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Recent Advances in Sustainable Concrete for Structural Applications

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ABSTRACT

Pressure is mounting on the construction industry to adopt sustainable development initiatives aimed at limiting the consumption of non-renewable materials as well as the generation of greenhouse gas emissions and demolition waste. This paradigm shift is requiring engineers to consider the environmental footprint of the materials used for construction projects. The concrete industry has recently made significant strides in this area, and there is a need to synthesize current knowledge and address remaining research needs. This paper reports on advances made in the last ten years with respect to the development and use of sustainable concrete for structural applications, with improved cement efficiency and incorporating recycled materials. Available literature supports the use of sustainable concrete as a viable alternative to conventional concrete for structural applications provided that appropriate design methodologies are employed and the characteristics of the constituent materials are properly considered. Despite the environmental and economic incentives, perceived inferiorities continue to limit the widespread adoption of sustainable concrete for field structures. Current research needs and opportunities are also discussed.

INTRODUCTION

The global construction industry has one of the largest environmental footprints of any sector. The production and transport of building materials as well as construction and demolition (C&D) waste contributes to a combined total of 10-30% of greenhouse gas (GHG) emissions, and 30-50% of all waste delivered to landfills (Busby 2002, Gorgolewski 2001, CCA 2001). Almost a quarter of all C&D landfill waste in Canada is concrete rubble (CAC 2009) which could potentially be recycled.

More than 2.5 tonnes of concrete are produced each year for every human being in the world (Aitcin 2000). Unfortunately, concrete production requires the consumption of large quantities of non-renewable materials and cement manufacturing generates 5% of all global greenhouse gas emissions (Huntzinger & Eatmon 2009). Cement often constitutes more than two-thirds of the total embodied energy of concrete (Goggins et al. 2010). With cement production expected to increase by a factor of 2.5 by the year 2050 (Muller & Harnisch 2008, CSI 2007, Damineli et al. 2010), new sustainable approaches are needed to reduce the environmental footprint of the concrete industry. Furthermore, strategies are needed to better manage the resources that we have at our disposal, including the re-use and recycling of C&D waste to divert them from landfills and limit our use of raw materials.

Despite countless advancements in concrete technology and the development of high performance materials and admixtures, the basic ingredients of conventional concrete have not changed. Aggregates make up the bulk of the concrete material and generally provide most of the stiffness and mass, while cement paste acts as a binder to form a composite material and allow for load transfer between aggregate particles. As stated by Scrivener & Kirkpatrick (2008), there are three main barriers to innovation in civil engineering industry:

1) **Structural safety**: structures are expected to have long service lives and the consequences of failure are great. Therefore a conservative approach to codes and standards is imperative, and pilot projects are needed to ensure good short and long-term performance in real conditions.
2) **Empirical knowledge base**: our knowledge of the processes underlying the performance of cementitious materials at the macroscale is limited, leading to incremental development.
3) **Market niche and critical mass**: the production efficiency of cementitious materials increases with scale, and a critical mass must be reached to achieve reasonable economies of scale.

Despite these challenges, sustainability is an important driving factor for change. It is important to note that sustainable development is a broad term that encompasses many ideals; it is defined in the Brundtland Report as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED 1987). Cultural and economic factors are critically important to a holistic view of sustainability and/or sustainable structures, as are design and construction management practices, resilience and longevity, embodied energy and energy use, operation processes, industrial ecosystems, performance specifications, life-cycle analyses, etc. (Muller et al. 2014, Miller & Doh 2015, Miller et al. 2015, Yeo & Potra 2015, Yeo & Gabbai 2011, Goggins et al. 2010, Ghali & Gayed 2014, Hooton & Bickley 2014, Foraboschi et al. 2014). To achieve a manageable scope, the current study focuses only on the direct environmental impact of the constituent materials used to produce structural concrete.

In this context, a great deal of work has been done related to the sustainability of concrete materials and structures over the past decade. This paper focuses primarily on the sustainable use of Portland cement-based concrete for structural applications, with the aim of synthesizing current knowledge, demonstrating the benefits of sustainable concrete for increased use in industry, and to identify areas for further research.

