An analysis of the potential for improving cement efficiency through functionally graded concrete elements with durability-driven concrete specification

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Abstract

Cement, the primary binding component of concrete, is responsible for 5-6% of global CO_2 emissions. In functionally graded concrete elements, properties are optimised by varying the concrete mix composition over the volume, allowing for allocation of cement intensive mixes only where necessary for resistance of load or aggressive substances. In practice, this is achieved by layering of different concrete mixes within the same formwork, providing an opportunity for reduction in overall cement content compared to conventional methods where a single concrete mix is used for entire elements. This work discusses possible applications for functionally graded elements that are optimised for durability resistance. Potential cement savings for various scenarios are calculated by comparison of traditional homogeneous concrete elements with functionally graded layered ones. The results show that the potential for reducing overall cement demand of structures whilst maintaining equivalent performance is significant.

Keywords: durability, mix design, functionally graded concrete

1 Introduction

Functionally graded concrete (FGC) describes concrete elements in which the material or structural properties are varied throughout the cross section. These variations are achieved by spatially varying the composition of the concrete mix. FGC is a growing area of research [1–4], owing to its potential for improvement of cement efficiency in concrete structures leading to a reduction in embodied emissions.

Concrete durability describes the ability of a particular concrete to resist damage from environmental exposure during its service life [5]. A durable concrete will effectively resist processes which lead to accelerated corrosion of steel (such as carbonation and chloride ingress [6]), as well as physical (e.g. abrasion, freeze-thaw weathering) and chemical deterioration (e.g. sulphate attack). Current design practice set out in the Eurocode BS EN 206:2013+A1 [7] requires designers to classify concrete elements into exposure classes dependent on the severity and nature of their environment – see Table 1.

Table 1. Exposure classes for durability specification, adapted from [[7]Table 1]

Class designation	Definition
X0	No risk of corrosion or attack
XC1 – XC4	Corrosion induced by carbonation
XD1 – XD3	Corrosion induced by chlorides other than from seawater
XS1 – XS3	Corrosion induced by chlorides from seawater
XF1 – XF4	Freeze-thaw attack
XA1 – XA3	Chemical attack (in UK this becomes ACEC)
XAS	Chemical attack from seawater

Mix design choices affect the overall durability of the concrete produced. Common measures used to improve resistance against various deterioration mechanisms are summarised in Table 2. Generally, durability of a traditional concrete is improved by reduction in the water/cement (*w/c*) ratio since this reduces the porosity of the material [8]. The consequence of this, for a workable mix, is an increase in the required cement content of the concrete.

Table 2 Mix design alterations to improve durability against various deterioration mechanisms

Deterioration Mechanism	**Mix design actions to improve durability**
Chloride ingress	Increasing the cover to reinforcement, decreasing the *w/c* ratio [12]
Carbonation	Decreasing the *w/c* ratio [13]
Sulphate attack	Decreasing the *w/c* ratio [14]. Use of sulphate resisting cements [15].
Freeze-thaw	Decreasing the *w/c* ratio and entraining microscopic air bubbles. [16,17]
Abrasion	Decreasing the *w/c* ratio, increasing compressive strength (up 60 MPa), applying surface treatments, and careful curing [18]

Cement manufacture is responsible for 5-6% of global CO_2 emissions [11] and is currently unable to be completely decarbonised owing to the chemical by-product of CO_2 in the clinker production process [9],[10]. Therefore, it is important to prevent over-prescription of cement through critical analysis of the durability design of concrete elements, which may drive up cement use.

The complimentary British standard to BS EN 206: BS 8500-1:2015+A2:2019 [19] is the British implementation of EN 206 [7]. BS 8500-1 places maximum *w/c* ratios, minimum strength requirements, and minimum cement content values on mixes deemed to satisfy particular exposure classes. More severe exposure classes require a higher minimum cement content, higher strength, and lower maximum *w/c* ratio. These limits from BS 8500-1 for a structural design life of 50 years and cement types CEM I, CEM IIA, CEM IIB-M or CEM IIB-S are summarised for XC and XD exposure classes by the heatmap in Figure 1. There are 13 different possible combinations of limits on cement content, strength, and *w/c* ratio in Figure 1. Similar trends are also observed in limits for XS exposure classes, whereby the required grade of concrete increases with severity of exposure classification, but are not presented here.

