).

The above tabulation is based on the use of a CEM-I type cement without additions of ground granulated blastfurnace slag (GGBS) or pulverized-fuel ash (PFA), both of which can significantly reduce the risk of ASR in the concrete mix.

High reactivity aggregates in the UK are generally restricted to crushed greywacke and other sedimentary rocks of similar composition or (as a precaution) to recycled aggregates. These were not encountered during these investigations. Low reactivity aggregates are generally either from igneous rock types or carbonate sediments plus crystalline discrete quartz in fine aggregates. All other aggregates and aggregate combinations are by default of normal reactivity, and include flint and chert, which are commonly present in concrete aggregates in southern England.

Petrographic Examinations

In all of the investigations undertaken, the original concrete batching data, including corrected alkali concentrations, were provided by the concrete producer. These frequently included identification of the aggregate and aggregate type. For many of these, relatively contemporaneous aggregate petrography certificates were available. If this was not the case, the currently-produced aggregate was subjected to conventional aggregate petrography in accordance with BS 812-104 [9], with particular emphasis being placed on the classification and quantification of normal reactivity and low reactivity constituents.

In some cases, especially when fine aggregate combinations (blended crushed and natural sands) were included in the concrete, additional quantitative petrographic analysis was undertaken on hardened concrete obtained from a suitably representative number of cores from site. Typically around 10 cores of 75mm were taken to represent a site. These cores were split lengthways along a diameter and (typically 2) large-area thin-sections prepared to represent the concrete, to account for any variations through the thickness of the concrete under investigation. Quantitative (point counted) petrographic examinations were undertaken for each core, to allow for the most detailed possible assessment of the aggregate combination reactivity. Our typical proceedure for point counting was to prepare 2 thin sections, covering the diameter and complete length of each core (assuming a maximum core length of 300mm, giving maximum section sizes of 150 x 75mm, adequate for assessment of up to 14mm aggregate concrete), with counting of approximately 750 points per section (therefore a total of 1500 points per core). This was judged to be sufficient to provide a reasonably reliable petrographic characterisation of the material [10}, especially given the commercial objectives of our investigations. Additionally, in almost all cases a number of cores were taken from each structure and concrete type present, so our conclusions did not rely on results of a single specimen. No direct assessment of precision of this point-counting procedure was undertaken during these investigations, and none has been reported elsewhere [10].

4 ASSESSMENTS

The exact means of assessment applied varied on a project-by-project, depending on a number of factors:

1. The calculated alkali levels in the concrete following correction of the cement alkali levels (with the batching data and corrected alkali levels being provided by the manufacturer)
2. The context of the concrete within the structure, both regarding exposure conditions and the likely risk of structural damage linked to ASR-related expansion
3. The nature of the aggregate reported to be present and the availability or otherwise of adequately contemporaneous petrography certificates.
4. The presence of aggregate combinations from mixed sources or from marine-dredged aggregate of variable characteristics.

Recalculation of Concrete Alkali Levels

The alkali levels in a construction concrete mix are generally calculated from the batching data from the readymix plant (computer controlled), with mixes being purposely designed to comply with alkali limits and consequently to keep ASR risk to a minimum.

The BRE Digest 330 calculation (as applied for new concrete comprising CEM-I type cement) can be summarised by the flow chart (Figure 1):

In these investigations, it was initially assumed for the purpose of these calculations that the aggregates were of normal reactivity. Furthermore, the cements involved in these investigations were mainly of high alkali (>0.75% Na_2O eq.) levels, with some being marginally below this level.

The recalculations undertaken showed that in most of the cases examined, the increase in cement alkali levels did not cause a non-compliance with regard to the alkali levels of the concrete. In all cases where a GGBS addition was included in the mix, the recalculated alkali levels were significantly below the maximum level applicable. In all cases where mixes remained compliant, this was reported to the client and the investigation ended.

The recalculations, as would be anticipated, indicated that stronger concrete (i.e. that with higher components of CEM-I) tended to exceed the maximum alkali levels more frequently than did weaker mixes. This is because the largest alkali contributor in most cases was the cement phase; in many cases, the alkali contribution from other sources was <0.20kg/m^3, therefore is negligible in the BRE Digest 330 calculations.