LITERATURE REVIEW

Background

Major advancements in cement production including efficient processing technologies and alternative energy sources (PCA 2011), while extremely important, have not kept up with the increasing global demand for cement-based materials (CSI 2009, Damineli et al. 2010). Blended cements or concrete incorporating supplementary cementitious materials (SCM) such as blast furnace slag, fly ash, silica fume, metakaolin, and natural pozzolans have been in use for decades and various guidelines are available (e.g. ACI 233R-03, 234R-06, 232.1R-00). Similarly, recycled concrete aggregates (RCA) have been considered as a replacement for natural aggregates (NA) since at least 1945 (Hansen 1986) and some technical guidelines on their use are available (ACI 555R-01, RILEM 2012). The replacement of cement particles by inert fillers is relatively new, but has been the subject of investigation for at least a couple of decades (Bentz 2005).

Many studies related to the material properties of sustainable concrete mixtures in their fresh and hardened state, as well as durability characteristics, are available in the literature and are not mentioned here due to the scope and space limitations of this paper. Various state-of-the-art reports which pre-date 2006 are also available (e.g. Hansen 1986). However, only a limited number of comprehensive studies have reported on the implications of sustainable concrete for large scale structures or structural members (e.g. Yagishita et al. 1994, Han et al. 2001, Maruyama et al. 2004a, b, Gonzalez & Martinez 2004, Santos et al. 2004).

Low-Cement Concrete

Cement is typically the most expensive constituent of concrete, and has the largest carbon footprint; about 0.5 kg CO_2 is released per kg of cement during clinker generation, in addition to the CO_2 emissions caused by fuel burning (Fennis & Walraven 2012). Durability and shrinkage problems also arise in concrete with high cement content. Minimizing cement content therefore has economic, environmental, and performance benefits, provided that the short and long-term structural behavior is not compromised. Various researchers have questioned whether minimum cement requirements are necessary and have suggested that these requirements should be revisited (Wassermann et al. 2009, Damineli et al. 2010).

There are currently no standardized performance indicators for estimating the efficiency of cement use. Damineli et al. (2010) proposed two indicators which they termed the binder intensity and the CO_2 intensity; using a large database from the literature, they showed that it is possible to produce concrete which can simultaneously achieve low binder and CO_2 intensities. This presents an important step towards the development of international benchmarks for cement efficiency.

Supplementary cementitious materials

Of the various strategies for reducing cement content in concrete mixtures, the use of SCMs such as fly ash, blast furnace slag, and/or silica fume is the most common. In North America, these are often added separately to the concrete mix by the concrete producer (Hooton & Bickley 2014) and can reduce the total embodied energy of concrete by 30% or more (Goggins et al. 2010). In addition to the environmental and cost benefits of SCMs, they can also provide technical benefits for concrete including reduced permeability, reduced heat of hydration, and increased strength over time (Zachar 2011).

While increasing cement replacement levels may be beneficial from an environmental standpoint, the use of SCMs in very large quantities is not necessarily a sustainable long-term strategy, since their availability is likewise becoming limited (Gartner 2004, Scrivener & Kirkpatrick 2008, Damineli & John 2012). Nevertheless, the combination of SCMs together with some of the other approaches described below may provide opportunities for a significant overall decrease in carbon emissions while maintaining good overall performance and durability (e.g. Kou et al. 2008).

Promising areas of development include natural pozzolans and mineral deposits (Gartner 2004, Scrivener & Kirkpatrick 2008). Currently, the availability and cost of these materials limits their widespread use, but the introduction of carbon taxes may change this situation. The structural implications of the use of natural mineral additions or geopolymer concrete is not very well known and warrants further study.

Particle packing

Due to the rapid growth of developing countries and significant expected increases in concrete demand in the coming years, cement replacement will not be a sufficient strategy for reducing CO_2 emissions (Damineli & John 2012). Cement content can also be reduced through optimization of the particle packing structure by tight control of aggregate gradation and replacing cement with microfine mineral fillers (Fennis & Walraven 2012, Fowler & Rached 2011).

