Low carbon concrete – what you need to know

Graham Couchman (SCI) and Jenny Burridge (the Concrete Centre) discuss the specification of 'low carbon' concrete for use in composite construction

Globally, concrete is the second most used material after water. In the UK we produce about 109 Mt of ready mixed concrete and precast concrete products annually (2017 figures). As structural engineers we therefore specify a lot of concrete every year, even when specifying steel-framed solutions given that most steel-framed multi-storey buildings use composite floors. More of us are now trying to lower our carbon footprint and produce lower carbon intensive projects. One of the ways we can do this is to look at how we specify the concrete we use, to ensure the most appropriate material is adopted. Significant improvements are possible, so alternatives are well worth considering.

Concrete mix and embodied CO_2

Concrete is made from aggregate, cement, and water. Admixtures can be (and normally are) included in the mix. In terms of embodied carbon for the different elements, aggregates and water have very low embodied carbon. Locally sourced primary aggregates have an embodied carbon of about 4kgCO_2/tonne. It is the cement, forming about 10-15% of the mix, which holds most of the embodied carbon.

All concretes to BS 8500[1] are based on Portland cement, or CEM1, but mostly contain additions, or other cementitious materials. These include:

- Ground granulated blast-furnace slag (GGBS)
- Fly ash
- Silica fume
- Limestone powder
- Pozzalana

These additions have a much lower embodied carbon than CEM1. Significant savings can be made to the embodied carbon of concrete by specifying mixes that include additions. Table 1 gives an indication of the savings that can be achieved by specifying the different cements.

Broad designation of cement type in concrete	Percentage of addition	Embodied CO_2 kgCO_2/m^3 of concrete
CEM1	0	283
IIA	6 - 20	228 - 277
IIB	21 - 35	186 - 236
IIIA	36 - 65 GGBS	120 - 198
IIIB	66 - 80 GGBS	82 - 123
IVB	36 - 65 fly ash or pozzalana	130 - 188

Table 1: Embodied CO_2 of UK concretes complying with BS 8500 (based on a cement content of 320kg/m^3 of concrete)

It is also worth noting that higher strength concrete requires a larger proportion of cement, all other things being equal, although this can be more than offset if the higher strength allows a lower volume to be used. Superplasticiser admixtures can also help reduce the embodied carbon by reducing the water/cement ratio. This provides a stronger concrete for the same quantity of cement.

To supplement concretes in accordance with BS 8500, most of the larger concrete producers have low carbon proprietary concretes. These are formulated to keep the embodied carbon down to a given level, and may therefore be particularly interesting to the specifier. The producers are happy to provide advice on what can be achieved for the location and needs of the project, but it is important that the structural designer knows how to interpret the information they provide. This is discussed here.

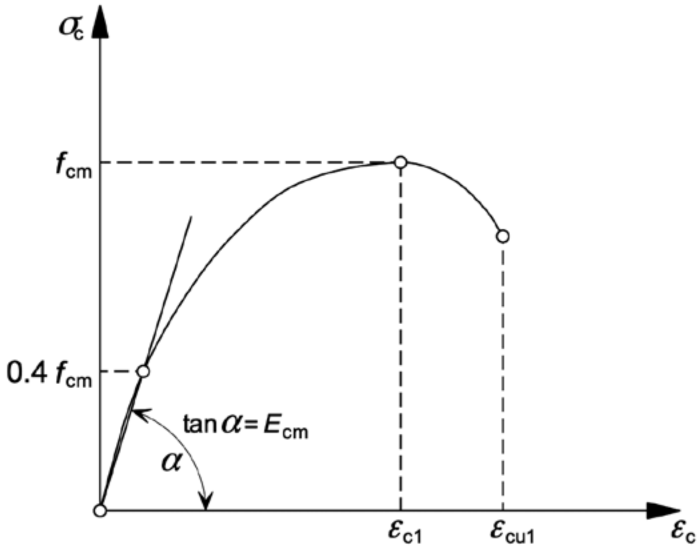

Figure 1: Schematic representation of the stress-strain relationship for structural analysis (the use of 0.4 f_{cm} for the definition of E_{cm} is approximate).

