Construction and Building Materials 164 (2018) 837–849

Contents lists available at ScienceDirect

Construction and Building Materials

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

Optimizing compressive behavior of concrete containing fine recycled refractory brick aggregate together with calcium aluminate cement and polyvinyl alcohol fibers exposed to acidic environment

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HIGHLIGHTS

- Acidic behavior of refractory brick aggregate concrete was investigated.
- Effect of PVA fiber and CAC on acid resistance properties of concrete was studied.
- An optimum solution for design parameters was presented.

ARTICLE INFO

Article history:
Received 29 August 2017
Received in revised form 21 December 2017
Accepted 28 December 2017

Keywords:
Corrosion
Polyvinyl alcohol
Fibrous concrete
Optimum solution
Ultrasonic pulse velocity
Calcium aluminate cement
Crushed refractory brick

ABSTRACT

Earthquake-induced structural wastes and other factors causing destruction, on one hand, and issues regarding the damaging effects of acidic environments, on the other, comprise some of the most challenging concerns of humanity, thus eliminating these challenges is one of the major goals in today's construction industry. To face this challenge, this research set out to investigate the compressive behavior of concrete containing fine recycled refractory brick aggregate together with calcium aluminate cement (CAC) and polyvinyl alcohol (PVA) fibers under an acidic environment. In order to achieve this objective, 96 fine aggregate concrete specimens were exposed to 5% sulfuric acid attack for periods of 0, 7, 21, and 63 days, then they were subjected to various experiments. First, to determine the extent of the specimens' corrosion, the weight variations test was conducted, then, the ultrasonic pulse velocity (UPV) test, a non-destructive concrete test to obtain the level of porosity and density, was carried out, and at the end of the experimental phase, the specimens were subjected to compressive testing after being visually inspected to examine the corrosion level. Finally, using response surface method (RSM), an optimum solution for the design parameters was presented by maximizing the compressive strength of fibrous concrete as well as making the concrete mix cost-effective. Generally, the results indicate that the specimens containing calcium aluminate cement together with PVA fibers demonstrate proper mechanical properties in terms of corrosion control against acid attack, while the specimens containing fine refractory brick aggregate showed a rather unsatisfactory performance in this regard.

1. Introduction

Annually, damages caused by corrosion due to the presence of concrete structures in acidic or other corrosive environments bring about a lot of destruction to these structures in addition to incurring huge economic losses. To eliminate these damages, retrofitting and rebuilding practices are being done on a large scale, which in turn lead to the production of a vast amount of concrete requiring the use of additional quantities of cement, ultimately further contributing to the environmental pollution induced by cement production. Although concrete structures are normally designed and built for a lifetime of at least 50 years, in some cases, due to the attack of corrosive solutions such as sulfuric acid, these structures experience local or global damage only after a few years. As the corrosion rate increases, the renovation and, in some cases, complete replacement of damaged structures, which is a very costly practice and entails many community issues, become inevitable. Since Parker discovered the existence of a bacterium responsible for the corrosion process in 1945, some research into the corrosion of concrete exposed to sulfuric acid has been carried out [1]. Finally, through performing many experiments and investigations,

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https://doi.org/10.1016/j.conbuildmat.2017.12.230
0950-0618/

the corrosion mechanism in concretes has been expressed as follows:

Concrete damage induced by sulfuric acid attack occurs of two phases [2]; in the first phase, sulfuric acid reacts with calcium hydroxide as one of hydration products to form gypsum ($CaSo_4 \cdot 2H_2O$), and in the second phase, the gypsum reacts with tricalcium aluminate (C_3A) to form ettringite ($C_6AS_3H_{32}$). The gypsum and ettringite occupy greater space relative to the original products, which results in expansion and the subsequent crack formation, in turn leading to a reduction in the member's load-bearing capacity. Although the formation of gypsum accompanies a volumetric expansion of about twice the volume of initial constituents [3–5], some researchers have stated that this reaction is only playing a secondary role in the corrosion process [4], and that the reaction between gypsum and C_3A, which produces ettringite, is far more dangerous. The volume of the reaction-produced ettringite is several times that of the initial compounds, with some researchers reporting a 2-fold increase in volumetric expansion [3,5], while some others even reporting a 7-fold increase [4]. Therefore, the formation of ettringite is the prime cause of expansion leading to an increase in the internal pressure as well as matrix destruction of concrete. Moreover, when concrete is being attacked by sulfuric acid, gypsum is deposited in the corroded layer, which in turn reduces the ability of acid to penetrate into the concrete [6,7].

