

# COMBINING DURABILITY AND SUSTAINABILITY IN MATERIAL SELECTION FOR CONCRETE

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**ABSTRACT.** The paper is concerned with selecting materials for concrete that is both durable and sustainable and the issues associated with achieving this. The paper starts by reviewing the current situation in standards and then progresses to consider the work of several studies exploring sustainability options for concrete (through novel cement combinations, efficiency in mix proportioning and alternative aggregates) and their influence on various aspects of durability (including carbonation rates, chloride ingress and freeze/thaw attack). It is demonstrated that these can be used to effectively match the performance of conventional concrete. The paper then explores the relationship between durability (chloride ingress) of various cement combination concretes and their environmental impact (measured in terms of embodied CO<sub>2</sub> (ECO<sub>2</sub>)). This suggests that there is likely to be the need for some compromise in achieving performance and lowest ECO<sub>2</sub>. It is also noted that some of the low ECO<sub>2</sub> concretes require longer times to attain the early strength necessary for structural applications. Thus factors relating to construction may also need to be included when considering durability and sustainability in the material selection process.

**Keywords:** Durability, Sustainability, Cement, Material selection, Embodied CO<sub>2</sub>

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## **INTRODUCTION**

Recent developments in concrete technology mean that there are now an increasing number of choices available for meeting specific construction needs. These include a broader range of cements and combinations, new admixtures and alternatives to natural aggregates. With the increased understanding of materials, their interaction, and how they function under different conditions, a growing number of issues require to be considered during the material selection process.

Among these, durability has received increasing attention, and with the research carried out and experience gained, this is now covered in greater detail within BS 8500 [1] than in earlier standards. There has also been a growing awareness by industry of the role of sustainability in the construction process. Indeed, many clients in the public sector are now insisting on this as a key design requirement and may select suppliers on the basis of their record in this area.

While these have become important matters with regard to design and material selection, they have tended to be examined separately. For progress to be made in this area, their collective consideration is required. Furthermore, this needs to be carried out with regard to other technical demands of construction. These represent the focus of this paper, which summarises the outcomes of research carried out at Dundee University in partnership with industry and looks ahead at how they may be achieved.

## **CURRENT MATERIAL REQUIREMENTS FOR CONCRETE**

Given the paper is concerned with sustainable options for cements and aggregate in concrete, it is appropriate to consider how these are covered in current standards. BS 8500 requires that the constituents of concrete conform to the appropriate standards, BS EN 197-1 [2] for cements and BS EN 12620 [3] for aggregates.

For cements and additions, including materials such as fly ash, silica fume, etc, the European standard, BS EN 197-1 defines the constituent properties and quantities they can be combined in and testing / conformity criteria that apply. Cement combinations are referred to in BS 8500, where they are used in the process of selecting mix proportions, strength of concrete and cover to reinforcement for different exposures.

BS EN 12620 defines aggregate as: (i) natural (from mineral sources subject to nothing more than mechanical process), (ii) manufactured (resulting from industrial process involving thermal or other modification and (iii) recycled (resulting from processing of inorganic material previously used in construction).

Coarse recycled concrete aggregate (RCA), as given in (iii) above, can be used in concrete, providing certain requirements are met. However, the adoption of their fine fractions is left to the project specification, which can take account of the particular source. For durability, coarse RCA can be used in less aggressive conditions (i.e., exposure classes X0, XC1-XC4, XF1, DC-1). Some details of coarse recycled aggregate (RA) are provided, however, it is considered that with their wide range of potential compositions, they need to be assessed on a case-by-case basis. Fine RA is not covered but again their use may be possible in individual cases.

## SUSTAINABLE OPTIONS FOR CONCRETE

In exploring sustainable options for concrete, three possible routes were considered. These can be classified in general terms under (i) **cement selection**, including binary and ternary combinations, (ii) **material proportioning** or combination and (iii) **recycled / waste materials** not covered in specification documents or standards.

