Construction and Building Materials 171 (2018) 634–642

Contents lists available at ScienceDirect

Construction and Building Materials

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

Micromechanical damage analysis and engineering performance of concrete with colloidal nano-silica and demolished concrete aggregates

Savaş Erdem [a,*], Serap Hanbay [b], Zeynel Güler [b]

[a] School of Civil Engineering, University of Istanbul, Avcilar Campus, Istanbul, Turkey
[b] Department of Civil Engineering, University of Altınbaş, Mahmutbey Campus, Istanbul, Turkey

HIGHLIGHTS

- Micromechanical damage analysis of concrete under fast-dynamic loading.
- Concrete with recycled aggregate and colloidal nano-silica.
- Nano-silica reduces the pore amount and stimulate toughening mechanism.
- Impact resistance increases in parallel with the increase in the percentage of nano-silica.

ARTICLE INFO

Article history:
Received 20 December 2017
Received in revised form 16 March 2018
Accepted 21 March 2018

Keywords:
Recycling
Micromechanics
Nano-structures
Mechanical properties
Surface analysis

ABSTRACT

In this study, different samples of concrete, containing natural and recycled coarse aggregates and different ratios of nano-silica, were delicately prepared to examine the micro-structure associated material behaviour, and to quantitatively characterize the fracture surfaces after fast dynamic fracture. The first specimen includes 100% of natural aggregates and for the second one, 100% of recycled coarse aggregates were used only. In the other specimens, 0.5%, 1% and 1.5% of nano-silica together with 100% of recycled coarse aggregates were used, respectively. A number of tests including compressive and flexural strength, non-destructive ultrasonic, impact and water penetration tests were conducted for all specimens. Furthermore, scanning electron microscopy (SEM), X-ray computed tomography coupled with image analysis and laser vertical interferometry were employed for the characterization of nano-silica and the impact damaged fracture surfaces of some mixtures. According to the results, recycled coarse aggregate weakened the mechanical properties of the natural coarse aggregate concrete and increased the water permeability. However, it has been demonstrated that this reduction can be mitigated by adding nano-silica into concrete, incorporating recycled coarse aggregate as confirmed by the quantitative X-ray spectroscopy micro-chemical analysis. In addition, it was also concluded from the fractographical surface analysis that nano-silica reduces the pore amount and produces the concrete less porous at the macroscopic level. This, in turn, may stimulate toughening mechanism and crack deflection, leading to low micro-roughness number but high impact resistance during the fast dynamic fracture event.

1. Introduction

Utilization of recycled materials, specifically for structural purposes, has become an essential issue in the recent times. As concrete is a significantly widespread engineering material, it is unhesitatingly beneficial to use wastes of it as recycled aggregates to produce new concrete which is a high-grade application. In literature, recycled aggregate usage in concrete mortar is investigated by several researchers in many aspects to make the process feasible. One of the most fundamental findings of the studies was the decrease in strength when recycled material usage is higher than 20% for fine or higher than 30% for coarse recycled concrete aggregate, respectively [1–5]. Furthermore, water/cement ratio has a fundamental role in the mechanical behavior in such a way that the quality of the recycled aggregate alters the strength of concrete only for the low water/cement ratio and higher reduction in strength is observed [3,6–8]. As a consequence, along with the recycled aggregate, it is necessary to seek for new materials to add to the mortar in order to improve the mechanical properties of concrete. Increasing interest of the researchers in nano particles

* Corresponding author.
E-mail address: savas.erdem@istanbul.edu.tr (S. Erdem).

https://doi.org/10.1016/j.conbuildmat.2018.03.197
0950-0618/

enables these novel materials to be scrutinized and utilized effectively in concrete technology [9].

In civil engineering, there are a variety of nano materials which affect the behavior and significant properties of concrete, and nano-silica, being used widely in last decades, is one of these materials. Two forms of nano-silica, crystalline structure and colloidal suspension, can be used in mixtures; however, it has been found that more desirable behavior is observed when adding colloidal nano-silica in cement mixture due to the highly dispersed and agglomerated free nature of colloidal nano-silica [10]. In several studies/research works, nano-silica is used in cement mortar to increase the performance of concrete in terms of compression, tensile and flexural strength, and durability or to decrease water permeability. High strength and durability, and low permeability are obtained in many studies due to the fact that the microstructure of concrete improves [11–14]. As shown by Konkol and Prokopski studies [15], the greater surface roughness of the fractures in concrete correlates well with the lower strength of concrete, including fracture toughness. The greater surface roughness of the fractures means also the higher number of defects in the concrete microstructure, which in the case of the recycled aggregate used is of great importance for the durability of these concretes. Research has shown that these defects have been significantly reduced by the use of nanosilica. A study about the influence of colloidal nano-silica on concrete including different binders exhibits that the mechanical properties and the durability of concrete generally increase when nano-silica particles are stirred into the mixture because small-scale particle of nano-silica means a larger surface area and hastens the rate of cement hydration and pozzolanic reactions [16]. Another study, which evaluates water permeability resistance behavior and microstructure of concrete with nano-silica, shows that the microstructure of the transition zone (ITZ) of aggregate/ surrounding cement matrix interface and the water permeability of concrete can be improved by nano-SiO2 [17].