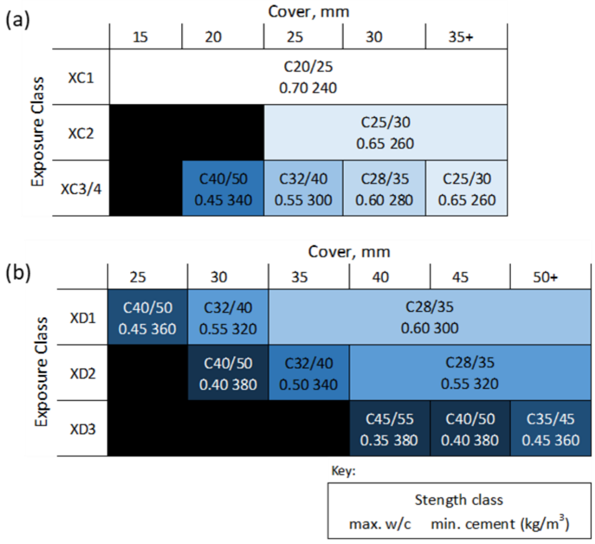

Figure 1 Limits imposed by XC and XD durability classes for a 50 year service life and CEMI, IIA, IIB-M or IIB-S concrete, adapted from BS 8500-1 [19]

For all XC, XD and XS exposure classes the required grade of concrete can be reduced by increasing the concrete cover. This recognises that the purpose of durability specification for these classes is to prevent aggressive substances (CO_2 molecules or chloride ions) from penetrating to the depth of the reinforcing steel during the service life of the structure. Therefore, durability can be improved by either increasing the distance to the reinforcement (nominal cover thickness) or the grade of concrete.

FGC also has promising applications to durability design since it enables those highly durable concrete mixes which satisfy higher exposure classes to be applied not only to the elements which are exposed to these conditions, but to the regions within elements where they are specifically required. Most durability concerns are superficial; they arise only at the surface of a concrete element. The concept of a using a high-durability zone on the exposed surfaces to protect internal concrete is therefore a logical optimisation of material properties. Studies indicate that there is strong potential for durability improvements with use of an FGC durability layer. For example, a surface layer of cementitious or polymeric material has been shown to be effective in improving durability against carbonation [20], permeability and crack-bridging performance [21], and chloride ion penetration [22], [23].

The following work initially presents a selection of designed virtual concrete mixes to establish baseline comparators. The XC and XD durability classifications of these mixes according to BS 8500-1 [19] are analysed with respect to the properties of the mixes and their cement contents. The use of a subset of these mixes in theoretical FGC elements are then compared to the same elements cast entirely from the mix that is required to satisfy durability requirements. This work aims to assess the potential for overall cement reduction with use of an FGC system.

2 Method

2.1 Virtual mix composition

A series of 11 virtual mixes were designed using the BRE method for design of normal concrete mixes [24] for mixes with characteristic cube strengths between 20 and 70 MPa, summarised in Table 3. Figure 2 shows how the proportions vary with strength in this family of mixes.

Table 3 Virtual concrete mixes

Mix	$f_{cube,k}$	w/c	Cement	Sand	Coarse agg.	Water
[-]	[MPa]	[-]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]
A	20	0.73	219	715	1331	160
B	25	0.66	241	680	1342	160
C	30	0.60	265	650	1349	160
D	35	0.55	289	622	1352	160
E	40	0.51	315	596	1351	160
F	45	0.47	343	572	1346	160
G	50	0.43	373	549	1339	160
H	55	0.40	405	527	1328	160
I	60	0.36	441	506	1313	160
J	65	0.33	480	485	1295	160
K	70	0.31	523	463	1272	160

All mixes are designed with a 52.5 N cement, a maximum (uncrushed) aggregate size of 20 mm, and a sand with 60% passing a 600-micron sieve. The assumed densities of these constituents are 3130 kg/m^3, 2600 kg/m^3 and 2600 kg/m^3 respectively. The target slump is 10-30 mm (slump class S1 in EN 206 [7]). This slump value was chosen since the layer stability in fresh-on-fresh cast FGC was found to be favourable for mixes of higher stiffness [25]. Furthermore, it is assumed that workability requirements for all mixes are constant for the study to be comparative (i.e. workability is constrained).

