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Review

Properties of recycled concrete aggregate and their influence in new concrete production

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ABSTRACT

This manuscript presents a review of the potential and challenge of using recycled concrete aggregate (RCA) as the substitute for natural aggregate (NA) in concrete mixtures. Using RCA in concrete preserves the environment by reducing the need for opening new aggregate quarries and decreases the amount of construction waste that goes into landfill. The properties of RCA such as specific gravity, absorption, and the amount of contaminant present in it contribute to the strength and durability of concrete. The quality of RCA depends on the features of the original aggregate and the condition of the demolished concrete. Some researchers have reported that the use of RCA degrades concrete properties while others have successfully produced RCA concrete with a performance that matched normal concrete (NC). In addition to the influence of RCA to concrete properties, this paper also evaluates multiple techniques to improve the performance of RCA concrete, reported cost savings in concrete production and recommendations regarding the application of RCA in concrete.

1. Introduction

Concrete is known as one of the most highly consumed construction materials. The primary ingredients of a concrete mixture are cement, aggregates (coarse and fine), water and admixtures (Mindess et al., 2003; National Ready Mixed Concrete Association (NRMCA), 2012). Among the aforementioned components, aggregate takes up about 70% to 80% of concrete's volume. Types of NAs that are commonly used in concrete application consist of crushed stone, sand, and gravel (USGS, 1997). These NAs are obtained through mining natural resources and opening aggregate quarries. The mining process of NAs generally takes place in vast aggregate quarries that involves heavy equipment and consumes an excessive amount of energy. The resources of NAs are abundant but finite (USGS, 1997). Challenges may develop in construction due to depletion and scarcity of the sources, restrictions on opening new sources and the increased production cost. Using recycled aggregate (RA) may help to address some of these challenges (ACPA, 2009; Verian, 2012). RA can be derived from existing concrete, and thus, termed as recycled concrete aggregate (RCA). According to de Vries (1996), the application of RCA in construction works has become a subject of priority throughout many places around the world. As indicators, 10% of the total aggregates used in the United Kingdom (UK) are RCA (Collins, 1996), 78000 tons of RCA were used in the Netherlands in 1994 (de Vries, 1996) while Germany has been aiming a target of 40% recycling rate of its building and demolition waste since 1991 (van Acker, 1998). According the data in 1997, 0.9 million out of 1.06 million metric ton of the recycled old concrete was used for construction in Denmark (Schimmoller et al., 2000). The annual production of recycled materials derived from old asphalt pavement reached 0.8 million metric ton in Sweden in 1999, in which 95% of it was used in the new asphalt pavement (Schimmoller et al., 2000). Florea and Brouwers (2012) have reported that due to the costly landfilling

Abbreviations: ACI, American Concrete Institute; ASR, Alkali-Silica Reaction; ASTM, American Society for testing Materials; BCA, Benefit-Cost Analysis; BFB, asalt Fiber; CH, Calcium Hydroxide; C-S-H, Calcium Silicate Hydrate; CTE, Coefficient of Thermal Expansion; DHE, Double Hooked-End; FA, Fly Ash; FT, Freeze-Thaw; FHWA, Federal Highway Administration; HCl, Hydrochloric Acid; IN, Indiana; INDOT, Indiana Department of Transportation; ITM, Indiana Test Method; ITZ, Interfacial Transition Zone; L.A, Los Angeles; MMA, Mortar Mixing Approach; NA, Natural Aggregate; NC, Normal Concrete; NMA, Normal Mixing Approach; JRCP, Jointed Reinforced Concrete Pavements; OPC, Ordinary Portland Cement; PP, Pozzolanic Powder; RA, Recycled Aggregate; RAP, Reclaimed Asphalt Pavement; RCA, Recycled Concrete Aggregate; RCPT, Rapid Chloride Permeability Test; RDME, Relative Dynamic Modulus of Elasticity; RMA, Recycled Masonry Aggregate; RMC, Reclaimed Mortar Content; rpm, rotation per minute; SCM, Supplementary Cementitious Material; SEM, Scanning Electron Microscopy; SEMA, Sand Enveloped Mixing Approach; SF, Silica Fume; SR, State Road; SSD, Saturated Surface Dry; TSMA, Two-Stage Mixing Approach; $TSMA_S$, Two-Stage Mixing Approach with Silica Fume; $TSMA_{SC}$, Two-Stage Mixing Approach with Silica Fume and Cement; UK, United Kingdom; U.S., United States; USGS, United States Geological Survey; w/b, water to binder ratio; w/cm, water to cementitious ratio

