Construction and Building Materials 72 (2014) 270–282

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effects of particle characteristics of lightweight aggregate on mechanical properties of lightweight aggregate concrete

Yan He, Xiong Zhang *, Yongjuan Zhang, Yun Zhou

Key Laboratory of Advanced Civil Engineering Materials of Education Ministry, School of Material Science and Technology, Tongji University, 4800 Can'an Road, Shanghai 201804, PR China

HIGHLIGHTS

- We use digital image processing to characterize the particle properties of LWAs.
- We investigate the interfacial roughness of LWAC by fractal theory.
- Optimization and multiple-factor analysis points out the optimum particle indexes.

ARTICLE INFO

Article history:
Received 19 October 2013
Received in revised form 11 June 2014
Accepted 16 July 2014

Keywords:
LWAs
Particle characteristics
LWAC
Mechanical strength
Interface roughness
Fractal dimension

ABSTRACT

Particle characteristics of lightweight aggregates (LWAs) have great influences on the mechanical performance of the corresponding concrete. In this research, particle characteristics of LWAs were measured through digital image processing (DIP), including particle sizes, gradation and shape properties, and the effects of LWA particle characteristics on mechanical performances of lightweight aggregate concrete (LWAC) were investigated through grey correlation analysis methods. The LWAC interfacial roughness was investigated with fractal theory, and the effects of LWA particle characteristics on the LWAC interfacial roughness were also investigated through grey correlation analysis methods. The results show that LWAC interfacial fractal dimension and mechanical performance exhibit good linear correlation. LWA particle specific surface area and LWA particle aspect ratio take greater effects on LWAC mechanical strength and interfacial roughness. LWAC mechanical strength would be greater when LWA specific surface area (*SV*) was within 586.4–633.7 m^2/m^3 and LWA aspect ratio was within 1.3262–1.3308. LWAC interfacial fractal dimension (*D*) would be greater when LWA specific surface area (*SV*) was within 539.1–633.7 m^2/m^3 and LWA aspect ratio was within 1.3262–1.3354. It is proposed that the change of the contact area between LWA particles and mortar phases will change the occlusal structures on the LWAC interface, which consequently changes the interfacial roughness, the interfacial bond strength and hence the LWAC mechanical strength.

1. Introduction

In recent years, more attention has been paid to the development of lightweight aggregate concrete (LWAC) [1,3]. LWAC substantially reduces building cost, eases construction, allows greater design flexibility and has the advantage of being a relatively 'green' building material, as the reduction in the concrete density results in superior thermal, acoustic and fire resistance and leads to a positive impact on the energy consumption of a building [1,2]. For high performance LWAC, the lightweight aggregate (LWA) is the main determinant of the properties of LWAC [3–5]. Because of the greater porosity and lower strength of LWAs, the weakest component of LWAC is not the cement matrix or the interfacial transition zone (ITZ) but the aggregates. So the mechanical performances of LWAC are not only controlled by the cement matrix quality but also the aggregates properties [4]. Particle characteristic is always a significant factor in aggregate test procedure, including the form, angularity, gradation, etc. LWA shape properties influence their mutual interactions and interactions with the stabilization agents and are related to LWAC mechanical performances [6]. Wasserman and Bentur [7] found that differences in LWAC strength would not fully depend on the differences in the LWA strength. The physical and chemical

* Corresponding author at: Room 447, School of Material Science and Technology, Tongji University, 4800 Cao'an Road, Shanghai 201804, PR China. Tel.: +86 13601688877.

E-mail address: xiong.zhang@vip.sina.com (X. Zhang).

http://dx.doi.org/10.1016/j.conbuildmat.2014.07.043
0950-0618/© 2014 Published by Elsevier Ltd.

interfacial processes have an influence on the overall strength. Cui et al. [1] put forward that the shape of LWAs had some influences on the compressive stress, strain and elasticity modulus of LWAC, as LWAs with higher shape factor contribute to higher LWAC compressive strength. In fact, aggregate size distribution is one of the key parameters of mixture design affecting the mechanical strength of concrete mixtures. During the mix design, void space between aggregate particles determines the amount of cement paste required to gain the expected strength of concrete [21]. When LWA is of proper particle gradation, it would decrease void content of LWA particles. In this way, it would reduce the dosage of cementitious materials and improve concrete performance. Therefore, fundamental research into LWA particle characteristics is essential for quality control of LWAC and understanding the influences of these characteristics on the behavior of LWA-mortar interface and mechanical performance of LWAC system.

As the importance of measurements into aggregate shape has been felt long back, in traditional manner, aggregate shape characteristics can be obtained using simple equipment, with each particle individually evaluated. Aside from being time consuming, such tests results determine a global index based on the averages, instead of using cumulative property distributions [8]. And these methods are not well appreciated as they give only a broad description of aggregate shape. For example, flakiness and elongation indices are used for the assessment of aggregate shape [9], which classifies aggregate shape into five classes, i.e. angular, subangular, subrounded, rounded and well rounded [1,25]. Limitation of available test methods has directed researchers towards seeking new technologies to measure aggregate shape accurately and rapidly [4,10]. With the advances of computers and software, digital image processing (DIP) techniques have been used to characterize several material properties, including aggregate particle properties, and concrete interface roughness [11,12]. Because of moderate hardware and software requirements, methods relying on DIP attract many researchers to perform an efficient and rapid analysis of aggregate characteristics. The form, angularity and gradation of LWAs can be accurately characterized through DIP techniques, including sphericity, roundness, form index, flat and elongated ratio, aspect ratio, etc.

