Why the BS 8500 durability tables are the way they are

The British Standard for concrete durability recommendations are set out in a format partly standardised at European level by EN 206[1] but extended to include cover where corrosion of reinforcement is considered. The recommendations were developed from a combination of UK experience and some consideration of durability modelling. As set out in BS 8500-1[2] Tables A.4 and A.5, they are for intended working lives of up to 50 and up to 100 years respectively. ***Chris A Clear*** *– of the* ***British Ready-Mixed Concrete Association*** *and chair of* ***BSI Technical Committees: B/517 Concrete, B/517/1 Concrete production and testing*** *and* ***B/517/1/20 Concrete – Specification and Production*** *– sets out some of the background, history and incorporated relationships to these tables.*

The BS 8500-1 guidance is deemed to be sufficient for the majority of civil engineering and building works but for particular applications reference to alternate Standards or specialist literature may be considered desirable.

For agricultural buildings BS 5502-21[3] and BS 5502-22[4] should be referred to and for maritime works then BS 6349-1-4[5] may be considered most appropriate. As the maritime Standard contains durability recommendations for seawater exposure then engineers have questioned why these are not the same as those contained within BS 8500-1. In terms of water:cement (w/c) ratio, the recommendations are aligned but the BSI committee responsible for BS 8500-1 decided to retain a standard set of relationships between maximum w/c ratio, minimum cement or combination content, and strength class, and this meant that complete alignment with BS 6349-1-4 was not possible.

Brief history

Standards committees generally adopt the policy of only modifying guidance where there is both a need and technical justification to do so. For this reason the history of the durability recommendations inevitably influenced how they are today. As a historical comparison, the various British Standard recommendations for the durability of reinforced concrete exposed to what is now called XS3 for a design working life of not less than 50 years, are summarised here in Table 1 (page 50), for both CEM I and CEM III/A concretes. It is important to note that the current BS 6349-1-4 and BS 8500-1 requirements are the same in terms of maximum w/c ratio and nominal cover, and almost the same in terms of minimum cement content and strength class. It is also interesting to note the small increase in cover for CEM III/A concrete from 50 to 60mm, from 1972 to 2015. For CEM I concrete, the increase is significantly greater – from 50 to 90mm – with the large recent increase to nominal cover from 60 to 90mm with publication of the most recent editions of BS 6349-1-4 and BS 8500-1. It can be argued that what is currently understood by XS3 is not the same as the terms severe, very severe and extreme, as used by previous Standards, and for this reason the current exposure classes are reviewed in the next section.

Exposure classes

The current exposure classes were first aligned with Eurocodes with the first publication of BS 8500-1 in 2002. This introduced the EN 206 exposure classes with environments classified by their deterioration mechanism with respect to concrete or reinforced concrete. Table 2 (page 51) is a summary for corrosion induced by carbonation classes XC3, XC4 as well as corrosion induced by chlorides from seawater for XS1, XS2 and XS3. The table includes abstracts from informative examples applicable in the UK from BS 8500-1 and descriptions from the maritime Standard BS 6349-1-4. This comparison is indicative of the difficulty in trying to fully align the BS 8500-1 recommendations with those of BS 6439-1-4, as trying to define the required quality of concrete for a particular exposure is difficult where there are different interpretations of the exposure classes themselves.

For BS 8500, XC3 moderate humidity and XC4 cyclic wet and dry are amalgamated into class XC3/XC4, as it is regarded as impractical to distinguish between them for design. There is some logic to considering carbonation and chloride ingress mechanisms separately but in real terms a reinforced concrete element exposed to corrosion induced by chlorides XD1, XS1, XD3 and XD4 will always be subject to moderate humidity or cyclic wet and dry and so must also be exposed to XC3/4 carbonation as well. The BS 8500-1 recommendations take this into account within its Tables A.4 and A.5. For exposure class XC3/4 in combination with XD3, XS1 or XS3 at any cover, then a minimum strength class of C25/30 is set, with a minimum cement or combination content of 320kg/m^3 at a maximum w/c ratio of 0.55 irrespective of cement type.

