Construction and Building Materials 162 (2018) 663–673

Contents lists available at ScienceDirect

Construction and Building Materials

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

Mechanical behaviors of nano-zirconia reinforced reactive powder concrete under compression and flexure

Yanfeng Ruan [a], Baoguo Han [a,*], Xun Yu [b,c], Zhen Li [a], Jialiang Wang [a], Sufen Dong [a], Jinping Ou [a]

[a] *School of Civil Engineering, Dalian University of Technology, Dalian 116024, China*
[b] *Department of Mechanical Engineering, New York Institute of Technology, New York, NY 11568, USA*
[c] *School of Mechanical Engineering, Wuhan University of Science and Technology, Wuhan 430081, China*

HIGHLIGHTS

- Properties of nano-zirconia (NZ) reinforced concrete with water and heat curing are compared.
- Mechanical behaviors of reactive powder concrete with heat curing were investigated.
- Heat curing is beneficial for improving strength of reactive powder concrete with NZ.
- NZ can reduce the stiffness and improve the compressive/bending toughness of concrete.

ARTICLE INFO

Article history:
Received 27 September 2017
Received in revised form 21 November 2017
Accepted 8 December 2017

Keywords:
Nano-zirconia
Reactive powder concrete
Heat curing
Mechanical properties
Reinforcing mechanisms

ABSTRACT

The properties of nano-zirconia (NZ) reinforced reactive powder concrete (RPC) with water curing and heat curing were compared. The underlying mechanisms of curing method to RPC were also studied through X-ray powder diffraction (XRD) analysis, thermogravimetry (TG) analysis and scanning electron microscope (SEM) observation. The mechanical behaviors of NZ reinforced RPC with heat curing were investigated. Experimental results showed that the flexural, compressive and splitting tensile strengths of RPC with 3% NZ cured in hot water at 90 °C for two days presents a 35.0%, 15.0% and 17.0% increase compared with that of RPC with 3% NZ cured in water for 28 days. Both of the calcium hydroxide (CH) mass and CH crystal orientation of RPC with heat curing are lower than that of RPC with the water curing. As a result, the compactness of the matrix was improved significantly. The elastic modulus of RPC with 3% NZ under uniaxial compression features a 12.7% decrease over that of RPC without NZ. The initial-peak deflection, initial-peak strength and fracture energy of RPC with NZ under four-point bending were increased by 78.2%, 5.6% and 85.7% compared to that of RPC without NZ, respectively. Whether incorporated with NZ or not, the ratio of the stress at precrack tip of notched beam to the bending strength of non-notched beam under three-point bending fracture is less than 1. The fracture peak load of RPC with NZ under four-point shear fracture increases by 25.4% compared to RPC without NZ when the crack-depth ratio is 0.25, and it decreases by 11.1% when the crack-depth ratio is 0.5. It can be therefore concluded that the introduction of NZ can reduce the stiffness of RPC and improve the compressive/bending toughness of RPC.

1. Introduction

Cementitious composites are the most widely used construction materials in the world because of their abundant raw materials resources, mature production process, high mechanical strength, strong adaptability and low price [1]. However, they possess various defects such as they are brittle and easy to form cracks. Numerous types of cementitious composites have been developed to solve these issues. One of the most representative cementitious composites is reactive powder concretes (RPC). It possesses excellent properties because of its excellent granular compactness and denser microstructures compared with conventional concrete or even high performance concrete [2–8]. The compressive strength of RPC is between 200 and 800 MPa, the elastic modulus is between 50 and 75 GPa, and the flexural strength can reach 140 MPa [6,9,10]. However, RPC is still quasi-brittle and confronted with potentially serious destruction or fatigue accumulations in harsh service environments due to the fact that there are still many unignorable defects in the interior and on the surface of RPC [11,12].