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process, which I some cases are more costly than recycling, many European countries have set a high bar for their recycling goals – between 50% to 90% of their construction and demolition (C&D) waste production.

In the United States (U.S.), nearly 100 highway paving projects by the mid-1990s had incorporated RCA in concrete for pavements, some of which are derived from pavements exhibiting D-cracking and alkali-silica reaction (ASR) damage (Burke et al., 1992).

As one of the solutions in preserving the environment and as it is rich in potentials, the use of RCA has been rising and is encouraged. For this reason, understanding the characteristics of RCA is critical to assure the success of its application. This manuscript presents information regarding the state-of-the-art of the characteristics of RCA, its effects on concrete properties, and various methods to optimize its application.

2. Benefits of using RCA

Using RCA instead of NA has positive influences in terms of the environment and economics. It can conserve NA consumption thereby reducing the need to open new mining areas (hence, preserve the environment (Mack et al., 2018)) as well as the energy/fuel consumption associated with hauling (for the same hauling distance, energy required to transport RCA is less than that of NA when the unit weight of RCA is lower than NA. The specific gravity of RCA and NA is discussed in Section 6.2). On the other hand, use of RCA reduces construction waste that usually ends up in landfills (Mack et al., 2018). Using RCA may also reduce construction costs. The price for every ton (1000 kg) of various RCA products ranges from $1 to $18 and vary at different areas (USGS, 2000). According to a study by Environmental Council of Concrete Organizations there is an estimated saving of up to 60% by using RAs as a replacement of NAs (Environmental Council of Concrete Organization, 2018). A study conducted at Purdue University, USA reported that using RCA has the potential of reducing cost as much as $2.26–$2.93 per ton (without considering additional potential saving from landfill) of pavement concrete (Verian et al., 2013). This study also developed a benefit-cost analysis (BCA) model which can provide substantial information for RCA usage (Verian et al., 2013). The overall environmental benefit of using RCA based on the life cycle cost analysis of concrete has also been reported by several studies (Ding et al., 2016; Serres et al., 2016; Knoeri et al., 2013; Marinković et al., 2010). A study by Hossain et al. (2016) revealed that the use of coarse RA obtained from the construction and demolition (C&D) waste in Hong Kong reduces the greenhouse gases footprints up to 65% and saves up to 58% of the energy consumption.

Several other studies have implied that concrete made with RCA can be designed in a way to match the quality of concrete made with NA without the need for additional cement. A study by Beltrán et al. (2014) has indicated that at water to cementitious ratio (w/cm) of 0.5, the use of RCA increased the compressive and flexural strengths of concrete when additional cement (up to 34 kg/m^3) was added into the mixture. According to Etxeberria et al. (2007), replacing natural coarse aggregate with RCA at 25% and 50% weight-base replacement levels improved the compressive and tensile strengths of concrete when adjustments in the mixture proportion were applied, such as increasing the amount of cement, lowering w/cm, adjusting the amount of additive and aggregate proportion. Verian (2012), Verian et al. (2011a) and Jain et al. (2012a) have also indicated that concretes containing 30% coarse RCA (w/cm: 0.43) outperformed the control concrete made with NA only (w/cm: 0.44). By using a modified mixing technique (i.e. two-stage mixing approach (TSMA)), Tam et al. have succeeded in improving the properties of concrete containing up to 30% of RCA to a level comparable or even better than the control concrete (Tam et al., 2005; Tam and Tam, 2007; Tam and Tam, 2008). The benefit of TSMA in improving the performance of RCA concrete is also reported by Brand et al. (2015). In his study, Brand et al. (2015) also found that the greatest strength properties of RCA concrete were achieved when the RCA was at least in the partially-saturated moisture state prior the mixing with TSMA method (Brand et al., 2015).

