Structural Concrete and Sustainability

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1. Introduction

It is well known that during the manufacture of Portland-type cements, significant emissions of carbon dioxide occur, some of which comes from the burning of fuel in the kiln, and the balance from the chemical dissociation of limestone ($CaCO_3$). In South Africa the typical specific CO_2 per ton of cementitious binder is about 765 kg. However, the effect of this is significantly diluted by the addition of aggregates (around 80% of the mass of a cubic metre of concrete) and cement extenders, of which many are industrial by-products (up to 50% of the mass of binder which typically is about 15% of the mass of a cubic metre of concrete). In order to optimise the embedded energy of a particular concrete structure it is necessary to make decisions on the selection of the concrete materials to be used on a particular project and the paragraphs below will give some guidance to the design and construction teams on how to make these decisions. The designer also needs to give consideration to passive design factors, as the most significant proportion of the energy consumed in a structure during its lifetime is taken up during the operation of the building through the provision of lighting, climate control etc.

Until recently, structures were designed to meet structural capacity needs only. However, durability considerations are being included in many more recent project specifications as recognition is being given to the cost and environmental impact of future maintenance actions. For instance, it may be possible to meet the structural capacity needs of a design by using 20 MPa reinforced concrete. However such concrete will relatively soon begin to suffer the adverse effects of exposure to the elements (i.e. a lack of durability) whereas a 40 MPa concrete, if correctly proportioned for durability, would provide the same structural capacity with more slender structural elements (i.e. overall reduction in concrete volume) and would withstand the same environmental exposure far longer, thereby increasing the longevity of the elements which has the resultant effect of reduced energy and CO2 consumption over the full life cycle of the element. The additional benefit is a reduction in maintenance and repair cost and energy over the life cycle of the element.

The designer should also bear in mind the issue of concrete quality control on the construction site. For a given characteristic strength requirement, the margin of compressive strength above the characteristic strength is dependent on the degree of quality control achieved by the contractor. Good control will allow the contractor to use a small margin without risking non-compliance with the specification, and this will result in a reduction in the binder content of the concrete thereby reducing the embedded energy of the concrete.

The Cement and Concrete Institute commissioned (2008) an independent assessment of the contributions made by each of the components in a cubic metre of concrete to its embedded energy and reference to this report should assist the designer to understand the relative contributions made by the various concrete materials. It is believed that this report should equip the designer with the ability to determine whether for instance, high-strength concrete might provide a more environmentally sustainable solution than a more conventional structural grade of concrete.

2. Know your cement and cement extenders

Cement for use in structural concrete may be a factory made common cement, or a site blend of a common cement and an extender. In South Africa factory made common cements must comply with SANS 50197. Cements may be "pure" cements (type CEM I) or blended cements (type CEM II, CEM III, CEM IV or CEM V) the latter being made up of a combination of finely ground clinker, extenders and additional minor constituents. Many different combinations of constituents are permitted (see C&CI pamphlet or SANS 50197 for descriptions). Some extenders are also commercially available for site blending. Those cement extenders available commercially as separate products in SA are fly ash, ground granulated blastfurnace slag, corex slag and silica fume, all of which have to comply with the requirements of the relevant part of SANS 1491. Extenders can be blended into the concrete on site, but the inclusion of such extenders should be done with due consideration of the extender content (if any) of the base common cement.

The abovementioned cement extenders are all by-products from other industries, and since they have been found safe for use in concrete and have the added advantage that they are also chemically reactive in the presence of cement, contribute certain technical benefits to hardened concrete they can potentially be used to render concrete more environmentally sustainable). This latter property comes about because these materials are derived from the waste streams of other industries, and therefore only contribute a small amount of additional embedded energy through their processing and transport requirements as well as avoiding the need to dispose of these wastes. The use of slag or fly ash will therefore tend to significantly improve the sustainability of a concrete mix.

When considering the use of one or more cement extender in structural concrete it is important to bear in mind the contribution to the total embedded energy made in transporting the material to site. As the geographic distribution of the sources of slag and fly ash is rather restricted, it may not be possible to take advantage of the apparent sustainability improvement offered by cement extenders at a particular construction site because of the long distance the cement extender has to be transported.

Structural concrete is typically proportioned to meet a 28-day characteristic strength required by the designer. When cement extenders are used in a concrete mix, the general trend is for the rate of compressive strength gain to be slowed, and this effect is more pronounced as the extender content of the concrete increases as a proportion of the total binder content. Typically a concrete mix will be designed to achieve a design compressive strength at 28 days. However, a direct substitution of an amount of extender for the same amount of portland cement may have the effect of a reduced compressive achieved at early ages and even at 28 days, although it is possible that the post 28-day strength development might result in the compressive strength catching up with that which might have developed using Portland cement alone; it is not recommended that this approach is used without the advice of a competent concrete technologist.

