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Design for durability: The key to improving concrete sustainability

R. Doug Hooton [a,*], John A. Bickley [b]

[a] Department of Civil Engineering, University of Toronto, 35 St George St., Toronto, Ontario M5S 1A4, Canada
[b] Leamington, Canada

HIGHLIGHTS

- Reductions in carbon footprint of concrete are discussed.
- Extending service life by design for durability are discussed.
- We discuss the processes required to make performance specifications work.

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ABSTRACT

There are many ways to reduce the carbon footprint of concrete including reduction in its portland cement clinker content by methods including: (a) optimization of total aggregate gradations, (b) use of water-reducing admixtures, (c) intergrinding clinker with limestone, and (d) use of supplementary cementing materials (SCMs). However, the most effective way to improve sustainability of concrete structures is by making them last longer through design for durability, and by minimization of construction defects. In almost every case, durable concretes will include all of the above listed aspects, but from a design approach, the emphasis needs to be on durability. Durability design includes more than the selection of concrete materials and mix proportions. It also requires that construction detailing, temperature control, adequate compaction, protection of fresh concrete, and curing be detailed in the specification and that inspection and testing be carried out to ensure that the specifications are being followed. The performance requirements need to be stated explicitly, and the objectives made clear. In addition to discussing various aspects of concrete durability, this contribution will discuss the merits of performance and objective-based specifications as well as the processes required to make them work.

1. Reducing the clinker factor of concrete

According to the World Resources Institute [1], portland cement production contributes 5% of global CO_2 emissions and 3.8% of global energy use. For every tonne of cement produced, there is 0.8–1.0 t of CO_2 produced (depending on kiln operation), 1700 kWh/t of energy consumed, and 1.5 t of raw material required. The estimated total quantity of cement produced in 2010 was 3,300,000 t.

But portland cement is only one component of concrete. However, approximately 90% of the carbon footprint of concrete is from portland cement (assuming portland cement is used as the sole binder) so reducing the portland cement clinker component will have an impact on reducing CO_2 emissions. The embodied CO_2 and energy per tonne associated with concrete production is relatively small compared to other construction materials, but concrete is the most widely used construction material, so the total CO_2 emissions and energy used are large [2].

Also, looking at the bigger picture, concrete has many other sustainable advantages, including:

- Concrete is resource efficient and the ingredients require little processing.
- Most materials for concrete are acquired and manufactured locally which minimizes transportation energy.
- Concrete building systems combine insulation with high thermal mass and low air infiltration to make homes and buildings more energy efficient.
- Concrete has a long service life for buildings and transportation infrastructure, thereby increasing the service life.
- Concrete pavement or exterior cladding, helps minimize the urban heat island effect – reducing the energy required to heat and cool homes and buildings.
- Concrete incorporates recycled industrial by-products such as fly ash, slag and silica fume that reduce embodied energy, carbon footprint and quantity of landfilled materials.

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[*] Corresponding author. Tel.: +1 416 978 5912.
E-mail address: d.hooton@utoronto.ca (R.D. Hooton).

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- Concrete absorbs CO_2 throughout its lifetime through carbonation, helping reduce its carbon footprint [3].

As well, in buildings regardless of the materials used, the construction phase only accounts for approximately 10% of its lifetime energy and CO_2 use while approximately 90% is used for power, heating, and air conditioning (HVAC) [4]; as new buildings are typically being built with better insulation, the 90% value is expected to reduce. Using exposed concrete finishes reduces volatile organic compounds (VOCs) associated with many interior finishes, and the light color of concrete can reduce lighting needs. Utilizing concrete's thermal mass and using concrete elements for pre-conditioning air will reduce HVAC needs.

Most concrete mix designs can be improved to reduce CO_2 footprints by:

1. Optimization of combined aggregate gradations. – reduces cement content by reducing paste content.
2. Use of water reducing admixtures – reduces required cement content for a given w/cm.
3. Use of portland-limestone cements (PLC) – reduces clinker content of cement.
4. Use of supplementary cementing materials or blended cements – reduces portland clinker content of the cementitious binder.
5. Use of recycled concrete as aggregates, where appropriate.

Most or all of these measures, as discussed below, can be used simultaneously to obtain dramatic reductions in portland cement clinker content of concrete, as shown by example in Fig. 1.

