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# Properties evaluation of silica-alumina based concrete: Durability and environmental friendly performance

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## HIGHLIGHTS

- Silica-alumina based concrete was developed based on simulation of rock formation.
- Silica-alumina based concrete possessed low shrinkage and excellent durability.
- Superior performance resulted from the compacted ITZ and refined pore structure.
- Silica-alumina based concrete is environmentally acceptable.

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## ABSTRACT

An eco-concrete prepared by silica-alumina based cementitious material was developed and defined as silica-alumina based concrete. Systematic properties investigation showed that the silica-alumina based concrete exhibited good mechanical properties, low shrinkage strain and superior durability including strong resistances to water penetration, carbonation, chloride penetration, freezing-thawing and seawater attack. These excellent performances can be related to the fact that it developed a dense and compacted interfacial transition zone between the cementitious matrix and aggregate, and the silica-alumina based cementitious matrix had a refined pore structure. Leaching toxicity and radioactivity results indicated that the silica-alumina based concrete is environmentally acceptable.

## 1. Introduction

Concrete is a porous and highly heterogeneous composite material containing aggregate, cement paste and interfacial transition zone between them. It is thought that concrete is the second most consumed material after water in the world. Cement is known as a key ingredient of concrete that binds the aggregates together through hydration. Portland cement is the most commonly used cementitious material in concrete, the production of which consumes more energy and natural resources. It is predicted that the service life of Portland cement concrete exposed to weathering is approximately 50–100 years [1]. Under the circumstance of resource shortage and environmental protection, more and more eco-materials are required for preparation of concrete with excellent durability.

Conglomerate can be viewed as a natural concrete (shown in Fig. 1), the appearance of which is similar to that of cement concrete [2]. Conglomerate is a sedimentary clastic rock in which clasts with particle size larger than 2 mm are cemented together by dissolved silicate minerals. Mealy sand, clay and chemical sediments are generally filled between gravels in the conglomerate. It is the superfine particles of silicate minerals that play an important cementing role in the conglomerate. These silicate minerals possess characteristics of secondary enlargement, dissolution and recrystallization. In the diagenetic process of sedimentary rock, the superfine silicate minerals were dissolved under the effect of rock forming liquid, and then re-crystallized with overgrowth and cemented the large particles together. All the micropores in the sediments were filled by the new formed silicate minerals, and thereby loose sediments were bond together into a hard natural rock. It illustrates that the rock forming liquid has a strong dissolution ability on the silicate minerals. Although the macrostructure of conglomerate and cement concrete is very similar, their microstructure is different. In the conglomerate, gravels and sands are firmly welded together by the fine silicate

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**Fig. 1.** Conglomerate: natural concrete.

minerals relying on Si–O covalent bonding and chemical bonding between grain boundaries. While in the traditional cement concrete, stones and sands are cemented together by C-S-H gels relying on Van der Waals' force [3].

Inspired by the microstructure of natural conglomerate, an eco-concrete with high performance and excellent durability was designed and prepared in this paper, especially in which silica-alumina based cementitious material was used as a binder, and thereby the produced eco-concrete was named silica-alumina based concrete. The silica-alumina based cementitious material was developed based on earth science to mimic natural rock formation [1–7], and its chemical composition is rich in silica and alumina unlike the Portland cement mainly consists of CaO. Silica-alumina based cementitious material mainly contains solid silica and alumina rich industrial wastes ground to a powder and rock forming agent. It is known that many industrial solid wastes rich in silica and alumina are similar to pozzolana material in chemical composition, so that they can be viewed as an artificial pozzolana [8]. The rock forming agent is comprised high concentrations of minerals in sea water which are necessary to accelerate the rock forming process in modern construction. The silica-alumina based cementitious material is generally produced by mixing the artificial pozzolana powder with the rock forming agent. The hydration and hardening process of the silica-alumina based cementitious material can simulate the process of natural rock formation in sea water at a normal temperature and pressure in short times instead of millions of years [1,7].

In this research, the mechanical properties, durability-related performance and environmental friendly performance of the silica-alumina based concrete were investigated systematically. Scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP) were adopted to correlate the microstructure with the concrete's performance.