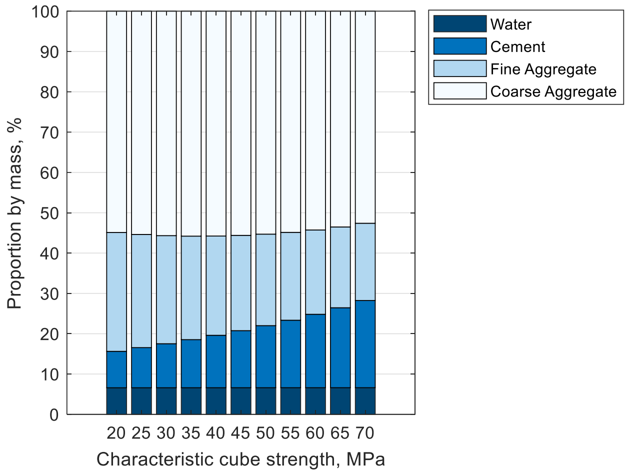

Figure 2 Mix proportions of the virtual mixes

2.2 The FGC durability layer

The durability layer thickness proposed for FGC elements in this work is kept constant such that all longitudinal reinforcement is encapsulated within this layer, as per recommendations of [26]. This also prevents issues with accelerated corrosion observed by [22] when the layer interface was at the level of the reinforcement. The durability layer thickness, t, is thus defined:

$$t = c + 1.5\phi \quad (1)$$

where ϕ denotes the diameter of the tensile steel and c denotes the cover distance from the extreme fibre of the tension steel to the near external face of the specimen. This is shown schematically in Figure 3. The structural depth, d, is defined as the overall specimen height, h, minus the cover, c:

$$d = h - c \quad (2)$$

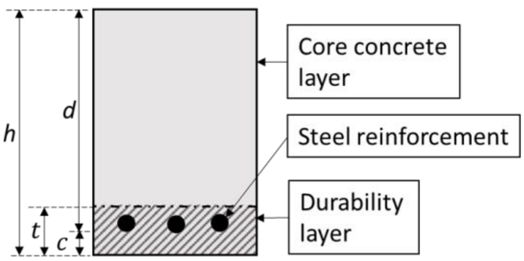

Figure 3 Example FGC element with durability layer

3 Results and Discussion

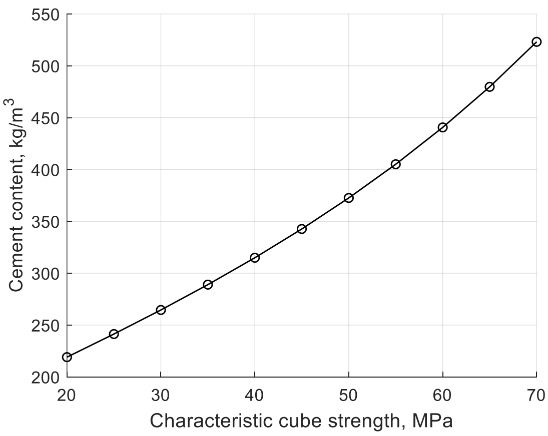

Figure 4 Characteristic cube strength vs cement content of virtual family of mixes designed by BRE method [24]

Figure 4 shows the strength of the virtual mixes plotted against their cement content. The cement content in kg/m^3, e_{mix}, may be used as a proxy for the environmental impact of a concrete mix as this is responsible for the majority of its embodied carbon [27]. As expected, the cement content is greater for higher strength concretes within this family of virtual mixes with the same constituents. This is consistent with the findings of Purnell and Black [28].

3.1 Durability classes of the virtual mixes

In the following analysis, limiting values on mix design parameters are taken from BS 8500-1 [19] for a structural service life of 50 years and cement types CEM I, CEM IIA, CEM IIB-M or CEM IIB-S.

