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Utilize nano-scale metrology techniques to investigate mechanical, structural, and chemical heterogeneity of mixtures contained incineration bottom ash aggregate

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HIGHLIGHTS

- The heterogeneity of MSWIBA at the nanoscale was discussed.
- A combination method of NI, FESEM, and EDX was developed.
- A statistical method was put forward to quantify the heterogeneous degree.

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ABSTRACT

The utilization of municipal solid waste (MSW) incineration bottom ash (IBA) in the infrastructure construction is a double-win solution to feed the fueling demand for building stones and binding materials. However, MSWIBA is a so highly heterogeneous and variable material that the macro-scale researched results cannot guarantee its behavior at any moment and under any conditions. Therefore, we should figure out why the heterogeneity will happen and how the heterogeneity affects the mechanical behavior of the mixtures. In this paper, the heterogeneity of mixtures contained IBA was investigated at nano-scale from the point of view of chemistry, microstructure, and micromechanics. Nanoindentation (NI) testing together with the image processing technique and statistical method was performed to evaluate the elastic modulus and creep parameters' variation in the measured regions. The test sample was then studied by FESEM observation to illustrate its disordered microstructure. Finally, elemental and phase investigation of the NI sample was carried out by Energy-dispersive X-ray (EDX), which further gave the fundamental arguments why the MSW IBA mixtures present apparent heterogeneous behavior. It can be concluded that nanoindentation elastic/creep testing, FESEM observation, and EDX chemical analysis give mutual verification to illustrate the heterogeneous phenomenon in IBA cement mixtures.

1. Introduction

Municipal solid waste (MSW) is one of the heaviest and most voluminous wastes generated in worldwide. A new report from the World Bank's Urban Development department estimates the amount of municipal solid waste will rise from the current 1.3 billion tonnes per year to 2.2 billion tonnes per year by 2025. At present, incineration has become a most effective solution for treating MSW. The first China incinerator was built in 1988 in Shenzhen, nowadays the large incineration plants have been extended to more than 200 in China. Incineration bottom ash (IBA) is the most abundant output from the municipal solid waste incineration (MSWI) residues, approximately one ton of waste can produces 200 kg bottom ashes [1–4]. IBA is a coarser or sand or clay in appearance, with a diameter varying between 0.1 mm and 100 mm. Traditional treatment of IBA is sanitary landfilled, may cause waste of land resources and environmental pollution. In the other hand, world's massive infrastructure construction is still in continued boom, greatly fueling demand for building stones and other binding materials. Therefore, the potential utilization of MSW IBA in the infrastructure construction is a double-win solution. For example, it probably can be used as substitute for aggregate, filler, or even cement in road construction, cement concrete structure, embankments or marine applications.

Utilization of incinerator bottom ash in engineering applications has already been researched for many years [5–10]. Abdulahi [11] used IBA as a natural aggregate replacement in an unbound road sub-grade, while Maria et al. [12] used it in a road sub-base. Based on physical, mechanical, and chemical tests, they all believed

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that IBA is a highly compactable material that can be adopted in paving applications, meanwhile no imply is found resulting in the negative environmental impact. Eymael et al. [13] reported that IBA can be used in asphalt mixtures as a partial replacement of natural aggregates in amounts of up to 25%, however, higher asphalt content is needed because of its porosity. Andrade et al. [7] evaluated the bottom ash used as a substitute for natural sand in concrete. From the compressive strength test results, it showed that the bottom ash concrete gave a satisfactory result with mixtures containing a maximum of 50%. Lee and Li [14] observed that the major constituents of IBA are similar to those of cement raw materials, when the ordinary cement was replaced by incinerator bottom ash partially, the lower flow values and higher shrinkage can be found, and however, the compressive strength will be highly enhanced. Kim et al. [15] thought that because of the pozzolanic activity in bottom ash, the particle bonding effect is enhanced, resulting in the increase of shear strength and stiffness of mixtures. Therefore, they mixed the IBA with marine dredged soil deposits and cement to upgrade the strength of bottom ash-added composite geomaterial [16].

Above literatures indicate that the use of MSW IBA in infrastructure construction is feasible from the point of view of both structural properties and environment safety. However, Forteza et al. [17] pointed out that MSW IBA is a so highly heterogeneous and variable material that the researched results cannot guarantee its behavior at any moment and under any conditions. A series of reports based on the physical and mechanical tests proved above statement [18,19,2,20]. For example, an unconfined uniaxial compression test of bottom ash materials was conducted by Chimenos et al. [21], they found out that the different specimens tested for a given curing time present a wide range of variation of both unconfined compressive strength and modulus of elasticity, see Fig. 1. Even for the parallel tests, a great difference between the lowest value and the highest value cannot be neglected, leading to a high variance. The key problem is that failure in the disordered materials always involves the progressive local concentrations of tensile stress [22]. Then, under that tensile stress, the micro-cracks are initiated and propagated at the stress concentrated area, finally resulting in the structure failure. Actually, the exact failure mode is highly dependent on the inhomogeneity of materials and the heterogeneity of microstructures [23–25]. Unfortunately, under most situation, inherent heterogeneity is rather complicated and uncertainty. Therefore, for most disordered materials, it is hardly possible to predict physical and mechanical phenomenon of damage processes accurately at structural scale.