Current specifications for fine and coarse aggregate gradations, which have not changed significantly in more than a century (Fuller & Thompson 1907), may result in non-optimal particle packing (Hooton &

Bickley 2014). By increasing the packing density of aggregate particles, the required volume of cement paste to fill the voids between aggregates is reduced. Inert powders, or microfines, which are produced during the aggregate crushing process, can also be used to replace cement particles as part of the paste. Particle packing is a function of both shape and grading, and the ideal particle size distribution will therefore vary for every concrete mix (Fowler & Rached 2011, Fennis & Walraven 2012).

Particle packing optimization methods can be divided into three main groups: optimization curves, particle packing models, and discrete element models (Fennis & Walraven 2012). Optimization curves are easy to use and understand, but do not typically consider particle characteristics like shape or packing density. Analytical particle packing models can be used to calculate the theoretical packing density of a mixture using mathematical equations to determine how particles of different sizes interact geometrically. Discrete element models can also be used to simulate a virtual particle structure from a given particle size distribution, but are not necessarily computationally efficient.

Packing models can provide information on cement particle spacing for better predictions of strength or hydration. They can also be used to optimize the use of SCMs. Although this approach has been shown to effectively reduce cement content by more than 50% while maintaining or improving performance in terms of fresh and hardened properties (Fennis & Walraven 2012), no published literature reporting on the behavior of structural reinforced concrete elements using this approach was found by the authors.

Recycled Materials

Coarse recycled concrete aggregates

Despite being the focus of many research studies, the use of RCA concrete for structural applications is still uncommon. One reason for this is that the characteristics of RCA can vary greatly between different concrete sources and quality control or aggregate pre-treatment methods can be time consuming as well as expensive. Secondly, many studies have reported that the performance of concrete with high proportions of RCA are highly dependent on the quality of the aggregates and may be inferior to similar concrete made with NA with respect to serviceability, strength, and durability (Corinaldesi & Moriconi 2006, Kou et al. 2012a, b, Butler et al. 2011, 2012, 2013a, 2014, McNeil & Kang 2013, Duan & Poon 2014, Behera et al. 2014, Arezoumandi et al. 2015, Knaack & Kurama 2014, Xiao et al. 2012, Singh et al. 2013).

Not all RCA sources are of suitable quality for structural applications. Butler et al. (2013b) proposed a performance classification system to assess whether a particular RCA source is suitable for structural applications, or only for plain concrete or as fill material. The proposed system was based on and compared to current standard specifications for NA from around the world. Some of the parameters considered include the amounts of deleterious substances present, the amount of adhered mortar, the density of the adhered mortar and relative density of the aggregates, abrasion resistance, and absorption. Some aggregate quality issues can be overcome using proper mix design methods. This classification system provides a very useful tool for assessing potential RCA material performance prior to use in structural concrete. The shape and gradation of RCA also has a significant effect on the properties of the concrete (McNeil & Kang 2013).

RCA is a two-phase material which is made up of both NA and adhered mortar. The residual mortar content (RMC) can vary greatly and can be as high as 60% of the RCA volume (Behera et al. 2014, Duan & Poon 2014). As a result, RCA tend to have higher absorption, lower specific gravity, and lower stiffness and crushing strength than NA, and concrete containing RCA will have multiple interfacial transition zones (ITZ) between new mortar and old mortar, old mortar and aggregate, and new mortar and aggregate (McNeil & Kang 2013, Behera et al. 2014). The multiple ITZ of RCA concrete tend to be relatively weak due to the presence of many small pores and cracks which has a significant effect on mechanical properties (Behera et al. 2014). Therefore, the RMC should be accounted for in concrete mix designs. It seems reasonable to consider the RMC as part of the total mortar volume rather than as part of the coarse aggregate volume as is implied by direct volume replacement mix design methods (Fathifazl et al. 2009a).

A number of pre-treatment protocols for RCA have been proposed to improve the aggregate properties through consolidation of the adhered mortar or reducing aggregate porosity, including carbonation, surface improvement agents, scrubbing, modified mixing methods, or use of mineral admixtures (Behera et al. 2014, Zhang et al. 2015, Xuan et al. 2016). Although it can effectively improve the mechanical properties of concrete with RCA, carbonation is not a practical solution for reinforced concrete applications because the lower pH of the concrete may result in increased susceptibility to steel reinforcement corrosion.