Case Study 1

Reassessment of the concrete alkali levels was undertaken for a multi-storey car park structure at a newly constructed business park. At the time of investigation the concrete was ??? years old. The concrete mixes included cement with alkali levels ranging between 0.75 and 0.89% Na_2O eq., with 5 different mix designations: Gen 3 + WRA, C32/40 + WRA, C16/20, C25/30 and C28/35 MCC 300 (WRA – Water Retaining Admixture, MCC – Minimum Cement Content). The total concrete alkali values were recalculated based on BRE and BS guidance, and compliance with published guidance assessed (Table 2). The first two of these mix types contained CEM-IIIA, including >40% GGBS, consequently all of these easily comply with permitted alkali levels despite including the highest cement alkali values. Both weaker cement mixes with CEM-I comply in all cases with the permitted alkali levels (being at most 90% of the maximum permitted), whereas the stronger C28/35 mix fails for all 7 batches recorded.

Structural Context

The significance of any non-compliance with published alkali levels in the concrete and consequent risk of damage caused by ASR varies depending on location. In several investigations, concrete mixes with non-compliant alkali levels were identified as occupying locations that were structurally insignificant (e.g. external paving) or where the concrete was thoroughly protected by tanking or cladding.

However, in a number of investigations, certain elements including non-compliant concrete were recorded in settings that would be prone to ASR development. One of these was a major new office development. In this, the ground slab and most other external concrete were constructed with cement from a different cement works (which had no issues with alkali levels), with the exception of some external columns and soffits (Plate 1). Further assessments were undertaken only on concrete from these elements.

Aggregate Type – Flint Gravel

In many areas of southern England, sand & gravel containing flint (a variety of chert derived from Cretaceous Chalk) is the most widely used aggregate. These aggregates can be from either land or marine-dredged deposits, and by default are considered as being of normal reactivity. Petrographic examinations of various sources indicate that coarse aggregate fractions tend to be almost exclusively flint-bearing (frequently >95% of the 20mm aggregate fraction), whilst the finer sand aggregates typically include a large proportion of quartz sand with lesser amounts of flint (typically being the coarser sand particles). Additionally, marine-dredged aggregates tend to be rather more variable over a period from a given depot than land-derived sources; for example a marine sand evaluated for one structure included 19% flint and 66% quartz according to a 2004 petrographic examination but 36% flint and 55% quartz according a repeat examination in 2005.

Older standard and other published guidance (e.g. [2], [4]) made reference to the 'pessimum proportion' of flint within the concrete, whereby if the flint content exceeded 60% of the total aggregate in the mix [11], and if the fine flint content exceeded 5% of the total aggregate, the concrete was generally considered not susceptible to ASR damage regardless of alkali levels (or at least could be classified as being 'low reactivity'). The usual explanation for this behaviour is that the high surface area of flint within the concrete reacts with (and therefore nullifies) any alkalis in the pore fluids at a large number of sites simultaneously, preventing any local elevations of alkali concentration sufficient to cause damaging ASR reactions.

This 'pessimum proportion' rule is no longer considered universally valid in the UK, as experimental work by BRE [3] showed a small number of flint-rich aggregates that exhibited expansion in some laboratory conditions (occurring for 5 test mix concretes out of 80 tested overall). Examination of these aggregates established that this expansive behaviour was only exhibited by flint of unusually high density and low water absorption, and with an unusually low abundance of flint cortex (the microporous surface coating typically associated with flint formation in Chalk).

Case Study 2

A food distribution centre, constructed with affected concrete during 2004, was evaluated, with the redeclared cement containing between 0.77 and 0.89 % Na_2O equivalent. Initial recalculation of the mix designs showed that one mix type (C28/35 + WRA) complied with alkali guidance in all cases; these mixes were used for the pad foundations and ground beams, and consequently considered to be at minimal risk of ASR. However, for the other two general mix types (C32/40 + WRA used for a perimeter strip to the ground slab, and C28/35 MCC 300 used for external paving), the majority of mixes were found to be non-compliant with the BS 8500 guidance (11 of 13 batches and 97 of 100 batches respectively). All of these concrete mixes were judged to be in settings potentially exposed to dampness and therefore environmentally susceptible to ASR.

The aggregate combination used in this case was 20/5 mm graded coarse aggregate and a 5 mm sharp sand . Petrographical examinations of both these aggregates had been undertaken by STATS in February 2003 in accordance with BS 812-104. These aggregate compositions are summarised in Table 3.

