Journal of Cleaner Production 152 (2017) 103–114

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Early-age behavior of recycled aggregate concrete under steam curing regime

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A R T I C L E I N F O

Article history:
Received 4 October 2016
Received in revised form
14 March 2017
Accepted 16 March 2017

Keywords:
Early-age
Recycled aggregate
Concrete
Steam curing
Mechanical properties
Shrinkage strain

A B S T R A C T

This study addresses the effects of accelerated hydration in recycled aggregate concrete (RAC) due to the incorporation of High Early Strength Cement (HESC) and employing the steam curing method. The RAC was formulated by the complete replacement of natural aggregates with recycled aggregates. The resulting compressive strength, elastic modulus, and shrinkage strain results at early-ages were assessed and compared with concretes incorporating natural aggregates and ordinary Portland cement (OPC). By employing steam curing with HESC as binder, 70% of the design strength could be achieved in one day, however for the contemporary concretes with OPC as binder, the 1-day strength was about 60% of design strength. With HESC as binder, the change in mechanical properties was found to be minimal after 48 h of casting whereas such change was observed at 72 h age for OPC containing concretes. Utilizing recycled aggregates led to a lower net shrinkage strain indicating improvement against early-age cracking. The cost-benefit analysis showed that for accelerated hydration in concrete, utilizing recycled aggregates leads to lower associated CO_2 emissions at reduced cost. Replacing OPC with HESC improves the resulting early – age properties, but the production cost also increases. The study suggests RAC and HESC are beneficial for concrete elements with larger surface area to depth ratio, like road pavements, floorings, reinforced concrete slabs, and precast elements.

1. Introduction

Persistently increasing amounts of wastes from construction sites and the demolition of existing structures governed by serviceability criteria is a critical issue. Consumption of natural resources in creating built environments has raised serious concerns from the sustainability point of view (Shi et al., 2015). One way to target both aforementioned issues is the recycling of concrete waste for producing coarse and fine aggregates, and utilize such aggregates (usually termed as recycled aggregates; RA) in producing new concrete, termed as recycled aggregates concrete (RAC). Replacing natural aggregates (NA) with recycled ones may be problematic due to the attached mortar which lowers the specific gravity while increasing the water absorption of the RA. This may seriously influence the resulting concrete properties. Research conducted in this subject area encourages fractional replacement of NA with RA. The detrimental effects are dominant at higher replacement levels. Research findings on mechanical properties and shrinkage (which is the focus of this paper), are summarized in the following sub-section.

1.1. Literature review

Studies have been conducted to evaluate the beneficial use of the fractional incorporation of RA in concrete; for example, Limbachiya et al. (2000) showed that utilizing 30% of coarse RA did not result in appreciable strength reduction. It was demonstrated that 30% substitution of fine RA has no appreciable effect on the durability of concrete (Zega and Di Maio, 2011). It was also reported that partial replacement of NA with RA may not affect the mechanical properties significantly (Gull, 2011). Certain other

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http://dx.doi.org/10.1016/j.jclepro.2017.03.107
0959-6526/

properties of RAC were also tested and evaluated, such as abrasion resistance (De Brito, 2010), porosity (Deshpande and Hiller, 2011) and structural performance (Wang and Xiao, 2013). Mechanical properties and durability related parameters of RAC were also studied under various curing conditions i.e. open-air curing (Amorim et al., 2012), moist curing, and painted curing (Abdel-hay, 2015). These findings enabled to establish the suitability of RA (in reasonable fractional replacement of NA) in concrete.

Salau et al. (2014) partially replaced natural aggregates with recycled ones and tested for shrinkage, and they found that the drying shrinkage was 2.56 times higher than that observed in normal concrete, whereas the total shrinkage strain was 1.26 times higher when compared to normal concrete. Recently, Gonzalez-Corominas and Etxeberria (2016) explored the effects of recycled aggregates on high performance concrete and it was concluded that with higher replacement levels of recycled aggregates, the plastic and drying shrinkage increased. Bendimerad et al. (2016) specifically investigated shrinkage induced cracking in concrete due to plastic shrinkage at an early-age and deduced that although the shrinkage increased with the substitution of recycled aggregates, the correlation was not linear and maximum shrinkage strain of 1100 μm/m was found for 30% replacement of NA by RA.

