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Experimental investigation on the durability performances of concrete using cathode ray tube glass as fine aggregate under chloride ion penetration or sulfate attack

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HIGHLIGHTS

- Durability performance of concrete containing CRT glass was investigated.
- Chloride diffusion coefficient of CRT concrete is lower than control concrete in long term.
- Relative increase in strength of CRT concrete is higher than that of control concrete.

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ABSTRACT

Cathode ray tube (CRT) funnel glass has been used to partially or totally replace natural sand as fine aggregate in concrete. It is an effective and environmentally friendly method of recycling the increasing number of discarded CRT in the electronic industry. However, little research has been performed on its durability performance under environmental attacks, in particular in the areas of chloride ion penetration and sulfate attack, the two major environmental attacks on reinforced concrete structures. This study presents an experimental investigation on the durability performances of concrete using CRT funnel glass as fine aggregate in 8% sodium chloride solution, 5% sodium sulfate solution and 10% sodium sulfate solution. Four volume replacement ratios (the ratio of CRT glass to natural sand), i.e. 0%, 30%, 60%, 100%, are considered. The chloride ion content along concrete depth direction, compressive strength and elastic modulus of concrete was measured with attack time. The test results show that although the compressive strength and elastic modulus decrease with increasing content of CRT funnel glass in concrete, the long-term resistance to chloride ion penetration is enhanced by using CRT funnel glass as fine aggregate. Furthermore, the compressive strength, rather than dynamic elastic modulus of concrete containing CRT glass, is more sensitive to sulfate attack. The relative increase in strength of CRT glass concrete is obviously larger than that of control concrete under sulfate attack. This study also provides a reference for the durability design of concrete structures using CRT funnel glass as fine aggregate.

1. Introduction

The recycle of cathode ray tube (CRT) has earned increasing attention with the rapid advances in the electronic industry. This is particularly the case in China after the "Replacement of Household Electrical Appliance Program" was established in 2009. Many researchers have been interested in exploring the feasibility of using waste CRT glass as fine aggregate in concrete [1–3]. It has been reported that about 12.6 billion tonnes of concrete raw materials are consumed globally each year, and the concrete industry is the largest user of natural resources in the world [4]. Consequently, using CRT glass as fine aggregate in concrete is beneficial for both the electronic and concrete industries.

As CRT funnel glass contains a significant amount of lead, i.e. 22–25% of weight [5,6], it is essential to have a proper method to treat the CRT funnel glass before it is recycled in concrete. Otherwise, lead leaching can easily cause environmental pollution and threaten public health [7]. Yamashita et al. [8] compared the lead leaching ability of CRT funnel glass in acidic, neutral and alkaline solutions, and found that acidic solutions have the best effect on removing the lead content. Grause et al. [9] reported a method for lead removal by chloride volatilization, which shows that 80% of the lead in funnel glass could be removed. Ling and Poon [10]

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developed a method for removing the leachable lead from crushed CRT funnel glass, which consists of crushing the funnel glass into small particles, immersing the particles in a 5% solution of nitric acid for 3 h and rinsing with water. Their further experimental results have also demonstrated that the leachable lead concentration in concrete is below 5 mg/L even if the fine aggregate is composed entirely of treated CRT glass [11].

The workability and mechanical properties of concrete or mortar using CRT glass as fine aggregate have been experimental investigated by many researchers. Ling and Poon [12] investigated the consistency of cement mortar incorporating treated CRT funnel glass as substitutions of natural sand, and found that consistency increases with the replacement ratio. Zhao et al. [13] reported that the initial slump height of concrete increases from 40 mm to 135 mm when natural sand was completely replaced by CRT glass. The improvement in the workability of concrete is mainly caused by the lower water absorption and smooth surface of the incorporated CRT glass [13,14]. As a result of weaker bonding between the cement paste and smooth surface of CRT funnel glass, many studies have reported a reduction in compressive strength, tensile strength and flexural strength with the inclusion of CRT glass [11,15,16]. Furthermore, this weaker bonding poses a greater impact on splitting strength and flexural strength, and their reduction is more obvious than that of compressive strength [11,14]. Another possible factor causing a decrease in strength may be that the lead derived from CRT funnel glass can retard cement hydration [17,18].