These aggregates were correctly classified as being of normal reactivity, based on the tabulated composition. However, the mix proportion information provided included the relative proportions of coarse and fine aggregate in for each of the mixes, allowing calculation of the total flint content and the contribution of flint in the fine aggregate. These calculations are given in Table 4. From the above, it is apparent that all mixes complied with the superseded pessimum rules of > 60% flint total and > 5% flint from fine aggregate.

Further evaluation of the flint from these sources showed that the majority of the coarse aggregate flint included attached cortex (83% of the particles examined). Based on these observations and the previous BRE observation that unusually expansive 60% flint concrete was restricted to that lacking cortex on the flint grains, it was judged reasonable to conclude that the aggregate combinations used in this project were unlikely to prove reactive in practice. However, it should also be noted that the current BRE Digest 330 clearly states that as a precaution all such aggregates and aggregate combinations should be regarded as having normal reactivity.

Aggregate Combinations and Quantitative Petrography

In a number of projects, the cement was judged non-compliant based on alkali content (for normal reactivity aggregate), at risk due to structural context and was not dominantly a flint-bearing aggregate complying with the pessimum proportions 'rule' detailed above. Generally, these were aggregate combinations including a limestone coarse aggregate (generally a low reactivity aggregate type in the UK) and a 1:1 mixed limestone fines and quartz sand fine aggregate fraction. In these cases, the aggregate combination overall was correctly classified as being of normal reactivity.

Owing to the relatively complex mix of aggregates within the concrete, it was deemed necessary to evaluate the concrete material actually present on site rather than relying on individual petrographic examinations of the aggregates as currently produced. To achieve this, a number of core samples were taken from different elements within the structures, sufficient adequately to represent the various concrete mixes used. For different projects, between 12 and 23 cores were taken, typically of nominal 75mm diameter and between 100 and 450mm length, depending on the nature of the structure and the anticipated consistency of the concrete composition. These cores were generally split lengthways along a diameter and prepared so as to produce a number of thin-sections covering their entire length of the core. These thin-sections were subjected to a quantitative (point counted) petrography to assess the relative proportions of low, normal and high reactivity components in the aggregates and consequently to enable re-assessment of the reactivity.

Comparison between the point-counted composition and the notional composition based on nominal mix design data indicated that the point counting method had some bias towards over-estimating the fine aggregate fractions relative to coarse. This may have related to the geometric properties of the aggregates. Obviously, it is not possible from a petrographic examination to determine whether a small piece of limestone (for example) within the essentially 2-dimensional thin-section represents the full size of an originally fine-grained particle or only a small slice through a much larger grain [10].

Generally, these aggregate combinations were found to be dominantly composed of low reactivity materials (e.g. limestone) based on the lists given in BRE Digest 330. More detailed guidance for aggregate combinations is given in CSTR 30 and in BS 7943 [12], which define the maximum amount of potentially reactive materials within the total aggregate to the following limits:

- At least 95% low reactivity materials in both coarse and fine fractions (CSTR 30)
- At least 97% low reactivity materials in total aggregate (BS 7943)
- A maximum of 3% flint, chert or chalcedony in the total aggregate (CSTR 30).

If the aggregate combinations comply with the above criteria, they can be classified as being of low reactivity overall.

Generally, the quantitative petrography of aggregate combinations (limestone + sand) showed that they complied with the maximum chert criterion, but not the minima for low reactivity materials because of the abundance of quartzite and sandstone. Alternatively, aggregate combinations can be reclassified (according to BRE Digest 330) as being of low reactivity on the basis of performance in concrete prism expansion testing to BS 812-123. Aggregate combinations exhibiting less that 0.10% expansion after 12 months can be considered as being of low reactivity.

BRE expansion test data ([2] and unpublished BRE data made available to the authors) show that for similar limestone + sand combinations (typically a 70-30% mix) from a range of sources show low expansion (i.e. <0.10%) provided that the chert content was below 3% and the total reactive material did not exceed 14%. Having established these criteria from the available test data, it was judged practical to infer the performance of an aggregate combination by comparison with the available data even in the case where direct test data were not available. Consequently, in several cases it was judged that the aggregate combinations used could reasonably be reclassified as being of low reactivity.