Fathifazl et al. (2009a) developed a new mix design method called the equivalent mortar volume (EMV) method, which includes the RMC in the calculation of the total mortar volume. This reduces the amount of cement paste needed for new concrete mixtures. Using this approach, they found that the structural performance of reinforced concrete members in flexure and in shear were equivalent, or even superior, to similar members made with conventional concrete mixtures at both serviceability and ultimate limit states (Fathifazl et al. 2009b,c, 2010, 2011a, 2012). The bond strength between steel reinforcing bars and RCA concrete proportioned using the EMV method were also similar to those with conventional concrete, but up to 33% higher than that of RCA concrete proportioned by conventional methods (Fathifazl et al. 2012).

High performance concrete can also be produced with RCA. Kou & Poon (2015) investigated the performance of concrete made with RCA from crushed concrete having strengths ranging from 30-100 MPa, and found that the resulting high performance concrete with up to 100% aggregate replacement had similar or higher compressive strength than similar concrete mixes with NA, as well as lower drying shrinkage and higher resistance to chloride ion penetration. However, the elastic modulus of the concrete with RCA was lower than the control mixes made with NA due to the RMC. The use of SCMs together with RCA has also shown promising results with respect to mechanical and durability properties of the hardened concrete (Kou et al. 2008, 2011, Kou & Poon 2013, Shaikh et al. 2015, Surya et al. 2015), but investigations of large-scale structural elements are still needed.

A comprehensive review of the long-term durability of RCA concrete is available by Xiao et al. (2014). Some of the main conclusions of this review were that the disparity in strength between RCA concrete and conventional concrete decreases with age, while shrinkage, creep, and permeability increase with increasing RCA content, and results related to carbonation and freeze-thaw resistance are inconsistent. Abbas et al. (2009) found that RCA concrete mixes proportioned by the EMV method had higher resistance to freeze-thaw cycles, chloride penetration, and carbonation than mixes designed with conventional methods, and the results satisfied current requirements for concrete exposed to severe environments. Fathifazl et al. (2011b) also found that the creep and shrinkage of RCA concrete proportioned by the EMV method were comparable or even lower than those in similar concrete made with NA.

A limited number of research studies have reported on the performance of full-scale concrete structures with RCA. Pachecho et al (2015) conducted experiments on the dynamic behavior of four full-scale structures with various RCA replacement ratios. The overall pattern of response of the structures were similar, although the use of RCA did slightly influence the stiffness of the concrete (lower elastic modulus values are an inevitable result of direct replacement mix design methods which do not account for RMC).

Fine recycled concrete aggregates

Relatively little research is available related to the performance of reinforced concrete members with fine RCA, which are typically viewed as low quality waste material. Fine RCA often includes large proportions of hydrated cement particles which have high absorbability and are generally believed to have a negative effect on the workability, strength, and durability of concrete (Chan & Poon 2006). Improving the particle packing structure presents a possible solution for the use of fine RCA particles and powders for structural concrete as a replacement for both fine aggregates and cement. The use of fly ash has also been used to overcome some of the challenges of fine RCA in concrete (Chan & Poon 2006). Additional research in this area is needed, particularly with respect to the structural implications for reinforced concrete structures.

Other recycled materials

Various other waste products, such as rubber and glass, have been incorporated into concrete mixtures with varying levels of success (Dumitru et al. 2010, Ling et al. 2013, Niang et al. 2014, Hall & Najim 2014). In this case, the main incentive is usually to divert these waste materials away from landfills and are generally not associated with performance benefits. While these practices are worthwhile in that they add value to waste materials and help reduce the environmental impact of other industries, they do not directly affect the sustainability of the concrete construction industry (i.e. "closing the loop" so that concrete materials can be continually recycled similar to steel) and therefore are not considered further here.

INTERNATIONAL STANDARDS AND GUIDELINES

A number of countries are beginning to produce guidelines, specifications, or standards that explicitly or implicitly address the use of sustainable concrete (due to space limitations, these are not listed here). These generally include conservative limits to control cement and aggregate replacement proportions. Further experimental research studies focusing on the behavior of large scale structural members made with sustainable concrete mixes need to be pursued using proper mix design and optimization procedures to increase confidence in the structural performance of sustainable concrete materials.