---

* Corresponding author.
E-mail address: hanbaoguo@dlut.edu.cn (B. Han).

https://doi.org/10.1016/j.conbuildmat.2017.12.063
0950-0618/

Most of the performance enhancements in RPC are accomplished by conventional methods such as the incorporation of small-sized steel fibers [6,13]. However, steel fibers are easy to rust, and they are easy to sink in RPC during the fabrication process because of their high density, thus leading to the uneven dispersion of them in RPC [14,15]. Nanotechnology is an emerging field related to the understanding and control of materials at the nanoscale. Because of the ultrafine size effect, quantum size effect and surface effect, nanomaterials have been gaining increasing attention and been applied in many engineering fields to fabricate new materials with enhanced mechanical properties or novel functions [16–18]. To date, applications and advances of nanotechnology have injected new vitality into cement and concrete materials [19–22]. Nanomaterials can improve the mechanical properties of cementitious composites effectively because of their remarkable properties and functions [1]. More specifically, nanomaterials possess boundary effect and small size effect, which can help them not only to fill the pores inside cementitious composites [23], but also to improve the interface structure between concrete and aggregate to increase the strength and toughness of cementitious composites [1,24]. For example, nanosilica as a type of typical inorganic non-metal oxide nanomaterials has been introduced to enhance the mechanical properties and durability of cementitious composites. There are many studies on nanosilica reinforced cementitious composites [25–28]. As a kind of inorganic metal oxide with high strength and high toughness, nano-zirconia (NZ) had been incorporated into ceramics to enhance mechanical strength and fracture toughness of ceramics [29]. Inspired by the application and the reinforcing effect of NZ in ceramics, NZ was introduced to cementitious composites by some researchers and its enhancing effect was investigated. For example, Soleymani observed that the flexural strength of ordinary Portland cement containing 0.5%, 1.0%, 1.5%, 2.0% NZ with water curing for 28 days presents a 13.6%, 25.0%, 20.5% and 6.8% increase over that of ordinary Portland cement paste without NZ, respectively. It indicates that the NZ enhancing effect on the flexural strength of ordinary Portland cement paste increases first then decreases. This is because that when the NZ content exceeds a certain amount, the enhanced extent of harmless and few-harm pores and the reduced extent of harmful and multi-harm pores in cement paste both decrease and the improvement on the pore structure of cement paste weakens [30,31]. Shekari et al. found that when the Metakaolin content is fixed at 15%, the compressive strength at curing age of 28 days in water of the ordinary Portland cement paste with 1.5% NZ can increase 20.2% compared with that of the cement paste without NZ [32]. Nazari et al. studied the mechanical properties, workability and setting time of NZ filled cementitious composites [33,34]. Nazari and Riahi also investigated the effect of limewater on compressive strength and setting time of NZ filled cementitious composites [35]. Han et al. found that the flexural, compressive and splitting strengths of RPC with NZ at curing age of 28 days achieve increases of 36.6%, 16.3% and 34.0%, respectively, compared to RPC without NZ [36]. On the one hand, previous studies mainly focus on the effect of NZ on ordinary Portland cement paste, only Han et al. investigated the reinforcing effect and mechanisms of RPC filled with NZ. On the other hand, although Han et al. studied the flexural, compressive and splitting strength of RPC filled with NZ, the effect and mechanisms of curing methods on mechanical properties of RPC with NZ, and mechanical behaviors of RPC (including the Poisson's ratio, elastic modulus, bending toughness and fracture) haven't been studied.

Therefore, this paper firstly compared the flexural, compressive and splitting tensile strength of NZ reinforced RPC with water curing and heat curing. Then X-ray powder diffraction (XRD) analysis, thermogravimetry (TG) analysis and scanning electron microscope (SEM) observation were used to analyze the underlying mechanisms of curing methods on RPC filled with NZ. Finally, the mechanical behaviors of NZ filled RPC with heat curing (including Poisson's ratio, elastic modulus, bending toughness and fracture) were investigated under compression and flexure (four-point bending, three-point bending and four-point shear).