Case Study 3

A water treatment works in the west of England was redeveloped in early 2004, with 10 large water treatment tanks. The suspended concrete slabs in these tanks were constructed using the cement under investigation. These slabs were situated below the untreated water, with the treated water accumulating beneath; the slabs are not waterproofed and will consequently remain wet for all the time the facility is operating. Due to logistical considerations, only one of the treatment tanks could be sampled; the tank selected was advised to include concrete supplied from two separate ready-mixed concrete plants and consequently included different aggregate combinations. These aggregate combinations were detailed as being:

1) Limestone (Quarry A) coarse aggregate with 50:50 mix of crushed Quarry A limestone + marine dredged quartz sand.
2) Limestone (Quarry B) coarse aggregate with 55:45 mix of Quarry B limestone fine sand and land-derived quartz sand.

In total, 14 cores were taken from the tank slab, with 6 being submitted for quantitative petrography. Of these, 4 were distinguished as a dark variant concrete, 1 as a light variant and 1 as being of mixed composition.

The cement used in this construction was advised (for recalculation) to include 0.8% to 0.85% alkali levels, therefore to be high alkali cement. The recalculations based on nominal mix design and batch data provided showed that alkali levels in the concrete were in the range 3.5 to 3.8kg/m^3 Na_2O eq, and therefore exceeded the limiting values of 3.0kg/m^3 Na_2O eq for concrete including high alkali cement and normal reactivity aggregate.

The initial quantitative petrography of the cores gave the data in Table 5:.

Based on these determined compositions, and by comparison with the CSTR 30 and BS 7943 guidance, the aggregate compositions were correctly classified as being of normal reactivity. All comply with the maximum 3% chert criterion, but not with the requirements for 95% low reactivity materials in each size fraction or 97% overall.

The above quantified petrographic data were then compared with various published and unpublished BRE expansion test data, to provide Table 6 for comparison

It was therefore judged, by comparison with the available expansion data, that all the concrete mixes used on this project were similar to those exhibiting low expansion behaviour, and could thus reliably be reclassified as being of low reactivity based on test performance. This reclassification of the aggregate allows an increase in the alkali limits for the concrete mixes from 3.0 to 5.0 kg/m^3 Na_2O eq., and therefore the concrete meets the standard requirements for control of ASR and consequently should not present a significant risk.

5 CONCLUSIONS

The misreported cement alkali levels has potentially caused a significant increase in the risk of concrete in a wide area and over a two-year period being prone to damaging alkali-silica reactivity.

In a large number of cases, despite this misreporting, many or most of the mixes produced still fell within the standard guidance for total alkali levels. Of those that exceeded the maximum permitted alkali levels, on the assumption of normal reactivity aggregate, most do so by only a relatively small amount.

Re-assessment of the petrographic data for various aggregates and aggregate combinations has allowed the reclassification of a number of these as being low reactivity. This has generally been done by comparison between the aggregate and the laboratory test data of expansion obtained through BRE.

Many flint-dominated aggregates have been reclassified as being of low reactivity as they are similar in composition to those from which the previous pessimum proportion rules were developed.

Some limestone plus sand aggregate combinations were reclassified as being of low reactivity by comparison with largely unpublished BRE expansion test data.

The use of quantified petrographic examinations of concrete cores has provided a very valuable tool in these assessments, and in many cases has allowed reassurance to be provided to building owners and developers that the risk of damaging ASR in structures affected by the cement misreporting was minimal.

6 ACKNOWLEDGEMENTS

We would like to thank BRE for allowing access to unpublished research data relating to the expansion testing of various aggregate combinations.

7 REFERENCES

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Table 1: Recommended maximum limits for alkali contents of concrete (based on BRE Digest 330).

Cement alkali class	*Low*	*Moderate*	*High*
Aggregate type	Na_2O eq kg/m^3		
Low	Self limiting	Self limiting	5.0
Normal	Self limiting	3.5	3.0
High	2.5	2.5	2.5

Table 2: Compliance of concrete mixes with BRE Digest 330 guidance.

