Construction and Building Materials 127 (2016) 828–842

Contents lists available at ScienceDirect

Construction and Building Materials

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

# Carbonation resistance and microstructural analysis of Low and High Volume Fly Ash Self Compacting Concrete containing Recycled Concrete Aggregates

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## HIGHLIGHTS

- The carbonation resistance of LVFA and HVFA based SCC made with coarse RCA have been investigated.
- Compressive strength for all the SCC mixes has been reported for reference.
- The microstructural investigation of LVFA and HVFA based SCC has been done by SEM and TGA tests.
- Electrical resistivity has also been calculated for all the mixes.
- The effect of replacement of NA with RCA has been evaluated in binary and ternary blended SCC mixes.

## ARTICLE INFO

*Article history:*
Received 30 June 2016
Received in revised form 7 October 2016
Accepted 9 October 2016

*Keywords:*
Low Volume Fly Ash
High Volume Fly Ash
Self Compacting Concrete
Coarse Recycled Concrete Aggregates
Accelerated carbonation

## ABSTRACT

The present study investigates the carbonation resistance of Low Volume Fly Ash (LVFA) and High Volume Fly Ash (HVFA) based Self Compacting Concrete (SCC) made with Coarse Recycled Concrete Aggregates (RCA). In order to study the carbonation resistance of LVFA and HVFA based SCC mixes made with RCA, accelerated carbonation tests were conducted for an exposure period of 4, 12 and 16 weeks. The results indicate that with the increase in RCA content as replacement of Coarse Natural Aggregates (NA), decrease in the carbonation resistance of SCC mixes has been observed. The inclusion of metakaolin (MK) as a mineral admixture has been found to compensate the loss in the carbonation resistance on account of substitution of NA with RCA to some extent. The current investigation also emphasises on the microstructural study performed by Scanning Electron Microscopy (SEM) and Thermogravimetric Analysis (TGA) for validation of observed results.



## 1. Introduction

The persistent process of constructing new civil engineering structures and swapping the long-standing ones has already shaped an environmental issue which certainly needs a well-timed concern. For example, the generation of solid waste from concrete industry has been expected to grow from 12.7 billion tonnes in 2000 to 27 billion tonnes in 2050. An increase from 1.7 times in 1980 to 2.2 times in 2025 has been projected in the amount of solid waste generation for 'Organisation for Economic Co-operation and Development' (OCED) countries [1,2]. This enormous quantity of inert material in the form solid waste generated from concrete industry has given rise to major environmental issues, either in the form of enormous amount of carbon dioxide ($CO_2$) emission or in the form of depleted landfills. The ultimate solution of this major problem is to recycle/reuse the C&D waste in construction industry. Many countries of Europe, Asia and America have already implemented the use of C&D waste in concrete industry [3]. The inert material obtained from C&D waste after crushing and grinding into smaller particles is known as Coarse Recycled Concrete Aggregates (RCA). For meeting the continuously increasing demand of cement in concrete industry and while keeping in mind the environmental aspects, a special kind of material is required that is having pozzolanic content and is also economical. As reported in previous studies, low and higher replacements levels of Fly Ash (FA) have been used in many investigations. On the basis of replacement levels, concrete containing FA up to 30% and more than 50% is termed as Low/Moderate Volume Fly Ash (LVFA) and High Volume Fly Ash (HVFA) concrete respectively [4,5]. Such forms of concrete has gained popularity world-wide due to its higher benefits in terms of sustainability, durability

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http://dx.doi.org/10.1016/j.conbuildmat.2016.10.067
0950-0618/

and cost effectiveness and other long term performance aspects [6–9]. The sustainability can also be achieved to some extent by reducing the quantity of clinker in concrete and this can be possible only by adding different cement additions like FA, Silica Fume (SF), Metakaolin (MK) etc., which are having inherent pozzolanic and binding properties [5,7]. Hence, the use of cement additions has increased in cement industry to minimise the Portland Cement (PC) content [9]. For achieving sustainability, adoption of FA in current concrete manufacturing system has become necessary while maintaining top priority for the durability aspect.

The production of Self Compacting Concrete (SCC) was initiated in Japan in the late eighties to compensate the shortcomings of Normally Vibrated Concrete (NVC). Due to numerous advantages in terms of improved mechanical and durability properties, the SCC has gained world-wide recognition in very short time [10–14]. As the trend of using SCC has increased, the researchers also put some efforts to make SCC more durable and sustainable by using different cement additions. The previous studies have reported that, addition of cement admixtures helps in enhancing the overall performance of the concretes e.g. the use of SF, MK, Blast Furnace Slag (BFS) has been found to improve its mechanical and long term properties [12,15]. However, the use of RCA in construction industry has been initiated in the last decade but its implementation has been constricted in only few categories due to its poor physical and mechanical properties [16–20]. The kind of inert material obtained from C&D waste in the form of RCA has been employed in NVC and SCC and the influence of these materials has been examined in terms of physical, mechanical, rheological and durability properties [21–25]. The literature confirmed that replacing Coarse Natural Aggregates (NA) with RCA degrades the performance of all types of concretes i.e. reduction in workability, compressive and tensile strengths etc. [26–31]. The reason behind the poor performance of using RCA lies in weak Interfacial Transition Zone (ITZ), micro and macro cracks, pores in adhered mortar, generation of fissures during its processing. Carbonation is a major risk for reinforced concrete structures because it lowers alkalinity of concrete which results in enabling the external aggressive agents to act [1,32]. Carbonation is a reaction of gaseous atmospheric Carbon Dioxide ($CO_2$) with the calcium-bearing phases of concrete and is known to cause lowering of alkalinity leading to the corrosion of steel bars embedded in concrete [7,9]. It depends on various factors like permeability of concrete, moisture content, concentration of environment's $CO_2$ and relative humidity.