In addition to research into the field of corrosion and its effect on concrete properties together with methods to control or improve corroded concrete, which are of particular interest, the provision as well as utilization of materials applicable to improve the resistance of concrete containing or lacking coarse aggregate against corrosion has also formed the basis of many studies. In the present study, materials (given below) in the concrete mix were investigated whose combined effectiveness in an acidic environment has not been analyzed so far.

1.1. Calcium aluminate cement (CAC)

Calcium aluminate cement (CAC) is a unique type of cement different from ordinary Portland cement (OPC) in terms of chemical composition, in particular with higher alumina content and lower silica content [8]. According to the research performed by some researchers into replacing OPC with CAC in fine aggregate concrete, as the level of OPC-replacing CAC in concrete increased, the compressive strength of specimens decreased [9], while in the work of some others studying concrete containing coarse stone aggregate and made with either type of cement (OPC or CAC), the opposite result was reported, and replacing OPC with CAC led to an increase in the compressive strength [10,11]. Since concretes containing CAC have a lower content of alkaline materials compared with that of OPC-containing concretes, it has been hypothesized that the activity of CAC to produce ettringite, which fills the pores existing within hardened concrete, is far weaker than that of OPC, and as a result, acid can penetrate into the concrete more easily, a reason underlying concerns regarding the corrosion of the steel bars within reinforced concrete made with CAC. However, the study of Gaztanaga et al. [12] led to the conclusion that rusting of steel bars in CAC-containing concrete is very unlikely. Hence, as a material giving concrete a proper corrosion resistance and workability, calcium aluminate cement may play a significant and useful role in concrete.

1.2. Polyvinyl alcohol (PVA) fibers

Fiber-reinforced concrete is being increasingly employed in the construction industry for designing and building infrastructures around the globe due to its capability to improve mechanical properties and durability of concrete. In this regard, polymer fibers such as microsynthetic fibers have gained a widespread application in the concrete industry [13,14]. Pure polyvinyl alcohol is a synthetic polymer soluble in water (at about 60 °C), stable in the dry state, odorless, nontoxic, and safe to handle manually. Research has shown that these fibers have a proper effect on reducing the corrosion level of concrete members [15]. Polyvinyl alcohol fibers work in microcracks through the bridging action, which prevents the growth and propagation of cracks as well as penetration of acid into concrete. Since polyvinyl alcohol fibers, as synthetic fibers, demonstrate superior resistance against acid attack relative to that of steel fibers, this fiber type has been receiving increasing attention. Steel fibers experience corrosion in the vicinity of the external surface of the concrete cover, and depending on the degree of fiber corrosion, reduction in concrete properties varies.

1.3. Silica fume (SF)

Silica fume is a type of pozzolan that can provide a considerable effect on improving the strength and durability of concrete structures if properly used. Enhancing the workability and increasing resistance to acid attack [16,17] are among the prominent features of this material. In recent years, by the use of pozzolan as a supplementary cementitious material, the production of concretes having different strengths, in particular, high strength concrete (HSC), has increased dramatically [18–20]. Employing materials such as silica fume limits the destructive effects of acid attack via reducing the content of calcium hydroxide (the factor causing the formation of gypsum and ettringite) as well as permeability in concrete [20].

With respect to the significance and properties of the discussed materials against acid attacks, one of the main incentives for performing the present study was to investigate and experimentally compare fine aggregate concrete containing PVA fibers in the presence of calcium aluminate cement (CAC) and silica fume, as well as evaluate the efficiency of combining these three constituents against sulfuric acid attack.

In recent decades, concerns regarding the ever-increasing volume of waste materials produced from the demolition of old buildings have risen, especially in the most seismically active countries where a huge volume of construction wastes is produced annually due to earthquakes [21,22]. On the other hand, increasing demand for constructing new buildings has led to the scarcity of constructional raw materials such as stone aggregates [23]. Recent applied studies have reported the use of crushed waste brick as aggregate in concrete mix in some countries across the three continents of Asia, Europe, and America [24,25]. However, in most experimental works, crushed brick has been introduced to the concrete mix as the coarse aggregate, while it has been used as the fine aggregate in a small number of these works [10,11]. Therefore, the second main incentive driving this research was to use crushed waste brick of the refractory type as the fine aggregate replacing natural sand in concrete specimens. Here, the corrosion and compressive strength loss levels of the concrete specimens containing crushed refractory brick as the natural sand replacement, refractory cement as the binding material replacing ordinary Portland cement (OPC), and PVA fibers as the reinforcing fibers were investigated. In doing so, 96 fine aggregate cubic concrete specimens were subjected to 5% sulfuric acid attack for the periods of 0, 7, 21, and 63 days, and then, the values of weight, UPV, and compressive strength variations were measured. In the end, an optimum solution for the design parameters for maximising the compressive strength of fibrous concrete was found via response surface method (RSM).