1.1. Improved aggregate gradations

Having to meet current North American specifications for individual fine and coarse aggregate grading envelopes can result in less than optimum particle packing and large portions of quarried and crushed stone being wasted. Many North American aggregate grading envelope requirements have not changed significantly in almost a century, and only recently have a few highway agencies allowed use of combined grading curves. This situation can be improved either by separating aggregates into different size ranges and recombining them, or use of an intermediate size aggregate in the 4–10 mm size range together with traditional fine and coarse aggregates. Microfine mineral fillers can also be added to extend total aggregate gradations to below the typical 80 μm size range.

1.2. Use of water-reducing admixtures

Water-reducing admixtures (WR) are used in most concretes for economy and to produce better quality concrete. WR disperses flocs of cement grains, providing improved workability and a more uniform distribution of cement grains, resulting in better utilization of cement. As a result, for the same workability and w/cm, less cement and water can be used (i.e. smaller paste fraction) also resulting in lower permeability and lower shrinkage. As well, high-range water reducers (HRWR) can provide both higher workability and reduce the cementitious binder content of concrete even further, provided that concrete temperatures do not get too high.

1.3. Portland-limestone cements

Cements with large quantities of interground limestone have been in use in many parts of the world, such as CEM IIA-L (up to 20% limestone) and CEM IIB-L (up to 35% limestone) in the European Union. In 2008 in Canada, the CSA A3001 specification introduced a new class of portland-limestone cements with up to 15% interground limestone. The CSA A23.1 concrete standard followed in 2009 [7] and this change was adopted in the Canadian and Provincial Building Codes in 2011. Use of these cements has a direct effect on reducing point-source CO_2 emissions at cement plants by approximately 10%. Similar portland-limestone cements have also been used in US since around 2005 under the ASTM C1157 performance standard for hydraulic cements. In 2012, the ASTM C595 standard for blended cements adopted a new category of cements with up to 15% limestone.

To increase their acceptance in the construction market, the CSA portland-limestone cements are required to meet the same set time and strength development properties as portland cement. They also have been found to work well together with slag additions at the concrete plant, and sometimes perform better than with portland cements. Typical strength and coulomb rating data are shown in Tables 1 and 2.

1.4. Supplementary cementing materials (SCM)

To provide flexibility to the concrete producer and for historical reasons, in North America almost all SCM are added

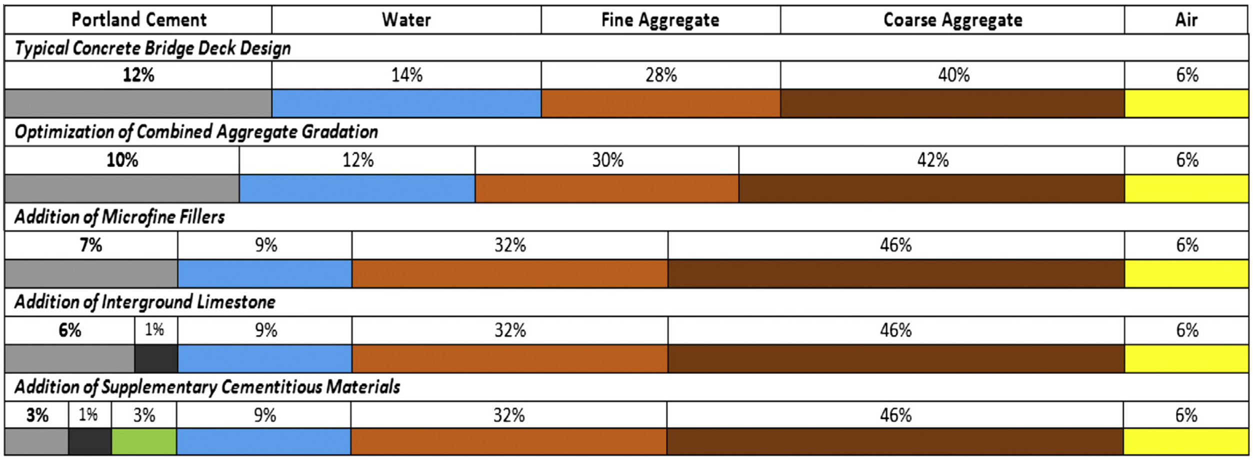

Fig. 1. Potential reductions in portland cement content of concrete with use of different innovations (unpublished work by M. Anson-Cartwright and R.D. Hooton).

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