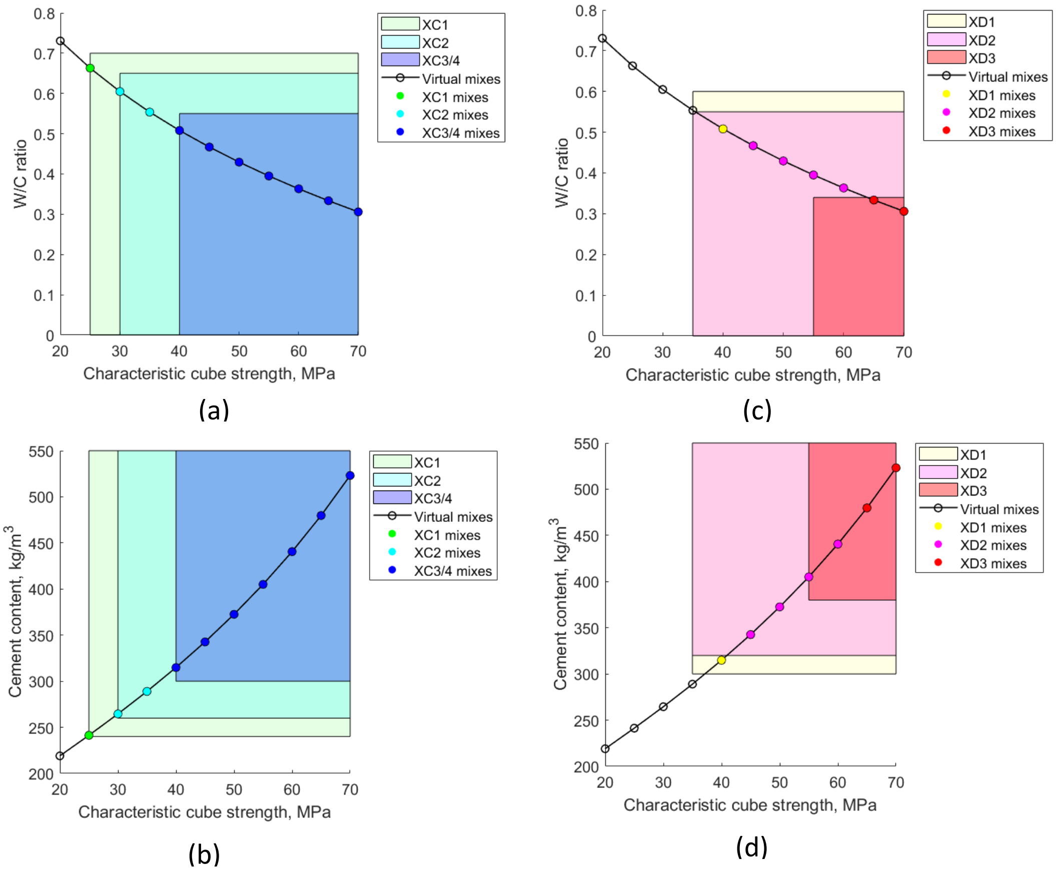

Figure 5 Class boundaries for a service life of 50 years according to BS 8500-1 [19] *compared to virtual mixes: (a) w/c ratio vs strength and (b) cement content vs strength for XC boundaries where c=25 mm; (c) w/c ratio vs strength and (d) cement content vs strength for XD boundaries where c=40 mm.*

3.1.1 Performance of virtual mixes

Figures 5(a) and 5(b) show the XC class boundaries for a fixed cover of 25 mm applied to the virtual mixes; whereas Figures 5(c) and 5(d) show the XD class boundaries for a fixed cover of 40 mm. The colour of the datapoint indicates whether all class requirements are satisfied by a particular mix. In all cases, satisfaction of a high class (e.g. XC3/4) implies satisfaction of lower classes of the same type (i.e. XC2 and XC1). In Figures 5(a) and 5(c) the limits on *w/c* ratio are maxima, so mixes with a satisfactory *w/c* ratio fall in the shaded region below this boundary. Conversely, as seen in Figures 5(b) and 5(d), limits on cement contents for the durability classes are minima, so the complicit regions lie above these limiting boundaries instead.

Using the relationship between *w/c* ratio and target strength from the BRE mix design method, which is adopted in these mix designs, the virtual mixes which satisfy the required compressive strengths all satisfy maximum *w/c* ratios specified by BS 8500 for the XC classes (Figures 5(a) and 5(b)). This is shown by Figure 5(a), in which all virtual mixes intersect the limits on strength but not *w/c* ratio. Conversely, Figure 5(b) shows that the limits on cube strength and cement content can both be limiting for the XC classes designed using the BRE method, as the virtual mixes intersect the corner of multiple class boundaries.