Due to the recent developments in modern construction practice, concrete structures may have to withstand various kinds of loadings before reaching maturity, like in precast and prestressed concrete (Soutsos et al., 2011). Other factors like occupancy and loadings due to wind and earthquakes demand a certain level of concrete strength which may be proportional to its design strength at early-age for which, conventionally, the concrete is not designed (Zhao, 1990). In order to attain adequate levels of strength at early-age, the use of high early strength cement (HESC) as binder and employing the steam curing technique for the accelerated cement hydration process is customary. Although such methodologies have proven to be effective in the development of early-age strength, however, the strength properties often come at a price in the form of shrinkage and cracking, as summarized earlier. Once the micro-cracks are generated at the early-age, the durability of the structure is compromised as these cracks may permit ingress of salts and ions, leading to corrosion, deterioration and eventual macro-cracking of the concrete.

At very early-age (a few hours after casting), horizontal concrete members with larger surface areas, like slabs, floorings and pavements may lead to cracking soon after the concrete placement, which is then followed by the progress of plastic and drying shrinkage (Darquennes et al., 2011) due to water loss, leading to the generation of stresses (Almudaiheem, 1991). Early-age properties become of paramount importance under such scenarios.

1.2. Research significance

A number of published studies on RAC have comprehensively evaluated the suitability of RA in concrete, but these are only focused towards concrete produced with ordinary Portland cement (OPC) as the binder and employed conventional wet curing techniques. These curing methods include ponding and immersion (in which water is retained on concrete structures by earthen or sand dikes), water sprinkling, and applying wet coverings (using burlap, cotton or jute mats/rugs) (Kosmatka et al., 2008). With the advent of modern construction practices and state of the art techniques, precast construction with expedited curing regimes (e.g. steam curing) and specialized binders (like HESC), has attained utmost importance. Evaluating the resulting concrete properties under these scenarios is highly imperative. Although RAC properties under various curing conditions have been studied, the steam curing effects on the properties of RAC made with HESC have not yet been determined. This demands for an in-depth evaluation of early-age behavior of RAC under aforementioned scenarios. The published literature on RAC properties presenting intriguing results further raises interest regarding the effects of faster strength gain due to the cement type and curing method on the shrinkage strains of concretes with RA incorporation. It is hypothesized that high quality RA, even when used at the 100% replacement level, may not potentially affect the resulting concrete in a negative manner.

This experimental study fills the current research gap by exploring the potential of using HESC and steam curing in producing high early-strength RAC so that it may be able to resist a higher percentage of the design load at initial stages of its life. Evaluation of the mechanical properties (compressive strength) and shrinkage strain was also carried out, whereas the overall benefit of using RA was determined by referring to the cost of producing the steam cured concrete and the associated carbon dioxide emissions. The emphasis in this study was on the complete replacement of fine and coarse RA which was neglected in the past findings.

2. Materials and experimental methods

2.1. Materials

Ordinary Portland cement (OPC) and high early strength cement (HESC) (with specific gravity of 3.15 and 3.18, respectively) conforming to Korean Standards KSL5201-1989, were used in this study. The cement used was produced in the Republic of Korea by the Sungshin Portland Cement Co. Ltd. NA used in the experimental program was common aggregate obtained from the quarries in Korea, complying with the Korean Standards for gradation of aggregates (Korean Standards, 2006). The maximum size of the coarse aggregates (both NA and RA) was 25 mm whereas well-graded fine aggregates, under 5 mm particle size were used in the experimental study. The aggregates recycled by the Insun recycling plant were used after bonded mortar was removed. Bonded mortar is removed by employing multiple treatments in various steps. These include mechanical processes (involving grinding/churning/sieving), thermal processes (involving microwave or conventional heating) and chemical methods (pre-soaking or cyclic soaking of the recycled aggregates in chemical solutions). Up to 95% of the bonded mortar could be successfully removed. The aggregates used in the study are shown in Fig. 1. Admixtures (high rate water reducing admixture and air-entraining admixtures) were utilized for maintaining the uniformity, consistency, and cohesiveness of the fresh concrete mix while stabilizing the air bubbles in the mix and improving its workability. Ordinary potable tap water (free from impurities and chemicals) was used for mixing the ingredients.

Prior to the mixture formulation, basic tests on the aggregates were performed to determine the properties of the aggregates. These properties help determine a suitable mix proportion for design strength and workability requirements. These tests were conducted under the guidelines of Korean Standards (KS) (Korean Standards, 2010, 2007a, 2007b, 2006). The testing included gradation, fineness modulus, water absorption and specific gravity. The properties of the aggregates are presented in Table 1 while the particle size characterization (gradation) curves are shown in Fig. 2. It was established that the water absorption of the recycled aggregates was higher whereas the specific gravity was lower than the natural aggregates which was already anticipated due to the bonded or adhered mortar with the recycled aggregates. The mix