Highest minimum cement content

The maximum strength of the aggregate largely controls the maximum strength that can be achieved by the concrete from which it is made. Where the cement or combination contains proportions of additions, such as fly ash in excess of around 20% or GGBS in excess of around 50%, then this also influences the 28-day ceiling strength. This may be because it may take two months or

Table 1 – Summary of reinforced concrete[A] durability requirements for exposure class XS3[B] for an intended working life of not less than 50 years

Code of Practice, British Standard	Concrete made with: Portland cement, CEM I				Concrete made with: Blast-furnace cement, CEM III/A[C]			
	mcc[D], kg/m^3	mwc[E]	$f_{ck,cube}$ MPa	c_{nom}[F] mm	mcc[D], kg/m^3	mwc[E]	$f_{ck,cube}$ MPa	c_{nom}[F] mm
CP 110-1: 1972	330	0.45	50	50	330	0.45	50	50
BS 6349-1: 1984	400	0.42	40	50	400	0.42	40	50
BS 8110-1: 1985	400	0.45	50	50	400	0.45	50	50
BS 8110-1: 1997	400	0.45	50	50	400	0.45	50	50
BS 6349-1: 2000	400	0.40	50	60	360	0.50	37	50
BS 8500-1: 2002	360	0.40	50	60	360	0.40	45	50
BS 8500-1: 2006	380	0.40	50	60	380	0.40	45	50
BS 6349-1-4: 2013	360	0.35	50	90	380	0.35	50	60
BS 8500-1: 2015	380	0.35	55	90	380	0.35	50	60

A) Maximum aggregate size 20mm
B) Assuming XS3 is equivalent to exposure classes previously described as severe, very severe or extreme
C) Assuming a nominal GGBS content of 40%, representative of UK Portland blast-furnace cements 1925–1990
D) Minimum cement or combination content
E) Maximum free water:cement ratio
F) Nominal cover assuming required minimum cover plus an allowance of 10mm.

more for these cements to react as much under standard curing as a Portland cement (CEM I) does in 28 days. Figure 1 shows a set of idealised relationships between 28-day strength and cement or combination content. Without testing, it is not possible to assess what the ceiling strength will be, but it is evident that the ceiling strength is approached where the cement or combination content is around 380kg/m^3. The highest minimum cement content in all the BS 8500-1 durability tables is set at 380kg/m^3.

Compressive strength class

For concrete design, the designer selects a compressive strength class and for the most economic design it is ideal if the strength class is just achieved at the maximum w/c and minimum cement content specified.

Due to the inherent differences in performance of the range of cements, additions and use of chemical admixtures across the UK, it will never be possible to define these relationships.

Notwithstanding this, there is some confidence that from a maximum w/c ratio and minimum cement content it is possible to identify an indicative strength class that should be achievable in most locations around the UK where local natural aggregates for concrete are used.

On this basis, a relationship is incorporated into BS 8500-1 within a combination of the carbonation tables and a table linking the maximum w/c ratio to a minimum cement content, for a range of maximum aggregate sizes. For designated GEN and RC concretes, and XC exposures classes to BS 8500-1 Tables A.4 and A.5, the incorporated relationships are summarised in Table 3 (page 52).

The 'associated strength classes' within Table 3 are largely indicative and the intention is to simply indicate a strength class that a designer could be reasonably confident of achieving at the maximum w/c ratio and minimum cement content. Where designated concretes are specified or where a strength class is specified then the strength class is a requirement and the producer may need to use a lower w/c ratio and higher cement content than that indicated to achieve the required strength class.

For XC exposure classes, the BS 8500-1 durability requirements are based on strength class, where the higher the strength the higher the resistance to carbonation. This comes from the established BRE view that for CEM I concretes, or concretes containing combinations of CEM I with either up to around 30% fly ash or up to around 50% GGBS, then the rate of carbonation just depends on strength class.

Chloride ingress

Resistance to chloride ingress is mainly dependent upon the cement type and the w/c ratio, with aggregate quality being a secondary factor. The 2002 version of BS8 500-1 introduced the concept that where higher proportions of fly ash or GGBS are incorporated as part of the cement in concrete then a lower strength class is to be expected. In the realisation that reinforced concrete exposed to chloride ingress is particularly vulnerable to corrosion, there is an increase in the standard minimum cement contents at each w/c from 0.35 to 0.60 by 20kg/m^3 relative to the recommendation for other exposure classes. A maximum w/c ratio for concrete exposed to chloride ingress was set at 0.60, but the 0.60 maximum only applied to the XD1 exposure class where carbonation is considered the dominate deterioration mechanism. These relationships that set the pattern for the current BS 8500-1 Tables A.4 and A.5 are summarised in Table 4 (page 52).