### Cement Selection

There are an increasing number of different cementing materials available beyond Portland cement (PC). These are physically and chemically different to PC (as shown in Table 1) and there is therefore potential for manipulating their combinations to achieve optimum binding capacity of aggressive, ingressing agents and densifying the microstructure.

Among the main materials finding use in Western Europe and elsewhere are those exhibiting pozzolanic or latent hydraulic properties including fly ash (FA) and ground granulated blastfurnace slag (GGBS). Other materials including silica fume (SF) and metakaolin (MK) have also been introduced more recently.

Table 1 Typical chemical and physical characteristics of common cements

PARAMETERS	PC	GGBS	FA	SF	MK
<i>Chemical Characteristics (Oxide analysis)</i>					
SiO <sub>2</sub>	20.0	37.0	48.0	92.0	55.0
Al <sub>2</sub> O <sub>3</sub>	5.0	11.0	26.0	0.7	40.0
Fe <sub>2</sub> O <sub>3</sub>	3.0	0.3	10.0	1.2	0.5
CaO	65.0	40.0	3.0	0.2	0.1
MgO	1.1	7.0	2.0	0.2	0.4
SO <sub>3</sub>	2.4	0.3	0.7	-	2.0
S <sup>2-</sup>	-	1.0	-	-	-
Na <sub>2</sub> O	0.2	0.4	1.0	1.2	-
K <sub>2</sub> O	0.9	0.7	3.0	1.9	-
<i>Physical Characteristics</i>					
Fineness, m <sup>2</sup> /kg	340	350	380	15,000	10,000
Loss on Ignition, %	1.0	-	5.0	-	-
Bulk Density, kg/m <sup>3</sup>	1400	1200	900	240	360
Specific Gravity, g/cm <sup>3</sup>	3.1	2.9	2.3	2.2	2.4

The characteristics of these materials mean that they can contribute one or all of the following, towards the provision of enhanced durability.

- High alumina content, (except SF; which in FA is 6 times that of PC, in GGBS 2 times and in MK 8 times). This is also likely to be in amorphous form, with a high chloride binding capacity.
- Large numbers of well dispersed fine particles available to absorb aggressive agents.
- Potential for blocking and increasing the length of pathways into concrete.

There has also been a growing awareness that it may be possible to get further enhancement of performance, e.g. strength and durability, by combining two or three materials with PC. Developments in the European cement standard (BS EN 197-1) where combinations beyond binary cements are permitted, means that the use of cements comprising a range of materials may start to be more widely considered. These materials should allow engineers, through careful selection and combination, to produce cement blends to meet particular concrete property requirements.

## Material Proportioning

The importance of mix limits (covering, cement content, w/c ratio and strength) for durability provisions in Standards is evident from the wide use of this approach. The basis for this has mainly been local experience and little work to evaluate their role on performance has been carried out. The influence of these parameters is clearly important for effective material use by engineers. From an environmental point of view, advantages could be gained if it was possible to reduce cement contents in concrete. In following this type of approach, it may be necessary to consider the wider use of fillers to achieve a closed structure and admixtures to control consistence.

Other developments have also seen the introduction of mix proportioning techniques, aimed at physically minimising the void space of solids in concrete, see Figure 1. This type of approach to mix proportioning [4] has started to find wider coverage and is based on the principle that when materials of different sizes are mixed together, smaller particles will tend to fill voids between larger ones to form a mixture with minimum voids. The method achieves this by taking account of the physical characteristics of the materials in the mix (including the mean particle sizes of all constituents, their voids ratio and relative density) and provides optimum proportions of each constituent.