Property	Notation	Value for C30/37
Characteristic compressive cylinder strength at 28 days	f_{ck}	30 MPa
Mean value of concrete cylinder compressive strength	f_{cm}	38 MPa
Mean value of axial tensile strength	f_{ctm}	2.9 MPa
Secant modulus of elasticity	E_{cm}	33 GPa
Compressive strain in concrete at peak stress	ε_{c1}	2.2 ‰
Ultimate compressive strain	ε_{cu1}	3.5 ‰

Table 2: Material properties influencing mechanical behaviour for C30/37 concrete (according to BS EN 1992-1-1)

Concrete properties that may affect structural behaviour

Although the potential benefits may be significant, care is needed when specifying alternatives to concrete covered by BS 8500. This is because concrete is specified on the basis of compressive strength alone (other than any special requirements for pouring etc). However numerous other concrete characteristics will, or could, affect the behaviour (short-term, long-term, fire) of composite construction, as considered below. The relationships between these various characteristics are only guaranteed, such that the material can be specified on the basis of compressive strength alone, for concrete mixes complying with BS 8500. It is worth noting that future versions of design software may therefore need the ability for certain properties to be inputted independently, to cover the presence of proprietary mixes on the UK market.

Mechanical behaviour

The strength and stiffness of the slab, and the mechanical interaction between steel and concrete *may*, and in some cases certainly *will*, depend on:

- Characteristic (compressive) cylinder strength f_{ck}
- Secant modulus E_{cm}
- Tensile strength f_{ctm} (which may be important for shear stud resistance as concrete 'cone' failure often governs in the presence of transverse trapezoidal decking)
- Crushing strain ε_{c1} – the upper fibres of concrete in compression must not lose strength before the steel decking reaches the anticipated level of stress

Figure 3.2 of BS EN 1992-1-1[2], reproduced here as Figure 1, shows the compressive stress-strain behaviour to be used in structural analysis, and defines some key variables.

Table 3.1 of BS EN 1992-1-1 defines certain rules that directly link various material properties. The key resulting values for a typical C30/37 (i.e. characteristic cylinder strength of 30 MPa) concrete are included in Table 2 here, for information and comparison purposes.

As noted above, these relationships mean that when a compressive strength is explicitly defined, the other properties are implicitly defined by the various formulae. Unless all those relationships are respected, or the derived properties are 'exceeded' (i.e. the value defined by the BS EN 1992-1-1 relationship is in fact conservative), for types of concrete not in compliance with BS 8500 the mechanical behaviour of the composite slab or beam could be adversely affected. Of course, performance could also be improved, depending on the concrete characteristics.

It is also worth noting that BS EN 1994-1-1[3] clause 9.8.2(4) allows explicit calculation of deflection to be ignored for composite slabs with a span to effective depth within certain limits. This relaxation inherently assumes a certain relationship between material strength and stiffness.

Long-term behaviour

The long-term behaviour of a composite floor is a function of the creep and shrinkage characteristics of the concrete. Generally, these 'deteriorations' in the concrete are less significant with composite construction than reinforced concrete, because the steel elements resist the concrete strains. Relevant properties are:

- Creep coefficient ø. BS EN 1992-1-1 Fig 3.1 provides a simplified method, in the form of a number of graphs from which ø can be determined.
- Total free shrinkage strain $\mathcal{E}_{cs}$ which is defined in BS EN 1994-1-1 Annex C as 325×10^{-6} for normal weight concrete in a dry environment.