The strength classes for XS and XD exposures were developed on an indicative basis although BS 8500-1 does not describe

Table 2 – EN 206 exposure classes XC3, XC4 and XS

EN 206 class designation		EN 206 description of the environment	BS 8500-1: 2015 Table A.1 – abstracts from informative examples applicable in the UK	BS 6349-1-4: 2013 Table 1 and 2 exposure descriptions
Corrosion induced by carbonation	XC3	Moderate humidity	External reinforced and prestressed concrete surfaces sheltered from, or exposed to, direct rain… …Reinforced or prestressed concrete surfaces protected by waterproofing	–
	XC4	Cyclic wet and dry		–
Corrosion induced by chlorides from seawater	XS1	Exposed to airborne salt but not in direct contact with seawater	External reinforced and prestressed concrete surfaces in coastal areas	Airborne salt environment – exposed to airborne salt but not in contact with seawater or splash
	XS2	Permanently submerged	Reinforced and prestressed concrete surfaces completely submerged or remaining saturated, eg, concrete below mid-tide level	Submerged environment – permanently submerged
	XS2/XS3	–	–	Frequently wetted lower tidal, backfilled
	XS3	Tidal, splash and spray zones	Reinforced and prestressed concrete surfaces in the upper tidal zones and the splash and spray zones, including exposed soffits above seawater	Infrequently wetted upper tidal, splash/spray, 'dry' internal faces of submerged structures

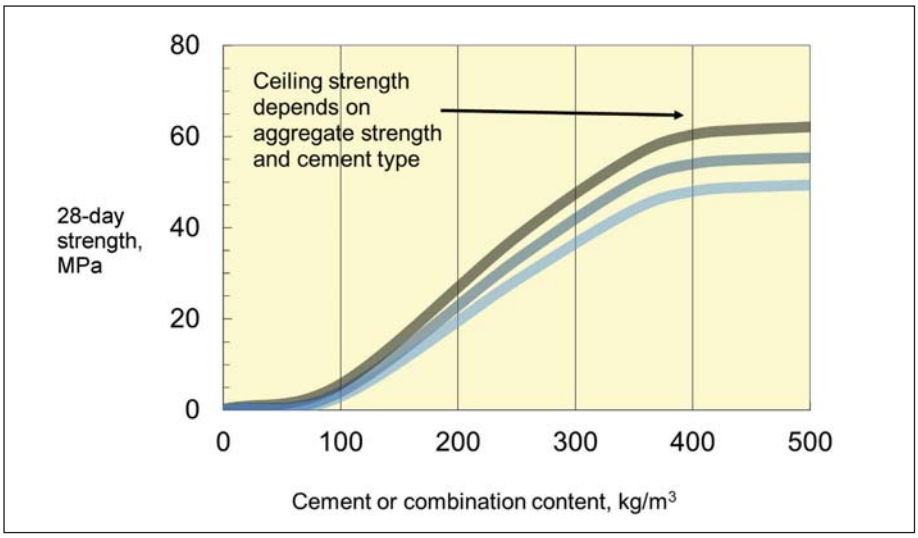

Figure 1: An idealised relationship pattern between 28-day strength and cement or combination content.

them as such, except for unreinforced concrete in seawater.

Lowest w/c values

Due to the most recent advances in admixture technology it is possible to produce and supply concrete at a maximum w/c ratio of 0.35, but as BS 8500 points out, it will not always be possible throughout the UK. Precast pre-tensioned concrete units made to a strength class of C40/50 or higher with cements containing less than 25% fly ash or 46% GGBS have been found to perform well. On this basis, for an intended working life of at least 100 years, a minimum cover of 35mm for XS1 exposure and 60mm for XS3 exposure is recommended for precast pre-tensioned concrete.

Freeze/thaw

Each 1% of entrained air is known to reduce 28-day strength by around 5% but strength is not as significant as entrained air for determining the durability against freeze/thaw conditions. For concrete to resist freezing and thawing, a minimum of 4% entrained air is recommended. So for air-entrained concrete it is not generally practical to compensate for the potential 20% or more strength reduction by using additional cement to reduce the w/c ratio where the strength class is C28/35 or higher. This is recognised within the BS 8500-1 Tables A.4 and A.5 where for air-entrained concrete exposed to freezing and thawing and ingress of chlorides the maximum strength class may be reduced to C28/35.