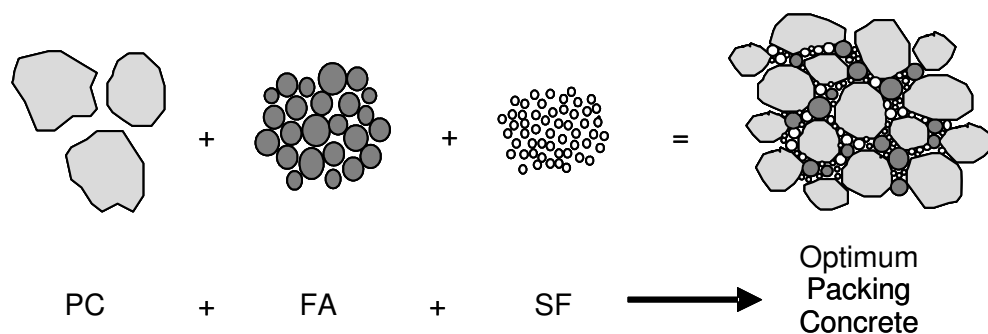


Figure 1 Concept of particle packing using different sized materials to minimize voids

## Recycled / Waste Materials not Covered in Standards

The potential for using domestic, industrial and construction waste products in concrete as cement components and aggregates is significant, as shown in Table 2. Whilst this is true, much of these materials are wasted by disposal at landfill sites. Although some have found use as a general fill, there is clearly scope for their use in higher value applications, such as concrete [5]. Carbonation is the process by which carbon dioxide present in air diffuses into concrete.

When used appropriately, it has been shown that these materials may,

- Create high performance aggregates to conserve natural mineral resources
- Contribute to sustainable construction
- Reduce waste disposal costs
- Minimise dependency on landfill

Clearly, given their novelty, the route to the use of these materials in construction needs to be research and development work and thereafter by site trials

## CONCRETE DURABILITY PERFORMANCE

Given the range of materials referred to above and the sustainable methods described, the following section provides selected examples to demonstrate their effects on various aspects of concrete durability.

Table 2 Potential quantities of material available for use in concrete in the UK

MATERIAL	ARISINGS (p.a.)	USES IN CONCRETE
Recycled aggregates	109 Mt	As coarse aggregate
Conditioned FA (moist)	> 4 Mt	As cement component/fine aggregate
Glass	> 2 Mt	As fine aggregate
Incinerator ash	1 Mt	As aggregate. Finer fractions have potential pozzolanic properties
Granulated rubber	> 40 Mt	Specialist applications

### Carbonation Rates

Carbonation is the process by which carbon dioxide present in air diffuses into concrete and chemically reacts with calcium hydroxide, produced during cement hydration. This leads to the formation of calcium carbonate with an associated reduction in alkalinity. Carbonation continues from the concrete surface and in time, the neutralisation effect breaks down the passive oxide layer protecting embedded steel. In the presence of moisture and oxygen, carbon steel reinforcement will corrode.

Results from a series of tests on concretes exposed for 2 years to laboratory and field conditions, and projected to 35 years service, using modelling techniques, are shown in Table 3 [6]. These indicate that at equal design strength, there was little or no difference in measured carbonation depth of concrete with different cement types. Not surprisingly, the environmental conditions were the most important factor. For specific aspects of concrete durability performance, including carbonation rate, chloride ingress, sulphate attack, freeze/thaw attack and abrasion, it is demonstrated, through the work of a series of projects, that the various sustainable options can be used effectively to match and in some cases give improvements in concrete performance compared to conventional concrete.

Table 3 Comparison of long-term carbonation performance of concretes based on estimations from laboratory and field data

EXPOSURE CONDITION	35 YEARS NORMALISED DEPTH OF CARBONATION OF 1 DAY STANDARD CURED 37 N/mm <sup>2</sup> CONCRETE, mm			
	PC	FA 30% <sup>(1)</sup>	MK 10% <sup>(2)</sup>	SF 5% <sup>(1)</sup>
Outdoor Sheltered	24	25	24	25
Outdoor Unsheltered	11	12	12	12

<sup>(1)</sup> Increased replacement levels showed slight increase in carbonation depth.

<sup>(2)</sup> Increased replacement levels showed slight increase in carbonation depth. Notable reduction in carbonation depth with increasing exposure to moisture. Outdoor unsheltered conditions showed little difference between PC, MK 10% and 15%.