Concrete Mix	**Gen 3 + WRA**	**C32/40 + WRA**	**C16/20**	**C25/30**	**C28/35 MCC300**
Cement Type	CEM-IIIA	CEM- IIIA	CEM-I	CEM-I	CEM-I
Cement content (kg/m^3)	106-145	195-237	235-275	290-305	315-375
Cement alkali range (%)	0.89	0.76-0.88	0.75-0.87	0.75-0.76	0.86
Non-cement alkali (kg/m^3)	0.33	0.18-0.32	0.18-0.31	0.26-0.29	0.42-0.43
Total alkalis (kg/m^3)	1.28-1.62	1.78-2.40	2.01-2.70	2.44-2.65	3.14-3.65
Maximum allowed (kg/m^3)	3.0	3.0-3.5	3.0-3.5	3.0-3.5	3.0
Compliance	All comply	All comply	All comply	All comply	All do not comply

Table 3: Aggregate constituents for flint gravel and sand.

Constituents	**Petrography BS 812-104. February 2003 by STATS**	
	% by mass, constituents	
	20/5 mm graded	**5 mm sharp sand**
Flint	93	21
Quartz/Quartzite	Trace	74
Sandstone	7	4
Ironstone	Trace	<1
Glauconite	-	<1

Table 4: Concrete mix designs evaluated for flint component in total and fine aggregate.

Concrete mix reference	**000050**	**000070**	**000090**
Concrete mix	C28/35 + WRA	C32/40 + WRA	C28/35 MCC 300 max W/C 0.55 + AEA + WRA
Compliance with alkali content requirements	All comply	Does not comply for 11 of 13 batches	Does not comply for 97 of 100 batches
Coarse aggregate (kg/m^3)	1118	1135	1127
Fine aggregate (kg/m^3)	755	677	596
Total flint in aggregate (%)	64	66	68
Flint from fine aggregate (%)	8.5	7.8	7.3

Table 5: Results of quantitative petrography carries out on 6 cores from site.

Constituents		**Description**							
		C2 (dark)	C5 (dark)	C7 (dark)	C8 (light)	C10 (mix)	C13 (dark)	Dark total	Light total
		Approximate %							
1	Crushed limestone	77.1	77.0	74.7	69.4	67.4	70.1	74.3	67.5
2	Quartz	17.3	16.5	18.8	15.5	21.2	20.5	18.5	17.7
3	Quartzite	5.2	6.0	5.8	6.2	7.2	8.4	6.5	6.2
4	Limestone sand + shell	0	0	0	1.1	0.3	0	0	0.9
5	Sandstone	0	0	0	2.6	1.0	0.	0	2.3
6	Coal	0	0	0	1.9	0.9	0	0	1.8
7	Chert	0.4	0.5	0.4	1.0	1.0	0.8	0.5	1.1
8	Ironstone	0	0	0.1	1.0	0.2	0	0	0.7
9	Feldspar	0.1	0	0.1	0.2	0.2	0.2	0.1	0.2
10	Igneous rock fragment	0	0	0	0.1	0	0	0	0.1

Table 6: Comparison of aggregate composition and expansion test results for laboratory test specimens and core samples.

Aggregate Source		**Aggregate combination tested**	**Aggregate composition** (mass, %)				**Expansion** %	**Age** (months)	**Reactivity class**
			Chert	Meta-quartzite	Sand-stone	Total reactive			
Bristol Channel		Sand + limestone coarse	1.5	Medium	High		0.036	17	Low
Bagshot Beds		Sand + limestone coarse	2	28	<1	30	0.000	35	Low
Trent valley aggregates	1	Sand + limestone coarse	3.3	8.1	2.7	14.1	0.162	56	Normal
		Sand & gravel	8.2	22.6	53.3	84.1	0.102	18	Normal
	2	Sand + limestone coarse	4.2	6	4.2	14.4	0.060	59	Low
		Sand & gravel					0.195	24	Normal
	3	Sand + limestone coarse					0.032	14	Low
		Sand & gravel					0.126	14	Normal
	4	Sand + limestone coarse					0.025	14	Low
		Sand & gravel					0.134	14	Normal
	5	Sand + limestone coarse	1.2	5.4	1.2	7.8	0.053	37	Low
		Sand & gravel	3.2	73	1.2	77.4	0.204	24	Normal
	6	Sand + limestone coarse	1.5	7.5	1.5	10.5	0.025	25	Low
		Sand & gravel	1.9	26.8	49.5	78.2	0.103	20	Normal
	7	Sand + limestone coarse					0.026	24	Low
		Sand & gravel					0.079	21	Low
	8	Sand + limestone coarse	2.1	4.8	4.2	11.1	0.028	24	Low
		Sand & gravel	2.1	20.9	58.1	81.1	0.156	21	Normal
Water treatment works concrete		Marine sand	1	6	2	9			
		Land-based sand	1	7	0	8			