Future developments

Knights[6] provides some background to the revision of the BS 6349-1-4 durability tables, where modelling was carried out based on that outlined by Bamforth[7]. In terms of the requirements for w/c ratio, BS 8500-1 has incorporated the BS 6439-1-4 recommendations for resisting corrosion induced by chlorides from seawater and there is a wish that the requirements will be further aligned. It is accepted that for specialist maritime structures then there will be scope for more detailed guidance than that provided in the general concrete Standard.

It is also accepted that durability modelling, particularly with validation by field testing and with development and adoption of appropriate test methods, should be the basis for the most sustainable concrete durability design. Until modelling or other performance-based methods are developed for use in general construction, it is likely that the deemed to satisfy limit value approach as set out in the current BS 8500-1 will continue

Table 3 – Relationships[A] between w/c ratio, aggregate size and associated strength classes for designated GEN and RC concretes, and XC exposure classes to BS 8500-1

w/c ratio	Minimum cement content for maximum aggregate size of:				Designated concretes	Associated strength classes
	40mm	20mm	14mm	10mm		
—	—	120	—	—	GEN0	C6/8
—	—	180	—	—	GEN1	C8/10
—	—	200	—	—	GEN2	C12/15
—	—	220	—	—	GEN3	C16/20
0.70	240	240	260	280	RC20/25	C20/25
0.65	240	260	280	300	RC25/30	C25/30
0.60	360	280	300	340	RC28/35	C28/35
0.55	280	300	320	340	RC30/37, RC32/40	C30/37, C32/40
0.50	300	320	340	360	RC35/45	C35/45
0.45	320	340	360	360	RC40/50	C40/50
0.40	360	380	380	380	—	—
0.35	380	380	380	380	—	—

A) Relationships where there is no exposure for corrosion induced by chlorides (XS or XD exposure classes). This includes the relationships incorporated within BS 8500-1 Tables A.4 and A.5 corrosion induced by carbonation (XC exposure classes), BS 8500-1 Tables A.7 and A.15

Table 4 – BS 8500-1 Tables A.4 and A.5 relationships between w/c ratio, minimum cement content and 28-day strength for XD2, XD3, XS1, XS2 and XS3 exposure

w/c ratio	Min. cement content	Cement type			
		CEM I,IIA, IIB-S, CEM I-SR0, CEM I-SR3	IIB-V, IIIA	IIB-V ≥25% fly ash, IIIA ≥46% GGBS	IVB-V, IIIB
0.55	320	C28/35	C25/30	C25/30	C20/25
0.50	340	C32/40	C28/35	C28/35	C25/30
0.45	360	C35/45	C32/40	C32/40	C28/35
0.40	380	C40/50	C35/45	C35/45	C32/40
0.35	380	C45/55	C40/50	C40/50	C35/45

A) Strength values included BS 8500-1: 2015+A1: 2016 Tables A.4 and A.5

to have a part to play for the design of durable reinforced concrete. ■

References

1. BRITISH STANDARDS INSTITUTION, BS EN 206. *Concrete – Specification, performance, production and conformity*. BSI, London, 2013, incorporating corrigendum May 2014.
2. BRITISH STANDARDS INSTITUTION, BS 8500. *Concrete. Complementary British Standard to BS EN 206. Part 1 – Method of specifying and guidance for the specifier*. BSI, London, 2015+A1:2016.
3. BRITISH STANDARDS INSTITUTION, BS 5502-21. *Buildings and structures for agriculture. Part 21 – Code of practice for selection and use of construction materials*. BSI, London, 1990.
4. BRITISH STANDARDS INSTITUTION, BS 5502-22. *Buildings and structures for agriculture. Part 22 – Code of practice for design, construction and loading*. BSI, London, 2003+A1:2013.
5. BRITISH STANDARDS INSTITUTION, BS 6349-1-4. *Maritime works. Part 1-4 – General. Code of practice for materials*. BSI, London, 2013.
6. KNIGHTS, J. Revised durability tables for reinforced concrete in the maritime environment. *Concrete*, Vol. 47, No.10, December/January 2013/2014, pp.40–42.
7. BAMFORTH, P.B. *Enhancing reinforced concrete durability. Guidance on selecting measures for minimizing the risk of corrosion of reinforcement in concrete*. Technical Report 61, The Concrete Society, Camberley, 2004.