Small-scale heterogeneity can always explain experimental variability and non-linearity. Since mixtures containing bottom ash aggregates are a class of complex chemo-mechanical materials that possess a high degree of heterogeneity from atomistic scales to the macroscopic scales, nano-scale metrology techniques can be adopted to establish the link among chemical-composition, microstructure, and micromechanical performance of bottom ash mixtures, which can be further used as evidences to illustrate why the heterogeneity will happen and how the heterogeneity affect the mechanical behavior of the mixtures. If we grasp these rules, then materials selection criteria and micro-structure combination schemes are ready to be put forward.

Nanometrology is concerned with the science of measurement at the nanoscale level. Some of the popular ones are Scanning Electron Microscopy (SEM) and Field Emission Scanning Electron Microscopy (FESEM) for morphology observations, X-ray Diffraction (XRD) and Energy Dispersive Spectrometer (EDS) for elemental analysis, and Nano-indentation (NI) and Atomic Force Microscopy (AFM) for mechanical test. Nanometrology techniques have been successfully implemented in civil engineering applications, such as the rejuvenating effect on asphalt binders [26], interfacial transition zone properties of recycled aggregate [27], viscoelastic behavior of time-dependent material [28], phase-to-mechanical property of cement-based materials [29], interface adhesion of multilayered films [30], etc.

The objective of this paper is to investigate the heterogeneity of mixtures contained municipal solid waste incineration bottom ash aggregate from the point of view of chemistry, microstructure, and micromechanics. In this regard, MSW IBA samples were prepared and basic properties at macro-scale, such as gradation, content, morphology, main chemical composition, and physical parameters, were tested. Nanoindentation testing together with the image processing technique and statistical method was performed to evaluate the elastic modulus and creep parameters' variation in the measured regions. The test sample was then studied by FESEM to observe its disordered microstructure. Finally, elemental and phase investigation of the NI sample was carried out by Energy-dispersive X-ray (EDX), which further gave the fundamental arguments why the MSWI BA mixtures present apparent heterogeneous behavior.

2. Materials and methods

2.1. Specimens preparation

2.1.1. Basic properties of municipal solid waste incineration bottom ash samples

The final solid residues used in the test were collected from a waste incinerator plant in Hangzhou 2014-July, China. Usually,

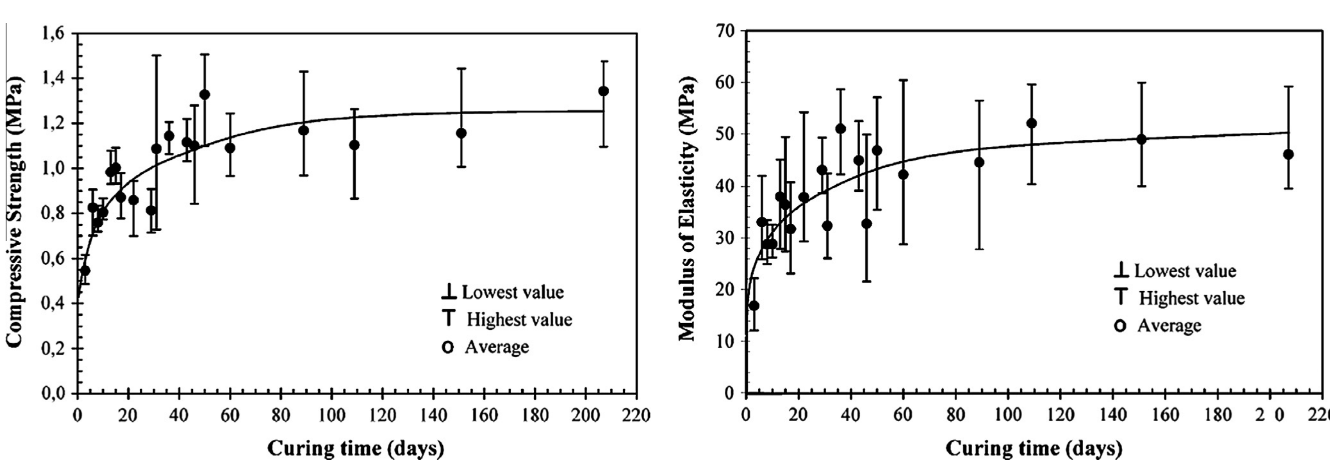

Fig. 1. Compressive strength and modulus of elasticity for IBA varying with curing time [21].