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Influence of aggregate materials characteristics on the drying shrinkage properties of mortar and concrete

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HIGHLIGHTS

- Fine aggregates significantly affect the drying shrinkage in mortar, but concrete.
- Limestone sand and blast furnace slag sand can reduce the mortar drying shrinkage.
- Coarse aggregate characteristics play an important role on the concrete drying shrinkage property.
- Coarse aggregate strain, specific surface area and pore structure of coarse aggregates are investigated.
- Total amount of water content parameter on drying shrinkage is introduced.

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ABSTRACT

This paper presents an experimental study to clarify the effect of various aggregate materials characteristics on the drying shrinkage property in mortar and concrete specimens incorporating fourteen kinds of fine aggregate materials (standard sand, natural sand, marine sand, various kinds of slag-type sand, and various kinds of crushed sand) and three kinds of coarse aggregate materials (andesite gravel, hard sandstone gravel, and limestone gravel). The test results revealed that the characteristics of fine and coarse aggregate materials play an important role in controlling the drying shrinkage property of mortar and concrete, respectively. Limestone sand and blast furnace slag sand can restrain the drying shrinkage of mortar specimens about 22% and 30%, respectively, compared to the case of mortar incorporating standard sand. The drying shrinkage strain of concrete specimens proportionally increases with the increase of aggregate shrinkage strain, specific surface area and 6–30 nm in diameter pore volume of aggregates, which implies the significant influence of aggregate characteristics on drying shrinkage development in concrete. It was also found that the drying shrinkage property in concrete can be affected by the static modulus of elasticity and total amount of water content, in which the water absorption ratio, unit mass of aggregate and unit water content were considered. Finally, the experimental results presented are useful information for providing a good perspective for the concrete mixture design practices taking into consideration that concrete drying shrinkage could be controlled by appropriate aggregate characteristics and reducing the total amount of water content.

1. Introduction

Drying shrinkage, which may lead to inevitable cracking in many concrete structures [1], can be defined as the volumetric change owing to the drying of concrete. This change in volume of the concrete is related to the volume of water lost. The loss of free water, which occurs first, may induce shrinkage. As the drying process of the concrete continues, the adsorbed water held by hydrostatic tension in the small capillaries is reduced significantly [2]. The loss of the water (free water and adsorbed water) may lead to tensile stresses, which force concrete to shrink causing cracks that can adversely affect the structural performances, such as durability and serviceability, if not appropriately considered in the design stage [3–5].

In order to ensure the high performance of concrete structures, the upper limit of long-term drying shrinkage strain for concrete should not exceed 800 micron, as defined in the revision of Japanese Architectural Standard Specification, JASS 5 of 2009, which has been discussed by many researchers [6,7]. It is worthy to mention that various kinds of aggregate materials have been used in the concrete production since last decades, among them aggregate comes from natural resources or from industry in the form of by-products. The continuous need of concrete structures for

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housing is increasing rapidly and could be estimated to be more than two million units. That would consume huge amounts of construction materials such as natural sand, marine sand, coarse aggregate and crushed stones, which in turn may affect the global environment [8,9]. Furthermore, the use of industrial by-products has been given attention in the concrete technology research since the beginning of the twentieth century [10–12]. Therefore, with the depletion of natural aggregate resources, the research on by-products aggregate materials, such as copper slag sand and blast furnace slag sand, becomes an important issue. However, it is difficult to evaluate if the determined upper limit by JASS 5 for drying shrinkage and its properties can be valid for concrete incorporating such kinds of by-products aggregates. Hence, more experiments are quite needed to clarify the raising point.

It is well known that drying shrinkage is an everlasting process when concrete is subjected to drying conditions; this can be explained by the loss of water held in capillary pores of cement paste [13]. The finer the capillary pores the more is the shrinkage. However, it was concluded in previous researches [7,13,14] that there is important influence of other parameters on the drying shrinkage properties of concrete, that are mineral admixtures, cement type, chemical admixtures and aggregate quantity. Also, it was revealed that the drying shrinkage of concrete progresses with the increase of its unit water content or water/cement ratio, which has been referred to as the major factor affecting the drying shrinkage properties [7,13]. Hansen et al. [15–18] reported that the coarse aggregate has an influence on the long-term drying shrinkage of concrete. Concrete shrinks less than mortar, and mortar shrinks less than cement paste. The aggregates play an important role in restraining the shrinkage of the cement matrix, which could reduce the shrinkage of concrete compared to plain hardened cement paste [19], but the shrinkage property of aggregate itself has not been fully investigated.