Other test results from a study examining the role of cement content on carbonation are shown in Figure 2 [7]. These indicate that there was a gradual increase in carbonation depth with time during the 20 weeks accelerated test conditions. However, variations in cement content at fixed w/c ratio had little influence on carbonation and, in fact, slightly improved performance was noted as cement content was reduced. These suggest less cement could be used in concrete for equivalent performance. In these cases, limestone filler and superplasticizing admixture were used to maintain the fines content and consistence. Studies using particle packing mix proportioning techniques have shown that such methods can be used to bring minor improvements to carbonation resistance [8].

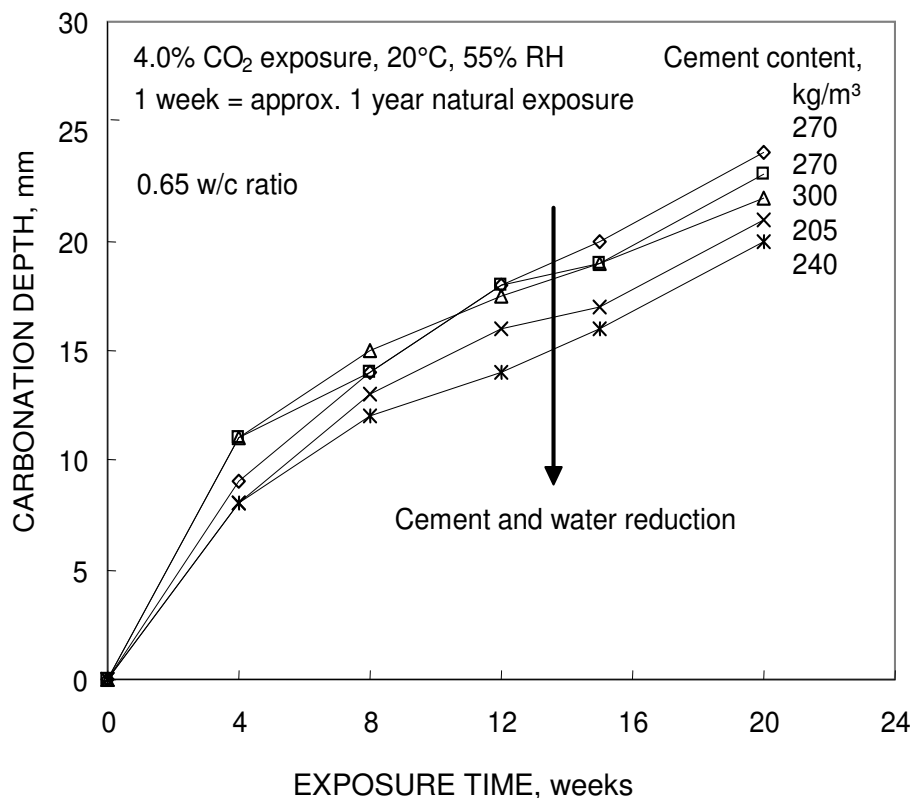


Figure 2 Role of cement content on carbonation resistance of concrete

## **CONCLUDING REMARKS**

The paper suggests that concrete for future construction needs to be durable, achieved following sustainable practices. Different options that may be followed, which fit within this are considered, including, cement selection, material proportioning and the use of recycled / waste materials are reviewed.

For specific aspects of concrete durability performance, including carbonation rate, chloride ingress, sulfate attack, freeze/thaw attack and abrasion, it is demonstrated, through the work of a series of projects, that the various sustainable options can be used effectively to match and in some cases give improvements in concrete performance compared to conventional concrete.

The paper concludes by providing an indication of how both durability and sustainability can be considered collectively and demonstrates that a compromise between these may be necessary. It is also noted that some of the low ECO<sub>2</sub> concretes extend the time to achieve early strength. As this may have implications for formwork removal and other construction-related processes, there is a need to either include such factors in the material selection process, or change the way construction is carried out, such as using on/off site precasting of certain key elements.

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