The lower strengths at early ages may cause problems for the contractor by delaying the removal of temporary structural support works, whilst the reduction in 28-d strength will cause problems for the designer by not meeting the characteristic design strength. It is possible to compensate for the lower strength by appropriately increasing the binder content of the concrete but this will increase the embedded energy of the structure at the construction stage although this may be offset by improved durability and the resultant reduction of repairs or maintenance over the life span of the structure. If the design age could be increased when using fly ash or slag, provided the concrete is well-cured, the potential for a straight replacement would increase as extended concrete mixes tend to continue to increase in compressive strength at a greater rate after 28 days than a plain cement concrete would. The proviso of proper curing is important, since because of the slower rate of strength development, fly ash and slag concrete is more sensitive to poor curing, especially at early ages.

The effect of the above-mentioned factors on the cost of the concrete or construction falls outside the scope of the current discussion, but would also need to be considered.

3. Selection of concrete aggregates

The choice of the aggregates to be used in a concrete mix to meet the project compressive strength and/or durability specifications can have a significant impact on the embedded energy of the structure and therefore due care should be taken to ensure that not only economic considerations play a role in determining which aggregates to use. It is possible that the engineer and client will elect to use a more expensive suite of materials for the concrete in pursuit of a more environmentally friendly completed structure. Reference to the Cement and Concrete Institute's report should assist the designer to understand the relative contributions made by aggregates and extenders.

Typically, aggregates derived from alluvial sources such as river sands and gravels will require less processing energy than those derived from hard rock quarries. Similarly, aggregates derived from industrial wastes (e.g. mineralogical slags, foundry sands etc.) may be considered to be more environmentally friendly due to the avoidance of disposal in landfill sites should they be used in concrete. Within the spectrum of commercially available aggregates, the "quality" will also vary. In this context the term "quality" refers to the effect the use of an aggregate has on the properties of the concrete, in particular the water requirement. The compressive strength of a concrete mix is determined mainly by the water:binder ratio of the mix (binder being the sum of cement and cement extenders), and the aggregates have the most significant effect on the water requirement of the mix. Therefore the "quality" of the aggregates will determine the quantity of binder in the concrete for a given compressive strength requirement, and as cement is probably the most energy intensive component of the concrete, the use of high "quality" aggregates will allow the binder content to be minimised.

In South Africa, the water requirement of a typical structural grade of concrete using 19-mm stone will fall in the range from 160 l/m^3 to 230 l/m^3, with the lower figure being considered good and the upper figure poor. The use of chemical admixtures will allow these figures to be reduced further and this will be discussed further in the next section. Increasing the coarse aggregate size will typically result in a reduction in water requirement and allow a reduction in binder content. However, caution is required as the coarse aggregate size should not exceed about one quarter of the least dimension of a concrete element, nor should it exceed the cover dimension. Conversely, a smaller coarse aggregate size will usually increase the water requirement and lead to increased binder contents.

As in the case of cementitious materials, the environmental impact of the transport of the aggregates must be included in the assessment of the suitability of aggregates. For instance, it may be possible to produce a less energy intensive structure by using a relatively poor “quality” aggregate from a local source rather than incur significant haulage of a better “quality” aggregate from further afield. Again, reference to the Cement and Concrete Institute’s report should assist the designer with decision making.

4. Use of admixtures

Chemical admixtures may be used to change the properties of fresh and hardened concrete. The most important change which will impact on the embedded energy of a cubic metre of concrete is water reduction as this allows a proportionate reduction in the cementitious binder. A small increase in aggregate content will be required to compensate for the reduction in volume resulting from the lowering of water and binder contents. Typically the addition of about 1 litre of admixture in 1 cubic metre of concrete will allow up to a 10% reduction in water (from about 200 l/m^3 to about 180 l/m^3) and similarly a 10% reduction of binder content (from say 380 kg/m^3 to about 340 kg/m^3). This can make a significant difference to the embedded energy of the concrete structure even though the admixture embedded energy tends to be quite high as the quantity used is very small.

The abovementioned reduction makes the use of admixtures look extremely attractive. However, the designer should note that the quantity of admixtures used must be within the ranges specified by the manufacturer; overdosing may be deleterious to the concrete.

5. Concrete reinforcement

Concrete has poor tensile strength and use is normally made of steel reinforcement to cope with the tensile stresses in a structural element. However, steel is an energy intensive material and may contribute about 50% of the embedded energy of a typical reinforced concrete section. Therefore the balance between concrete strength, the quantity of steel reinforcement and the slenderness of the element needs to be weighed up by a qualified structural engineer in terms of embedded energy as contributed by the steel vs the cement. Other techniques such as the use of pre- or post-tensioning may also offer reductions in steel percentage used. It is believed that the report commissioned by C&CI will make it possible to optimise the compressive strength/reinforcement relationship to produce the most sustainable concrete for a given project.

Conclusion

In order to optimise the embedded energy of a particular concrete structure it is necessary to make decisions on the selection of the concrete materials to be used on a particular project. The designer also needs to give consideration to passive design factors, as the most significant proportion of the energy consumed in a structure during its lifetime is taken up during the operation of the building through the provision of lighting, climate control etc.