## 2. Experimental

### 2.1. Materials

The silica-alumina based cementitious material was obtained from an experiment and manufacture base in Shandong province of China. In general, it was developed according to the [$SiO_4$] polymerization degree of raw materials, which can be categorized as three types: high degree of [$SiO_4$] polymerization material (high-alumina fly ash, coal gangue), middle degree of [$SiO_4$] polymerization material (blast furnace slag, steel slag), and low degree of [$SiO_4$] polymerization material (clinker). These three types of raw materials were milled to a powder and mixed with an appropriate dosage of gypsum and rock-forming agent to produce the silica-alumina based cementitious material, the chemical composition of which was designed by calculating the $CaO/(SiO_2 + Al_2O_3)$ ratio less than 1.5. The fine aggregate used in the tests was river sand with particle size smaller than 5 mm. Crushed limestone with size between 5 and 25 mm was used as coarse aggregate in all the concrete mixes. Polycarboxylate superplasticizer was used in all the concrete mixes, and 42.5 ordinary Portland cement with specific surface area of 380 $m^2$/kg was selected to prepare Portland cement concrete as a reference to compare with the silica-alumina based concrete. The chemical composition of silica-alumina based cementitious material and 42.5 ordinary Portland cement used in this research is shown in Table 1. The physical properties of silica-alumina based cementitious material is presented in Table 2.

### 2.2. Experimental procedure

The cementitious material, aggregate, polycarboxylate superplasticizer and tap water were mixed together to prepare concrete according to the designed proportions shown in Table 3. The hardened concrete samples were cured in a moist room at 20 °C with humidity of 95%. The slump and air content of fresh concrete were tested following the relevant ASTM Standards [9,10]. The compressive strength and flexural strength were tested according to the relevant methods in BS EN 12390 [11,12]. The concrete shrinkage was tested according to ASTM C157/C157M [13]. The tests of water penetration, carbonation and seawater attack were performed according to GB/T50082-2009 [14]. The chloride penetration test was carried out following the electric flux method specified in ASTM C1202-12 [15]. The freezing and thawing test was performed according to ASTM C666/C666M [16].

JSM-6480LV scanning electron microscope was used to observe the interfacial transition zone between the hydrated paste and aggregate on the 28-day hydrated mortars of silica-alumina based cementitious material and 42.5 ordinary Portland cement. The mortar specimens were prepared in size of 40 mm × 40 mm × 160 mm with a water/cement ratio of 0.50 and cement/sand ratio of 1:3. They were cured in an isothermal curing cabinet at 95% humidity and 20 °C for 28 days.

Mercury intrusion porosimetry analysis on the 28-day hydrated pastes of silica-alumina based cementitious material and 42.5 ordinary Portland cement was performed with an Autopore IV 9510 instrument. The paste specimens were prepared in size of 20 mm × 20 mm × 20 mm with a water/cement ratio of 0.30. They were cured in an isothermal curing cabinet at 95% humidity and 20 °C for 28 days.

The leaching toxicity test of silica-alumina based cementitious material was carried out according to the solid waste—extraction procedure for leaching toxicity—horizontal vibration method (HJ 557-2010) [17]. The leaching procedure was as followed: 100 g (dry weight) of samples were extracted using distilled water at an liquid/solid ratio of 10:1 (L/kg) for 8 h with vibration frequency at 110 ± 10 times/min and amplitude of 40 mm. After quiescence for 16 h, the solutions were filtered through a 0.45 μm membrane filter. The concentrations of heavy metals in the leachates were tested by OPTIMA 7000DV ICP optical emission spectrometer. The samples were conducted in triplicate and the results presented were the average values.

## 3. Results and discussion

### 3.1. Workability

The slump and air content values for the fresh concrete are presented in Table 4. Both of the fresh Portland cement concrete and silica-alumina based concrete showed good workability under the designed mix proportion. It is observed that the slump and air content values of the silica-alumina based concrete were higher than those of the Portland cement concrete. As introduced in Section 2.1, the silica-alumina based cementitious material was mainly composed of industrial solid wastes such as high-alumina fly ash, coal gangue, blast furnace slag and steel slag. The workability of silica-alumina based concrete can be improved by a better

**Table 1**
Chemical composition of the silica-alumina based cementitious material and 42.5 ordinary Portland cement.

| Oxides (%) | Silica-alumina based cementitious material | 42.5 ordinary Portland cement |
|---|---|---|
| CaO | 44.86 | 60.92 |
| $SiO_2$ | 30.52 | 20.83 |
| $Al_2O_3$ | 11.98 | 5.29 |
| $Fe_2O_3$ | 1.81 | 3.34 |
| MgO | 4.63 | 3.94 |
| $Na_2O$ | 0.37 | 0.17 |
| $K_2O$ | 0.69 | 1.11 |
| $SO_3$ | 3.20 | 2.85 |
| $TiO_2$ | 1.06 | 0.83 |
| $CaO/(SiO_2 + Al_2O_3)$ | 1.06 | 2.33 |