BS EN 1994-1-1 clause 5.4.2.2 allows for both shrinkage and creep using a modular ratio approach for determining long-term deflections. The modular ratio increases with time as the steel modulus is unchanged, and the concrete modulus reduces (reducing the contribution of the concrete part of a composite cross-section). In the majority of cases, for buildings, a simplified approach is taken whereby the concrete properties described above are not explicitly considered (nor are inputs otherwise required, such as time of first load application and duration of loading). The modular ratio for a member under a mixture of short and long-term loading is taken as $2n_0$, where $n_0 = E_a/E_{cm}$ (i.e. the modular ratio at time zero). The validity of this assumed halving of the concrete stiffness with time should be justified, or otherwise, by considering the creep and shrinkage characteristics of any 'non-standard' concrete.

BS EN 1992-1-1 Annex B defines the relationship between modular ratio, and shrinkage and creep properties.

Fire behaviour

BS EN 1994-1-2 clause 3.2.2 Table 3.3 shows strength retention (it's actually reduction) with temperature. As an example, normal weight concrete has lost 25% of its strength at 400 degrees, and over half its strength at 600 degrees. Strain capacity also reduces with temperature. Current design software adopts these values, with no allowance for user modification. Any higher, or lower, rate of loss of strength with temperature of a given material would adversely, or beneficially, affect the mechanical resistance of a composite floor in fire.

BS EN 1994-1-2 clause 3.3.3 Fig 3.8 gives thermal conductivity values. Conductivity is important because the insulation provided by a concrete floor controls the temperature of the upper surface when the floor is exposed to fire from below. Fire tests on floors consider three failure criteria, one of which concerns the temperature achieved on the upper surface after the regulated period of fire exposure. Lower insulation would therefore invalidate a fire test result for a given slab. Clearly the existence of a relevant fire test, using the concrete material under consideration for substitution, would avoid the need for material properties to be defined.

Density

From a loading point of view, it is important to know dry density and wet density, and if stated values include an allowance for reinforcement (or are the concrete alone). Clearly the appropriate values must be used in any design software. The Eurocodes state 2600kg/m³ wet and 2500kg/m³ dry, but we reduce these by 50kg/m³ because composite slabs have less reinforcement than a typical RC slab.

Density may also affect the acoustic performance of a slab.

Rate of strength gain

An important point to note is that the higher the proportion of additions within the concrete, the slower the strength gain of the concrete. This might not influence the programme if the concrete does not need to be struck quickly or support load shortly after being cast. For composite construction, lower strength (and stiffness) gain may be less relevant than for in-situ reinforced concrete, because of the permanent formwork provided by the steel decking. However, it could impact on timing of removal of props, or application of loading. SCI publication P300 states that props should not be removed until a floor has reached 75% of its design strength, and suggests that this is normally achieved in seven or eight days. That indicative timing may no longer be valid, depending on the concrete type and the external temperature.

Conclusions

Any designer, contractor or manufacturer considering using 'non-standard' concrete (i.e. not covered by the scope of BS 8500) – whether to reduce carbon or for any other reason - should ensure that all relevant properties are known for the concrete they are considering, and justify the assumed performance of the composite construction. Doing this correctly, in consultation with all relevant parties involved in the design, material supply and construction of the project, should ensure that significant benefits are achieved without structural performance being compromised.

SCI offers a third-party assessment service whereby we will review the claimed performance characteristics of any proprietary concrete and confirm suitability for use (or advise how performance may be affected).

Acknowledgement

Content concerning the different types of concrete originally appeared in 'How to Specify Lower Carbon Concrete', authored by Jenny Burridge and published by The Institution of Structural Engineers (*https://www.istructe.org/resources/guidance/how-to-specify-lower-carbon-concrete/*). ■

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1. BS 8500-1:2015 + A2:2019: Concrete – Complementary British Standard to BS EN 206. BSI, 2019
2 BS EN 1992-1-1: 2004: Eurocode 2: Design of concrete structures. General rules and rules for buildings (+A1:2014) (incorporating corrigenda January 2008, November 2010 and January 2014)
3 BS EN 1994-1-1:2004: Eurocode 4: Design of composite steel and concrete structures. General rules and rules for buildings (incorporating corrigendum April 2009)