3. Production of RCA

There are many types of materials that can be recycled and used as a substitute for NA in construction. These materials include, but not limited to, concrete, brick (Kabir et al., 2012; Cachim, 2009; Khalaf and DeVenny, 2005), ceramic (Binici, 2007; Torkittikul and Chaipanich, 2010; Medina et al., 2012; Senthamarai et al., 2011; Pacheco-Torgal and Jalali, 2010; Senthamarai and Devadas Manoharan, 2005), rubber (Atahan and Yücel, 2012; Najim and Hall, 2012; Papakonstantinou and Tobolski, 2006; Richardson et al., 2012; Sukontasukkul and Chaikaew, 2006; Topcu, 1995; Batayneh et al., 2008; Sukontasukkul, 2009), glass (Henry and Morin, 1997; Polley et al., 1998; Nemes and Józsa, 2006; Xie et al., 2003; Shayan, 2002; Du and Tan, 2013; Shao et al., 2000; Federico and Chidiac, 2009; Meyer et al., 2001; Ismail and AL-Hashmi, 2009; Canbaz, 2004), etc. This section emphasizes on the RA derived from concrete. RCA is produced by crushing existing concrete to be used as aggregates in new concrete. The production process of RCA should be designed in a way that optimizes the production of usable RCA in terms of both quality and quantity. The quality of RCA is driven by several different factors, such as the quality of the original concrete, the presence of contaminants (Noguchi et al., 2015) and the processing of the RCA itself (ACI Committee, 2001). Several steps in recycling concrete include evaluation of the source concrete, concrete preparation, concrete breaking and removal, removal of any contaminants (i.e. steel mesh, rebars or dowels), crushing the concrete and sizing the RCA, and beneficiation process (removal of any additional contaminants such as old mortar) (ACI Committee, 2001).

4. Percentage replacement of RCA in concrete mixture

The amounts of RCA used in concrete mixtures varied among different researchers as did the inclusion of fine RCA. A brief survey on the replacement levels of NA with RCA is presented in Table 1. The results of the studies presented in Table 1 have indicated that coarse and fine RCA have the potential to be used as aggregates in concrete application.

5. Consideration for using fine RCA

The concern of using fine RCA in the concrete mixture is mainly associated with the higher mortar and impurity contents of the fine RCA as compared to coarse RCA. The adhered and loose mortars contribute to the angularity, rough surface texture and high absorption of fine RCA particles (Evangelista et al., 2015). These properties of fine RCA, in many cases, were reported to be responsible for the workability problems (Obla et al., 2007), reduction in concrete strength, and significant increases in volumetric instability (i.e., shrinkage, creep and coefficient of thermal expansion (CTE)).

A study by Fan et al. (2015) indicated that mortars containing 25% to 100% of fine RCA experienced higher drying shrinkage than the control specimens at all tested ages (7, 14, 21 and 28 days) due to the higher porosity of this constituent which enables water to evaporate rapidly. Smith (2018) observed that fine RCA contained many impurities which degraded the strength of concrete. Zaharieva et al. (2003) stated that the use of fine RCA is often prevented due to its negative effects on concrete. According to the study results by Evangelista et al. (2015), the smaller size fractions (125–500 µm) of fine RCA possess high mortar content while bigger fractions (1–4 mm) of fine RCA present a considerable amount of cracks at the paste-aggregate ITZ. Obla et al. (2007) made an estimation that additional cost (about $2/ton) is required when aggregate producer separates the RCA into coarse and fine fractions as compared to coarse fraction only. Evangelista and de Brito (2007) used fine RCA which is derived from concretes that are specifically made in laboratorial conditions which