2. Experiment

2.1. Materials

The raw materials used to fabricate RPC specimens are listed as follows. P·O 42.5R Portland cement used as the binder material is produced by Dalian Onoda Cement Co. Ltd. in China. The chemical composition and mineral composition of P·O 42.5R cement are listed in Tables 1 and 2, respectively. The NZ used as the filler is purchased from Nanjing Haitai Nanomaterials Co. Ltd. in China, its SEM image is shown in Fig. 1 and its properties are listed in Table 3. Quartz sand with a size range of 0.12–0.83 mm is provided by Dalian Lianxin Quartz Sand Factory in China. It is used as the fine aggregate. The fly ash used as the mineral admixture is purchased from Dalian Daokete Building Materials Co. Ltd. in China. Silica fume is a commercially available product produced by Elkem Materials Ltd, its properties are listed Table 4. RHEOPLUS 411 (BASF) superplasticizer was used to assist NZ dispersion and adjust the workability of RPC. Steel sheets with a width of 10 mm or 20 mm and thickness of 2 mm are used to make precracks in the specimens.

2.2. Preparation

All the specimens with NZ were fabricated by adding NZ into RPC to replace some of the cement. In order to improve the fluidity of RPC and reduce the dosage of cement, the fly ash was introduced into RPC to replace some of the cement. In all specimens, the water to binder (cement, fly ash and silica fume) ratio was fixed at 0.24, which is referred to the water to binder ratio of reactive powder concrete purposed by Richard in 1995 [6]. In addition, 0.24 of water to binder ratio can guarantee the workability of reactive powder concrete to be well modeled. Therefore, 0.24 of water to binder ratio was selected in this study. The process of fabricating specimen is as follows: (1) All the raw materials were weighed according to the detailed mix proportions as shown in Table 5. (2) NZ (control specimens don't contain this material) and superplasticizer were added to water, then the suspension was mixed by a cement mortar mixer at low speed for 10 s. (3) The silica fume was put into the mixing pot and the mixture was mixed at low speed for 60 s. (4) The cement and fly ash were put into the mixing pot then stirred at low speed and at high speed for 120 s in sequence. (5) The sand was put into the mixing pot, then the mixture was mixed at low speed firstly for 60 s and then at high speed for 240 s. (6) The homogeneous mixtures after stirring were poured into the corresponding oiled molds of 40 mm × 40 mm × 160 mm (Specially, the size of the specimens used for splitting tensile strength test is 40 mm × 40 mm × 40 mm), and the oiled molds filled with specimens were put onto the vibrating table for 60 s, after that the mixtures were smoothed with a spatula. (7) The specimens were demolded after conserved in standard maintenance box with 95% relative humidity and temperature of 20.0 °C for 24 h, and then the specimens were cured in water for 27 d.

It should be noted that cement paste was used to manufacture the specimens for TG and XRD test because the existence of sand in the specimens may affect the test accuracy. On the one hand, with the increase of temperature, the weight of dry sand doesn't decrease. Moreover, the sand content in the specimen used for TG test is random, which will cause the hydration products percentage in the sample mass different. On the other hand, the XRD characteristic peaks of sand are too strong to make XRD peaks of cement hydration products observable.

The above are the processing steps of specimens filled with 3% NZ with water curing. The sample code of these specimens is marked as O. As for specimens with heat curing, "the specimens were cured for 27 d in water" in Step 7 should be changed to "the specimens were cured for 2 d in hot water at 90 °C". The sample code of these specimens is marked as H. All the following numbered specimens also adopt heat curing.

Table 5 lists the all samples fabricated in this study. The sample codes of the specimens under uniaxial compression are as follows: U-0 (blank RPC specimens) and U-3 (RPC specimens filled with 3% NZ). The sample codes of the specimens under four-point bending are as follows: F-0 (blank RPC specimens) and F-3 (RPC specimens filled with 3% NZ). The specimen manufacturing steps of Group U and Group F are the same as Group H. The sample codes of the specimens under three-point bending are as follows: 3-10-0 (blank RPC specimens with precrack size of 10 mm), 3-20-0 (blank RPC specimens with precrack size of 20 mm), 3-10-3 (RPC specimens filled with 3% NZ with precrack size of 10 mm), and 3-20-3 (RPC specimens filled with 3% NZ with precrack size of 20 mm). The numbering rule of the specimens under four-point shear is same as that under three-point bending, and it only requires to change 3 to 4 at the beginning of the sample code, and the meanings of the rest parts in the sample code are same. The specimen manufacturing steps of Group 3 and Group 4 are the same as that of Group H except for the step to mold the specimens. In Group 3 and 4, after molding the specimens, the steel