A further point of research is the measurement of fractal dimensions by image analysis, which is based on different fractal systems [13]. The quantitative description of rough surfaces and interfaces has been a serious challenge for many years. In most cases, man-made objects have contours and surfaces which are linear or curvilinear, corresponding to Euclidean geometry in which points, lines, surfaces, and volumes have topological dimension of 0, 1, 2, and 3, respectively [14]. However, natural objects like broken concrete interfaces are commonly rough, fragmented, and composed of mountains and valleys. In this way, the word 'fractal' describes objects that are too irregular to fit into a traditional geometrical setting. The main tool of fractal geometry is the fractal dimension of the object in question. Fractal geometry provides a mathematical framework for 'irregular' sets which has earlier been treated as pathological objects in classical geometry. Fractal analysis is a simple and powerful tool for quantifying the roughness and irregularities of fractures interfaces of LWAC. The roots of fractal dimension go back to Hausdorff's definition of dimension [15,16]. The fractal dimension correlates very well with interface roughness. The rougher the interface is, the higher the fractal dimension would be [10]. Automatic image analysis is well developed for the measurements of fractal dimensions. The technique is independent of the image source and the actual scale of the objects. It also offers fast algorithms for arithmetic, morphologic and Boolean operation, including the measurements of those parameters necessary for the calculation of fractal dimensions. A further argument for automatic image analysis is the achievement of very fine resolution and density of data points in acceptable measurement times. What's more, previous studies concentrate on micro-structural characteristics of aggregate-mortar interface and concrete ITZ using scanning electron microscope (SEM), which neglected the integrality and quantifiability of interface roughness. With DIP techniques and fractal theory, quantitative description of concrete interface can be conducted in the perspective of three-dimensional bonding action.

Several studies have been carried out to investigate the effect of LWA types, proportions, physical and mechanical properties on the mechanical performance of LWAC. However, available literatures dealing with the relationship between LWA particle characteristics and LWAC mechanical performance are relatively scant. The objective of this research is to improve the understanding of the relationship between LWA particle properties (including particle size indexes, gradation indexes, shape indexes, etc.) and LWAC mechanical performance (i.e., compressive strength, splitting tensile strength and flexural strength). To better characterize the particle properties of LWA, digital image processing and relevant algorithm were explored and the particle property parameters obtained from these tests were further used to quantitative analyze the influence of LWA particle properties on LWAC performance (i.e., interface roughness and mechanical strength). The LWAC interface roughness was characterized with the concept of fractal dimension, and a mono-parameter linear regression analysis was conducted to evaluate how interfacial roughness would affect mechanical strength of LWAC. The relationship between LWA particle characteristics and LWAC mechanical performance was evaluated through grey correlation analysis. The relationship between LWA particle characteristics and LWAC interfacial fractal dimension was also evaluated through grey correlation analysis. These tests and analysis results would provide researchers with useful tools to evaluate and predict the effects of LWA particle characteristics on concrete performance.

2. Experimental investigation

2.1. Materials, mix proportion and performance test

Cementitious materials were comprised of 90% ordinary Portland cement and 10% Class II fly ash. The chemical composition and physical properties of the cement were tabulated in Table 1. The fly ash was fine grained, with fineness of 4800 cm^2/g, and apparent density of 2.85 g/cm^3. Natural graded river sand with a fineness modulus (FM) of 2.8 was used as fine aggregate (FA). The absorption ratio of FA was 1.50%, and bulk gravity was 1520 kg/m^3. Liquid type polycarboxylate superplasticizer was used as water reducing agent (WRA) in present research.

High-performance shale ceramsites from Xintongchang Ceramsite Company in Shanghai were used as LWAs, with tube crushing strength of 5.8–8.2 MPa, water absorption $\leqslant$1.6% at 1 h, and water absorption $\leqslant$1.9% at 2 h, water absorption $\leqslant$2.7% at 24 h. The bulk density, tube crushing strength and water absorption of LWAs were determined by GB/T 17341.2-1998 [17], while the shape index was evaluated via digital image processing (DIP). Total porosity of the LWA particles was calculated based on specific gravity of the aggregate particles and specific gravity of the solid material as follows:

$$f_a = 1 - \frac{\rho_b}{\rho_s} \quad (1)$$

where f_a was the porosity of aggregate (%, by volume), ρ_s was the specific gravity of solid material and ρ_b was the bulk gravity of aggregate particles. The specific gravity (ρ_s) of the solid material was determined by helium pycnometer using a ground LWA sample passing through a 150 μm sieve. The bulk gravity of the aggregate (ρ_b) was determined according to ASTM C128 [18]. These high performance ceramsite were of low water absorption ratio and low density. They had a dense outer shell, which was ceramic or enamel, and would be partly water-proofing and gas-retaining. Inside the LWAs, there were fine alveolate micropores, which were mainly closed holes, and were not unicom holes.

The mix proportion used in this study was tabulated in Table 2. The LWAC mixture design was based on LWAC technology procedures, (its w/cm was 0.3, polycarboxylate superplasticizer content was 5.2 kg/m^3, and cementitious materials was 520 kg/m^3 which comprising of 90% ordinary Portland cement and 10% Class II fly ash) which meant to represent the type of mixture used in high durable concrete