A lot of research has been carried out to evaluate the carbonation resistance of NVC made with NA and RCA and SCC made with NA using low and moderate volumes of FA [21–22,33–42]. In addition to this, direct influence of FA on carbonation depth for various types of concretes has also been studied by numerous researchers [31,33]. An increase of the order of 1.3–2.5 times in carbonation depths of NVC made with RCA has been observed compared to NVC made with NA [24,31]. The exceptional effects of FA was noted in another study in which carbonation depths of NVC made with RCA were found to be lower in comparison to NVC made with NA [33,35]. Another similar research was conducted in order to evaluate the effect of FA in NVC made with RCA. The results showed that, addition of FA affects the carbonation resistance. It has also been found that addition of FA decreased the carbonation resistance of NVC made with RCA for longer exposure periods [31,35]. Few of the investigations done on SCC indicated its higher durability performance over NVC [21,36–37], with the presence of cement additions which supports in enhancing the microstructure and carbonation resistance [22,38]. In addition to this, the carbonation depths for RCA concrete depends mainly on water/cement (w/c) ratio and curing periods, as higher and lower carbonation coefficients (CC) have been noticed respectively [40,41]. Since carbonation phenomenon is complex in nature as conflicting results have been mentioned by many researchers.

However, to the best of knowledge of the authors, no information on the carbonation resistance of LVFA and HVFA based SCC mixes made with RCA is available. Thus, the main objective of this paper is to evaluate the carbonation resistance of LVFA and HVFA based SCC mixes made with different replacement levels of NA with RCA. The emphasis here is to achieve a most sustainable SCC that can be used in civil engineering construction which comprises alternative materials both in the form of binders and RCA. The current investigation includes, in total ten number of SCC mixes differentiated according to content of FA (LVFA and HVFA based mixes) and replacement levels of RCA. Herein, the study examines the carbonation depth as main parameter of LVFA and HVFA based binary and ternary blends (PC, FA and MK) of SCC mixes made with varying quantities RCA. The performance of all the SCC mixes has been judged on the basis of their observed carbonation depths. Also, in present study an effort has been made to characterise those compounds which are key parameters for carbonation phenomenon, like Calcium Silicate Hydrates (CSH), $CaCO_3$, $Ca(OH)_2$ etc., as all the mixes have been tested for micro structural characterization. Specifically, Scanning Electron Microscopy (SEM) and Thermogravimetric Analyses (TGA) have been used to explore the carbonation mechanism at the microscopic level. In addition to this, the compressive strength and electrical resistivity of all the LVFA and HVFA based SCC mixes have also been evaluated.

## 2. Experimental programme

### 2.1. Materials and mix proportions

Portland Cement (PC) of grade 43 was used throughout the experimental programme. Locally available natural fine aggregates and NA of maximum size 10 mm were used. The RCA were prepared in the laboratory by crushing and the maximum size of RCA was also kept as 10 mm. Two basic SCC mixes containing low and high volume FA content and 100% NA were prepared as shown in Table 1.

These mixes were designated as LVFA and HVFA based mixes respectively. In each of these mixes, the replacement levels of NA with RCA were kept at 0%, 50% and 100%. Fly ash was also replaced approximately by 10% of MK in the mixes containing 50% and 100% RCA to obtain ternary blended mixes. Appropriate doses of poly carboxylic-ether based superplasticizer and viscosity modifying agent were used to obtain adequate workability and viscosity respectively. The particle size distribution of PC, FA and MK is presented in Fig. 1. The grading curve of RCA was purposely kept comparable to the grading curve of NA used in present study. The grading curves of NA and RCA used in the present study are shown in Fig. 2.

A total number of 10 SCC mixes were developed with a water/binder (w/b) ratio of 0.45 and total binder content of 615 kg/m$^3$. The binary control SCC mix of LVFA based mixes has been designated as CFL-R0, whereas the rest of the mixes are designated as CFL-R50, CFL-R100 containing 50% and 100% of RCA respectively. Similarly, the ternary blended mixes containing MK are designated as 'CFLM-R50' and 'CFLM-R100'. Similar to LVFA based SCC mixes, the binary mixes of HVFA based SCC mixes has been designated as CFH-R0, CFH-R50 and CFH-R100, whereas the ternary mixes are designated as CFHM-R50 and CFHM-R100. For details of the various mixes, their designations and description, reference may be made to Table 2.