Within the XD class boundaries (Figures 5(c) and 5(d)) there are instances where either the maximum *w/c* ratio and/or minimum cement content is limiting whether a particular mix satisfies an XD class, rather than only the strength requirement. The result is that some mixes may appear in the shaded region of one class, but do not satisfy it completely and are therefore categorised as the class below. This suggests particular significance of the cement content to chloride resistance classification.

Figure 5 demonstrates that it is possible to satisfy durability classes with multiple mixes, and that selection of the mix with the lowest cement content for each class could enable immediate reduction of cement consumption in any project.

3.1.2 The influence of the concrete cover

In the plots in Figure 5, the concrete cover is fixed. However, Figure 1 shows there is an optimisation possible between cover to reinforcement, which ultimately results in greater volume of concrete being specified, and the cement content of that cover. For the majority of durability classes, selection of a higher cover enables a mix with a lower cement content to be utilised.

In conventional single-mix elements, the specification of a greater cover $c_2 > c_1$ with a lower cement content mix $e_{mix2} < e_{mix1}$ can result in overall decrease in the total cement content if:

$$d > (e_{mix2}c_2 - e_{mix1}c_1)/(e_{mix1} - e_{mix2}) \qquad (3)$$

assuming an increase in cover to bottom reinforcement of an element with structural depth *d*.

Of the mixes in this study, those with minimum cement content to satisfy XC3/4 for various values of cover are shown in Table 4.

Table 4 Minimum cement mixes from this study to satisfy XC3/4

Cover, *c*	**Optimal Mix**	**Cement content, *e***
[mm]	[-]	[kg/m^3]
20	G	373
25	E	315
30	D	289
35	C	265

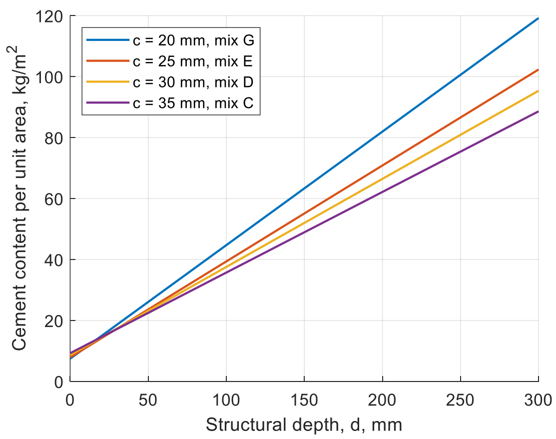

Figure 6 Minimum achievable total cement content vs structural depth to satisfy XC3/4 using the virtual mixes, shown for optimal mixes at various values of concrete cover

Figure 6 shows the cement content per unit area (calculated as $h \times e_{mix}$) of an element made from each of the Table 4 mixes which satisfy XC3/4 for a different value of cover, plotted against structural depth, *d*. For all structural depths greater than 17 mm, the lowest overall cement content per unit area is achieved using the highest cover (35 mm) and mix C. In this case, the lower cement mix has a greater effect on the overall cement content of the element than the required increase in cover when compared to the alternative options.

Conversely, in functionally graded concrete with a durability layer thickness $t = c + 1.5\phi$, the specification of a lesser cover $c_2 < c_1$ with higher cement content $e_{mix2} > e_{mix1}$ can result in a decrease in cement content of the durability layer, *t*, if:

$$e_{mix1}t_1 > e_{mix2}t_2 \tag{4}$$

When the core mix is unchanged, with cement content e_{mix1}, the result is a decrease in total cement content of the element.

Using the mixes from Table 4, Figure 7 shows that for a required XC3/4 class concrete, the cement content of the durability layer is minimised by using a cover of 25 mm and mix E for any bar diameter below 18 mm. Above this diameter, a durability layer of mix C with cover of 35 mm is optimal instead.

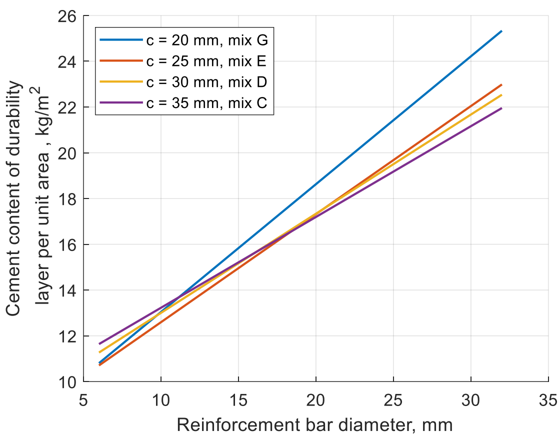

Figure 7 Minimum achievable cement content of durability layer vs reinforcement bar diameter using the virtual mixes to satisfy XC3/4, shown for various values of concrete cover

In the case of FGC, there are further opportunities for cement savings accessible by changing the mix used in the core of the element (e_{mix1}) to one with an even lower cement content than permitted by the durability class (e_{mix3}) such that $e_{mix3} < e_{mix1}$.