In the previous studies [18–21], it was observed that the magnitude of concrete drying shrinkage could be reduced by using limestone aggregates, and the static elastic modulus of aggregate has a considerable effect on the shrinkage behavior. Moreover, it was found that not only the modulus of elasticity, but also the shrinkage strain of normal aggregate and lightweight aggregate can control the drying shrinkage of concrete [22,23], which should be paid more attention. Snowdon and Edwards [24] revealed that aggregate materials having the property of low water absorption ratio can reduce the aggregate shrinkage for the case of normal coarse aggregates. Nevertheless, it could not be used to comprehensively evaluate the shrinkage of different kinds of coarse aggregates. This is based on the findings by Goto et al. [25] who revealed that the lightweight aggregate with higher water absorption ratio has a relatively smaller shrinkage strain than the normal aggregate with lower water absorption ratio, implying that there is another parameter affecting the drying shrinkage that is the aggregate pore structure. The lightweight aggregates usually exhibit relatively greater volume of large size pores and smaller volume of micro pores compared to the normal aggregates, resulting in decreasing the internal surface area, which is related to the pore structure characteristics of aggregate materials. Also, it has been reported that the volumetric change of aggregate caused by shrinkage can be controlled by the aggregate specific surface area [25,26]. In spite of the preceding studies, the behavior of the shrinkage property of aggregate materials inside the concrete matrix is still complicated and has not been fully clarified. Most of those studies concerned with natural sand as fine aggregate materials, while the studies about the drying shrinkage evolution in concrete incorporating slag-type fine aggregates are particularly few [27].

Based on the above discussion, it is obvious that extensive research on the drying shrinkage of mortar and concrete incorporating various kinds of fine and coarse aggregate materials is quite needed to understand the shrinkage properties, maintain the structural performances of concrete, investigate the applicability of slag-type aggregates, and save the natural resources as well. Therefore, the objective of the current study is to clarify the influence of fine aggregate materials (Japanese Industrial Standard – JIS standard sand, natural sand, marine sand, various kinds of slag-type sand, and various kinds of crushed sand) and coarse aggregate materials (andesite gravel, hard sandstone gravel and limestone gravel) on the drying shrinkage evolution in mortar and concrete by discussing how their characteristics can affect the developed drying shrinkage strain. Various characteristics of aggregate materials related to shrinkage property, which are aggregate shrinkage strain, aggregate pore structure and aggregate specific surface area, were examined. Moreover, the effects of static modulus of elasticity and total amount of water content on the drying shrinkage were discussed. The measurements of aggregate pore structure and aggregate specific surface area were conducted by mercury intrusion porosimetry (MIP) and water vapor adsorption measurement, respectively. Also, the static modulus of elasticity was measured as a stress to strain ratio value for hardened cement based materials according to JIS A 1149 compression test, and total amount of water content was calculated by the water absorption ratio, unit mass of aggregate and unit water content. Finally, the obtained results are valuable information to enhance the practical design codes for drying shrinkage of mortar and concrete, and open the door to further studies, in particular, regarding the applicability of by-products fine aggregate materials in the concrete production field.

2. Experimental work

The experiments were designed to achieve the objective of this study, which is to evaluate how the characteristics of aggregate materials can affect the development of drying shrinkage in mortar and concrete specimens made with various kinds of fine and coarse aggregate materials brought from different producing areas. The description of used aggregate materials (14 kinds of fine aggregates and 3 kinds of coarse aggregate materials), preparation of test specimens (mortar and concrete specimens), and applied test procedures (JIS A 1129-3 dial gauge method, JIS A 1149 compression test, attaching strain gauge to aggregate surface method, MIP method and water vapor adsorption method) for the experimental measurements (the drying shrinkage evolution, static modulus of elasticity, coarse aggregate shrinkage strain, coarse aggregates pore structure and aggregates specific surface area, respectively) are discussed in this section as following.

2.1. Materials

The physical and chemical properties (chemical composition, density and blaine fineness) of ordinary Portland cement (OPC), which was used in casting of all tested mortar and concrete specimens, are given in Table 1. Fourteen kinds of fine aggregate materials (JIS standard sand, natural sand, marine sand, various kinds of slag-type sand, and various kinds of crushed sand) were used in the preparation of mortar specimens, while, three kinds of coarse aggregate materials (andesite gravel, hard sandstone gravel and limestone gravel) were used for concrete specimens. The physical properties of used fine and coarse aggregate materials are described in Table 2. Concerning the given symbols for the various kinds of fine aggregates in Table 2, symbols with lowercase letters refer to fine aggregate materials used in

Table 1
Physical and chemical properties of cement.

Oxide (%)	Value
SiO_2	21.06
Al_2O_3	5.51
Fe_2O_3	2.69
CaO	65.47
MgO	1.66
K_2O	0.40
Na_2O	0.24
SO_3	1.91
Density (g/cm^3)	3.17
Blaine (cm^2/g)	3390