In terms of the durability properties of concrete incorporating CRT glass, most studies focus on the shrinkage and Alkali-Silica Reaction (ASR). Ling and Poon [11] conducted a test on the drying shrinkage of concrete specimens and found that drying shrinkage decreases with increasing replacement ratio of CRT funnel glass used in concrete. This variation can be attributed to the low water absorption of CRT funnel glass [14,19]. Other literatures [12,13,20,21] reported that the ASR expansion of concrete is increased by incorporated CRT glass, and higher CRT funnel glass content leads to higher ASR expansion. This expansion is mainly caused by the potential reaction between hydroxyl ion in cement and amorphous silica in CRT glass [13]. However, the unexpected expansion induced by ASR can be mitigated by replacing cement with fly ash [22]. In addition, Ling and Poon [15] evaluated the performance of carbonation of concrete incorporated with barite and CRT funnel glass as coarse and fine aggregates, and found that the carbonation depth increases with the CRT funnel glass content.

To sum up, the lead leaching, density, workability, strength, dry shrinkage, and ASR of concrete with incorporated CRT glass have been experimentally investigated. It is generally accepted that the addition of CRT glass in concrete has a negative effect on the lead leaching, ASR, compressive, tensile and flexural strength, while a positive effect on the drying shrinkage, density and workability. However, the durability performance under chloride ion penetration and sulfate attack is rarely evaluated. These environmental attacks are two major threats to the durability of reinforced concrete structures [23,24]. In this study, the chloride ion content and chloride diffusion coefficient were measured under chloride ion penetration, as were the compressive strength and dynamic elastic modulus under sulfate attack. Durability performances of concrete under chloride ion penetration and sulfate attack were discussed.

2. Experimental investigations

2.1. Raw materials

2.1.1. Cementitious materials

Portland cement of type 42.5 N and Class F fly ash provided by Mawan power plant were used as cementitious materials. The chemical compositions of these cementitious materials are shown in Table 1.

2.1.2. Coarse and fine aggregates

The coarse aggregate is natural stone of granite with maximal diameter of 26.5 mm and fineness modulus of 3.68. Granite mainly consists of quartz, feldspar, mica, and amphibole minerals [25]. The fine aggregate contains CRT funnel glass and natural sand. The CRT funnel glass provided by Tianjin XinRen Corporation. The fineness modulus of natural sand and CRT funnel glass is 2.45 and 2.13, respectively. Fig. 1 shows the appearance of the two types of fine aggregates. The grading curves of the coarse and fine aggregates are shown in Fig. 2.

2.2. Mix proportions

In this study, four different mixtures were considered, including a control concrete and three CRT concretes, for which natural sand was replaced by CRT funnel glass at 30%, 60%, and 100% volume ratio. In order to mitigate the potential ASR expansion, 20% of cement was replaced by fly ash [22]. For all concrete mixes, the cementitious material content, i.e. cement and fly ash, was kept constant as 360 kg/m^3. The details of mix proportions are given in Table 2.

2.3. Specimens and measuring method

Twenty-four concrete specimens with dimensions of 100 × 100 × 100 mm and twelve specimens with dimensions of 100 × 100 × 300 mm were cast. The casting and curing methods were based on the "Standard for Test Method of Mechanical Properties on Ordinary Concrete (GB/T, 50081)" [26]. The slump test was carried out to investigate the workability of fresh concrete mix following method suggested by "Standard for test method of performance of ordinary fresh concrete (GB/T, 50080)" [27]. The density and water absorption of the concrete were determined by referring to the method recommended by ASTM C642 [28]. The toxicity characteristic leaching procedure (TCLP) was used for evaluating the lead leaching from the concrete as suggested by US Environmental Protection Agency method 1311 [29]. The compressive strength and static elastic modulus tests were carried out at the curing age of 28 days as described by standard GB/T, 50081 [26]. All test results were averaged using data from three specimens.

2.4. Chloride ion penetration and sulfate attack

The concrete specimens were immersed in chloride or sulfate solution at the curing age of 28 days, and the aggressive environments of chloride ion penetration and sulfate attack are specified in Table 3. High ion concentration, i.e. 8% NaCl, 5% and 10% Na_2SO_4, were used to accelerate deterioration. For the chloride ion penetration test, the 100 mm^3 cubic specimens were used to determine the concentration profile of chloride ion in concrete at different

Table 1
The chemical compositions of cementitious materials.

Chemical compositions (%)	Cement	Fly ash
Calcium oxide (CaO)	61.88	3.84
Silicon dioxide (SiO_2)	21.82	59.63
Aluminium oxide (Al_2O_3)	6.12	19.67
Ferric oxide (Fe_2O_3)	3.92	0.28
Magnesium oxide (MgO)	1.92	2.17
Sulfur trioxide (SO_3)	1.36	1.21
Sodium oxide and potassium oxide ($Na_2O + K_2O$)	–	2.32
Others	2.98	10.88
Loss on ignition	1.34	0.82