3.2 FGC layered element

A typical horizontal flat element is proposed to be made from the virtual mixes. The conceptual element is assumed to have a structural depth requirement of 150 mm and an exposed soffit, such that the exposure class must be satisfied by the concrete at this surface only. The element is shown schematically in Figure 8, for the scenarios with and without the FGC durability layer.

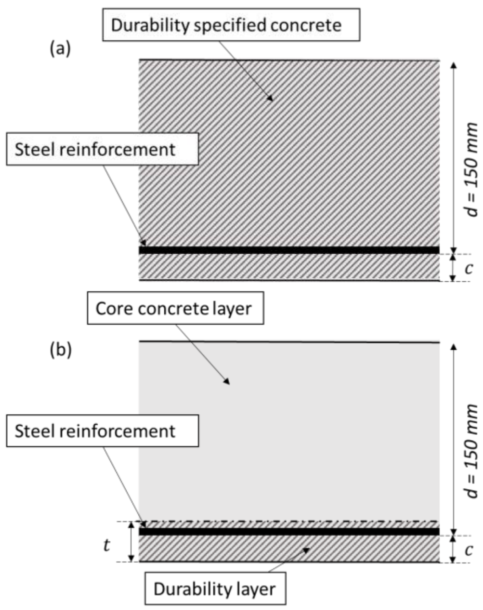

Figure 8 Proposed flat element (a) without FGC durability layer and (b) with FGC durability layer

For any given exposure class, the cement content savings through use of FGC will depend on optimisation of the relative cement content of the two mixes and the cover to reinforcement.

3.2.1 Relative savings from horizontal layers

For a generic horizontal prismatic element similar to that in Figure 8(b) with a horizontal durability layer of thickness t made from a mix with cement content $e_{durability\ mix}$, a bulk mix with cement content $e_{core\ mix}$ and total height $h = d + c$, the cement savings compared to a base case with $e_{durability\ mix}$ over the whole height can be seen in Figure 9.

Figure 9 shows that the total cement content of the element for a fixed $e_{durability\ mix}$ and height, h, can be reduced either by reduction of $e_{core\ mix}$ or increase in durability layer thickness, t. Alternatively, for fixed durability thickness, t, Figure 9 demonstrates that greater savings can be made in larger depth elements, when the higher-cement durability mix forms a smaller proportion of the structural depth and t/h is low.

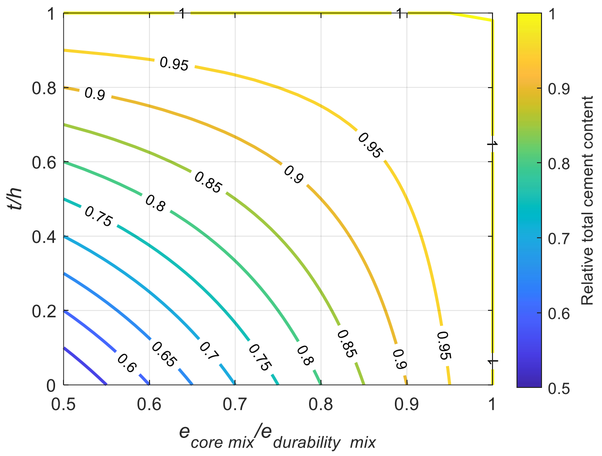

Figure 9 Cement content per unit exposed area of a layered section of total thickness h with layer thickness t, relative to $e_{durabiltiy\ mix}$

3.2.2 Possible savings

There are, therefore, four steps in the optimisation of cement content in a horizontal element with durability-driven concrete specification. These are:

1. For a traditional element with a single concrete mix, choose the concrete with the minimum cement content that satisfies the durability class required.
2. Adjust the cover on the traditional element in (1) so that the total cement content is minimised.
3. Use an FGC durability layer with the mix from (2) and replace the concrete in core of the element with the minimum structural grade mix containing the minimum cement content.
4. Adjust the cover on the FGC element from (3) to ensure that the cement content of the durability layer is minimised.