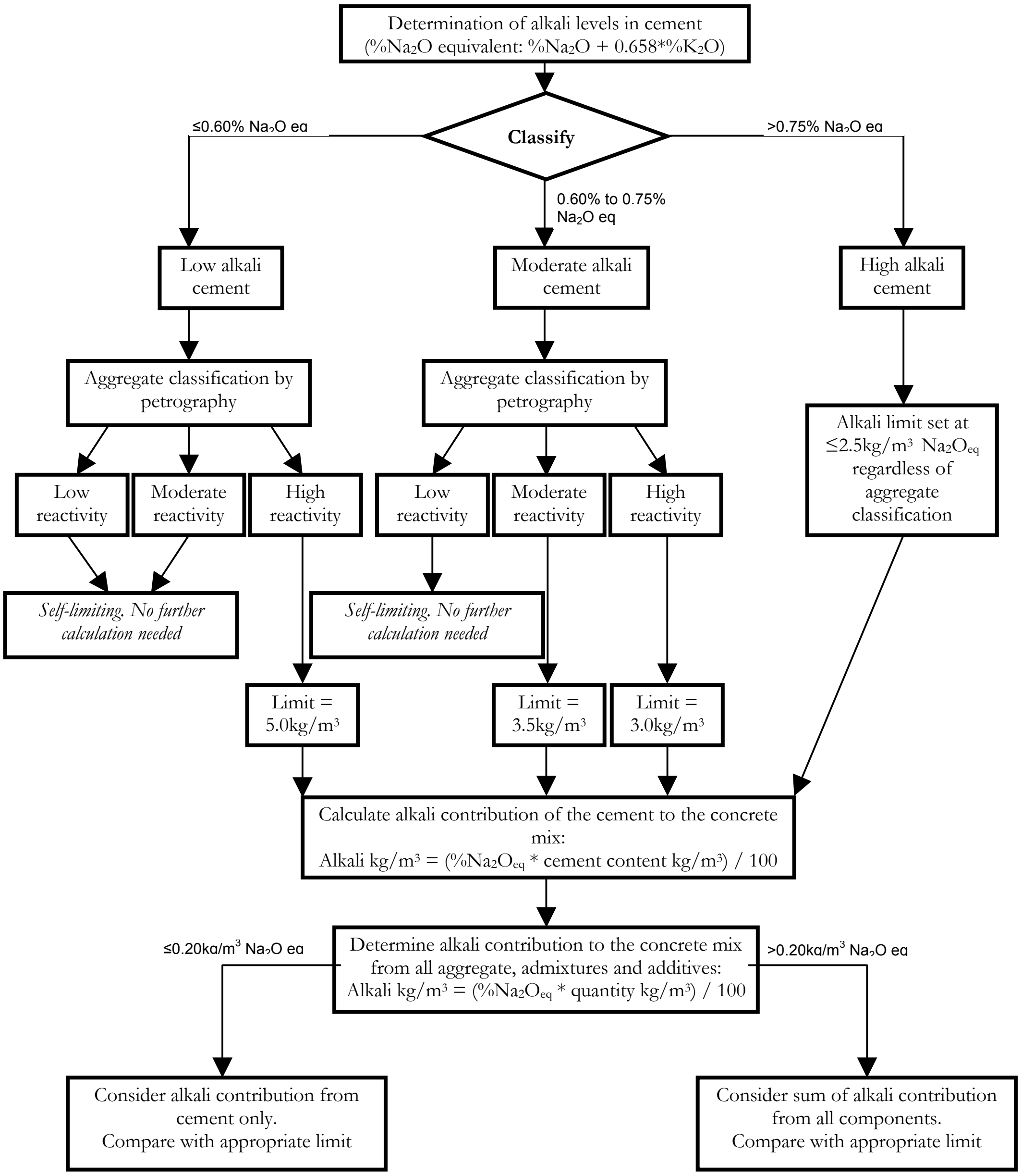

Figure 1: Flow chart of alkali level calculations for normal CEM-1 concrete mixes.

Plate 1: Columns and soffits of investigated office building, Hampshire.