CASE STUDIES

A temporary concrete recycling facility was set up in Hong Kong in 2002, which was used to produce RCA for the various structures of the Hong Kong Wetland Park (Poon & Chan 2007). A total of 13000 m^3 of concrete using RCA was used for this project for structural elements including pile caps, ground slabs, and mass concrete. Cement content was deliberately increased by 4% to compensate for the high water content required by the RCA to maintain a similar water-cement ratio as the control concrete mix. It should be noted that increasing cement content to compensate for RCA content is contrary to the overall sustainability objective, and hence is not a desirable approach for the design of RCA concrete.

A three-storey civil engineering laboratory was constructed in China using recycled concrete in 2007 (Xiao et al. 2012). The RCA were produced from demolished concrete pavements and building waste. After an earthquake in the Sichuan Province of the People's Republic of China in May 2008, many buildings were damaged or destroyed. The construction and demolition waste generated from removing these collapsed and dilapidated buildings were used to produce RCA for new building projects.

In 2010 a six-storey building in Ludwigshafen, Germany, targeted for office space and residential use was constructed using almost entirely recycled concrete (Messari-Becker et al. 2014). The building was constructed primarily using two-way slabs, full-depth beams/walls, and columns. The cantilever balcony slabs were also made from reinforced concrete. A total of approximately 500 m^3 of recycled concrete was used for this project. RCA was used for the structural concrete elements with a stated objective of not increasing cement content through the use of SCMs. The use of RCA did not require any adjustments to the overall structural design. The authors also noted the energy advantage of using RCA from nearby sources instead of transporting NA from quarries over a much greater distance.

Limited research exists related to the use of sustainable concrete for large-scale columns, walls, slabs and foundations. RILEM (2012) has also documented the use and experience with RCA concrete in various parts of the world and readers are encouraged to consult that document for further information. The above case studies highlight that there is still a long way to go before the use of sustainable concrete will become widely used in the industry for structural applications. At present, the use of recycled materials and low-cement concrete are mainly limited to novelty projects. In order to increase confidence for the engineering community, more research regarding the structural use of sustainable concrete is needed.

RESEARCH NEEDS AND OPPORTUNITIES

Based on an overview of existing literature, it is clear that some research findings related to the use of sustainable concrete are not well understood and there remains a significant gap between recent research and the use of sustainable concrete in practice. A lack of comprehensive investigations on the optimal use of sustainable concrete for structural applications are available, as well as limited experimental data on the overall structural performance of reinforced concrete elements subjected to various loading and environmental conditions. The relationship between optimized concrete materials and structural response through multi-scale assessments have not been adequately investigated to date. A few of the proposed areas for further research, particularly with respect to experimental structural testing, include:

- The short and long-term structural implications of geopolymer and low-cement concrete as well as investigations of the applicability of current minimum cement content requirements;
- Investigations on the use of properly graded fine RCA for structural concrete;
- The structural performance of reinforced concrete, including flexure, shear, torsion, axial loading, bond, and fatigue, with various combinations of SCMs, RCA, and particle packing methods to develop new optimized mix design methodologies for sustainable structural concrete;
- The long-term behavior of reinforced concrete members made with sustainable concrete, including the effect of corroded reinforcement and other deterioration mechanisms;
- Going beyond material recycling through the re-use of structural elements, including investigations of the disassembly of concrete structures;
- Sustainable concrete with corrosion-resistant reinforcement (i.e. FRP bars or dispersed fibers).

CONCLUSION

The following general conclusions can be drawn from a review of the presented literature:

- With proper design methodologies and consideration of the characteristics of the constituent materials, sustainable concrete can be used for structural applications with equivalent or superior performance to conventional concrete;
- More research is needed on the use of low-cement concrete with RCA to develop optimized mix design methodologies for sustainable concrete for structural applications;
- Multi-scale assessments are critical to develop a deeper understanding of the physical and chemical processes affecting the behavior of sustainable concrete materials at the microscopic and macroscopic scales, and correlate the material characteristics to large-scale structural response;
- Experimental research is needed to comprehensively investigate the behavior of large-scale structural elements made with sustainable concrete to increase confidence for their use in field applications.

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