Considering all of these factors, usage of both nano-silica and recycled aggregate in concrete would be an influential study in terms of sustainability and superior mechanical properties. In previous studies, several aspects of addition of nano-silica and recycled aggregate in different amounts to concrete have been investigated. As a result, microstructural improvements, enhancement of tensile and compressive strengths and non-destructive properties have been demonstrated [18–20]. However, no study combining the quantitative microstructural and fractographic analysis of recycled aggregate concrete with nano-particles has been reported so far. Through this study an attempt is, therefore, made to evaluate the compressive and flexural strengths, non-destructive properties, impact resistance and water permeability of the concrete containing 100% of coarse recycled aggregate and 0.5%, 1%, 2% of nano-silica by weight of cement. Moreover, scanning electron microscopy (SEM) and laser vertical interferometry are employed for the quantitative characterization of the microstructures of the aggregate-matrix interfaces and the impact damaged fracture surfaces of the samples, respectively.

2. Experimental program

2.1. Materials used and concrete mixtures

Portland Cement Cem I 52.5 N was used to produce all concrete mixes in this experimental study. Natural sand (specific gravity of 2.66) constituted the fine aggregate portion for concrete mixtures made with recycled aggregate as well as concrete made with conventional aggregate. The crushed limestone was employed as a natural coarse aggregate and the recycled coarse aggregates were obtained from demolished concrete blocks. The same size percentages were selected for the conventional coarse and recycled coarse aggregates to eliminate the effect of grading difference on concrete performance. The main characteristics of the aggregates are tabulated in Table 1.

Colloidal form of nano-silica (Fig. 1) has been used as it helps maintain uniform distribution of nanoparticles in the cementitious matrix and reduces agglomeration tendency of nanoparticles which contributes to improvement of nano-particles performance in concrete [20]. Nano-silica used in this study (commercially known as new technology Cembinder 17) has been manufactured by EKA Chemicals (Istanbul, Turkey). Nano-silica is being manufactured with a solid content of 40% and particle size in the range of 5–20 nm. Sample Cembinder 17 used in the present study has a density of 1.3 g/cm^s and pH value of 9.4.

2.2. Production of concrete mixtures

All the concrete mixtures were designed by the volume method, and the mix proportions are tabulated in Table 2. The water cement ratio was kept constant at 0.4 for all concrete mixes and three different amounts of nano-silica (0.5%, 1% and 2%) by weight of cement were used for the production of concrete mixes. A total of five concrete mixtures were produced, namely: control concrete containing natural coarse aggregate without nano-silica (CC), recycled aggregate concrete without nano-silica (RAC), recycled aggregate concrete with 0.5% nano-silica (RAC-0.5), recycled aggregate concrete with 1% nano-silica (RAC-1) and recycled aggregate concrete with 2% nano-silica (RAC-2). The quantity of water present in the colloidal nano-silica has been taken into consideration when calculating the total amount of water to make concrete mixtures.

The recycled aggregates were used in the saturated surface dry condition and extra water was used to compensate for water absorption in the natural aggregates. Therefore, the quantity of mixing water used ensured that the water/cement ratio (0.42) was the same in all batches and other components in the concrete mixes were determined in the proportions as shown in Table 2. Following the mixing process, the freshly mixed concrete was placed into 150 mm cubes and into 100 × 100 × 500 mm prisms in two equal layers and were then consolidated by using a mechanical vibrator to remove all entrapped air. Finally, the moulds were removed after 24 h and the specimens were cured in lime water that was placed in a room with 65% relative humidity. Four concrete cubes and three concrete prisms were prepared for every batch.

2.3. Tests conducted

A digital image processing (DIP) technique was used to analyze the particle shape characteristics of the coarse aggregates. Image acquisition was performed by the author using a Cambridge Instrument Quantimet 570™ DIP system connected to a CCD camera. After acquiring the images, a computer software program (Image Pro^{+TM}) was used for the quantification of aggregate shape characteristics.

Table 1
The physico-mechanical properties of the aggregates used.

Characteristics	Natural aggregate	Recycled aggregate
Specific gravity (g/cm^3)	2.82	2.43
Water absorption	0.6	4.3
Angularity	1.18	1.16
Roundness	1.25	1.19
Impact value (%)	9.7	32.9