Considering a flat element with structural depth requirement of 150 mm, longitudinal steel diameter of 12 mm, and a minimum strength for structural resistance of 25 MPa (C20/25 grade concrete), the lowest cement mix that could be used in any scenario is mix B. Therefore, this is the core mix that would be used in FGC layered elements of this geometry. However, mix B is unlikely to satisfy aggressive exposure classes. Table 5 shows the impact of following steps 1-4 on the total cement content per area of exposed surface of this element for various XC and XD exposure classes. All the mixes are selected from the virtual mixes in Table 3.

Table 5 Cement reduction of exemplar element designed for durability resistance, from step 1 to step 4

Key:
Durability mix / Core mix
Concrete cover [mm]
Cement content of element [kg/m²]

Durability class	Step 1	Step 2	Step 3	Step 4	Total reduction
	B*	B*	B*/B	B*/B	
XC1	25	15	15	15	6%
	42.2	*39.8*	*39.8*	*39.8*	
	C	C	C/B	C/B	
XC2	25	25	25	25	7%
	46.3	*46.3*	*43.2*	*43.2*	
	E	C	C/B	E/B	
XC3/4	25	35	35	25	18%
	55.1	*48.9*	*45.9*	*45.4*	
	E	E	E/B	G/B	
XD1	40	35	35	25	20%
	59.8	*58.3*	*48.5*	*47.9*	
	F	F	F/B	F/B	
XD2	40	35	35	35	23%
	65.1	*63.4*	*50.0*	*50.0*	
	J	G	G/B	G/B	
XD3	40	50	50	50	37%
	91.1	*74.5*	*57.2*	*57.2*	

* mix limited by structural strength requirements, not durability design

The base case, step 1, is already partially optimised such that the lowest possible cement mix is chosen for a standard value of cover (25 mm for XC classes and 40 mm for XD). The durability mixes are selected for this case using Figure 5.

By applying steps 2-4, up to a further 37% in savings is achieved, when compared to the partially optimised solution of step 1. Improvements are revealed through a combination of optimisation of mix design, cover, and implementation of the FGC durability layer. The resultant specimens have lower total cement content without loss of durability.

Of the four steps in Table 5, the greatest reduction is consistently observed at Step 3 – with the introduction of an FGC durability layer. Overall, the greatest reductions are possible in more severe exposure classes, where minimum cement content limits for durability design are highest.

The same analysis is possible for different specimen geometries and would give different numerical results. However, 150 mm + cover is considered a typical enough thickness that these results are representative of a trend for significant possible cement reductions in flat elements with application of an FGC durability layer. In this scenario a single exposed surface was modelled, but this could be extended to two durability layers on both the soffit and topside if required.

Alternative blended cements, service life requirements and exposure class groups (e.g. XA, XS, XF) are not covered in this work, but the trends highlighted are representative since the general behaviour of increasing cement content for increasing severity of exposure is true for any broad designation cement, service life duration or exposure class in BS 8500-1 [19].

4 Conclusions

For any given type of cement blend, the durability of concrete is increased by reduction of the *w/c* ratio. For fixed workability requirements this leads to an increase in the total binder content of a concrete mix.

Many different concrete mixes can satisfy mix design constraints enforced by BS 8500 for any particular exposure class. Selection of the mix with minimum cement content to satisfy exposure requirements is vital in reducing overall cement specification whilst conforming with EN 206.

Cover to reinforcement plays a role in the durability class specification, acknowledging that, in diffusion driven processes such as carbonation and chloride ingress, both the distance to reinforcing steel and resistance of the material in the concrete cover will influence the eventual time for aggressive substances to reach the steel. In both traditional single mix elements and functionally graded concrete (FGC) layered elements, altering the cover can lead to a reduction in total cement content through reducing total concrete volumes or reducing cement content requirements of the concrete.

Functionally graded concrete offers significant potential for reduction in total cement content by replacing most of the concrete in an element with a lower grade mix with lower cement content. Savings of up to 37% compared to an already optimised selection of concrete for exposure class XD3 were estimated.

5 Acknowledgements

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