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Chloride ion resistance of self-compacting concretes incorporating volcanic materials

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HIGHLIGHTS

- The incorporation of alternative materials in the production of self-compacting concretes (SCCs) as a great option to increase its acceptance and reduce the cement consumption.
- The incorporation of different volcanic materials had important role in the fresh and hardened properties of the SCCs, and high durability in the presence of aggressive agents (chlorides).
- The use of the volcanic materials as partially replacing the cement provide savings on the use of others additives, like viscosity modifying agents, which results in a lower production cost.

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ABSTRACT

This paper examines the effect of incorporating considerable amounts of Colombian volcanic material to self-compacting concrete (SCC) as a pozzolanic addition for rheological improvement, including the effects on the mechanical properties and chloride resistance. In particular, the volcanic materials used as parts of binary and ternary concrete mixtures in this study were Tolima (TVM), Puracé (PVM) and Bocayá (BVM). This paper shows that incorporating volcanic materials, both inert (TVM) and pozzolanic (PVM and BVM), results in SCCs with good workability, moderate mechanical properties and high durability in the presence of aggressive agents such as chlorides.

1. Introduction

Self-compacting concrete (SCC) has been gaining popularity in the construction industry in recent years because of its numerous advantages over conventional concrete. The most important advantages of SCC include a shorter construction time, improved conditions for workers because mechanical vibration is not necessary and easier application in complex architectural designs and densely reinforced structures [35]. Many researchers have studied the use of alternative materials for the production of SCCs to increase their acceptance and reduce cement consumption while maintaining a high fine content to preserve self-compactability. Rodriguez et al. [43] evaluated the possibility of obtaining lower-strength SCC using cement kiln dust CKD) as a partial cement replacement and found that the use of high percentages of CKD and different water/fines ratios allowed the amount of cement required to obtain SCC of medium strength with lower production costs to be optimized. Several researchers have developed SCCs with high percentages of marble powders [50], limestone powders [22] and palm oil and fly ash waste [41].

Volcanic materials are formed during volcanic eruptions, and their vitreous states depend on the magma composition and the solidification process [39]. The reactivity of a volcanic material is determined by its chemical composition, the physical structure of the particles and their potential to react and form cementing compounds [34]. Volcanic materials have been widely utilized in the production of blended cements due to their properties and worldwide availability. Regarding SCC, researchers such as Hossain and Lachemi [30] investigated the use of volcanic ash as a partial cement replacement in the production of economical and environmentally friendly SCCs with good mechanical properties and high durability. Guneyisi et al. [27] evaluated the influence of incorpo-

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rating volcanic pumice stone powder (VP) on the properties of fresh SCC. The results demonstrated that the fluidity of the SCC increased with the VP content without segregation.

The type of construction and the components of the concrete mixture must meet certain conditions based on environmental exposure. These conditions are basically expressed in terms of three parameters: mechanical strength, volume stability and chemical resistance. This set of features ensures that concrete performs well during its service time [47]. In regard to concrete, *chloride* is among the most common and damaging corrosive agents. The motion of chloride ions is restricted not only by the porosity of the structure but also by the exposure conditions, the concrete's moisture content, the agent concentration, the type and characteristics of the concrete components, etc. [5]. For the chloride-induced corrosion being initiated, the passivity layer must be penetrated. Chloride ions surrounding the reinforcement react at anodic sites (such as cracks and defects) and destroys the passive protective film on the steel. This area serve as anode, while the rest of the undamaged surface serves as a cathode. This effect is usually called pitting corrosion. Finally, the chloride ions and Fe^{2+} react to form chloride or oxychloride compounds ($FeCl_2$ and $FeOCl$) [10, 17]. Chloride ions and the binder hydration components may combine to form Friedel's salt ($Ca_3Al_2O_6$-$CaCl_2$-$10H_2O$), which is in equilibrium when the chloride concentration is constant, or be physically adsorbed on the surface of an amorphous calcium silicate hydrate CSH) gel [33]. However, Yuan et al. [51] mentioned that chloride binding is a very complicated process and is affected by many factors, such as chloride concentration, cement composition, hydroxyl concentration, cation of chloride salt, temperature, supplementary cementing materials, carbonation, sulfate ions and electrical field. Unlike chemically bound chlorides, physically adsorbed chlorides move toward lower-concentration areas on a gel surface. However, the free chlorides in the pore water move faster than the absorbed chlorides, which means that the former dominate the diffusion process. Some of the chloride ions bond, which causes the free chloride ion concentration to decrease and, therefore, mitigates the corrosive effect on the concrete structure [32].

AFm (monosulphate) phases and incoming chlorides interact to form Friedel's salt. Therefore, the binding capacity of the chlorides in the hydration products is determined by the binding agent's chemical composition. The amount of C_3A in the binding agent and the amount of available SO_3 govern the AFm phase composition as well as the amount of the Aft (ettringite) phase [23].

Celik et al. [16] utilized natural volcanic pozzolan and limestone powder in the production of SCC with high compressive strength and high resistance to chloride ion penetration. Generally, SCC has been widely used in the ready-mixed concrete industry for structural applications. However, this concept has led to a moderate development in the use of SCC in some applications or products that require lower strength. Therefore, this paper evaluates the mechanical behavior of and the effect of an aggressive medium, such as chlorides, on SCCs with large amounts of fine powders (mineral additions) derived from a Colombian volcanic material.

2. Experimental methodology

2.1. Materials

General-purpose Portland cement was used in this study. Tolima (TVM), Boyacá (BVM) and Puracé (PVM) volcanic materials were used. These materials can be found in the Tolima, Boyacá and Cauca departments, respectively. The physical properties and chemical compositions of the Portland cement and the volcanic materials can be found in Table 1.

Table 1
Physical properties and chemical compositions of the materials used in this study.

Characteristic	General-purpose Portland cement	TVM	BVM	PVM
Chemical composition (%)				
SiO_2	20.73	64.36	71.09	87.45
SO_3	3.14	0.00	0.00	0.00
S	0.00	0.00	0.61	0.04
Fe_2O_3	5.63	4.92	1.98	1.89
TiO_2	0.24	0.54	0.43	1.16
Al_2O_3	4.54	15.90	14.16	0.23
Ba	0.00	0.08	0.10	0.13
CaO	52.69	4.71	2.14	0.07
Na_2O	0.15	5.38	0.14	0.05
MgO	2.24	1.80	0.22	0.05
P_2O_5	0.14	0.17	0.08	0.03
K_2O	0.41	1.49	1.00	0.02
Zr	0.00	0.01	0.02	0.02
Cr	0.00	0.00	0.00	0.01
Cu	0.00	0.00	0.00	0.01
Sr	0.00	0.09	0.00	0.00
SrO	0.16	0.00	0.00	0.00
Mn_2O_3	0.06	0.00	0.00	0.00
Cr_2O_3	0.03	0.00	0.00	0.00
ZnO	0.01	0.00	0.00	0.00
Loss on ignition (%)	9.85	0.40	7.99	8.35
Density (kg/m^3)	3,100	2,090	2,290	2,180
Average particle size (μm)	22.00	20.20	26.30	21.00

In this study, the fine aggregate was river sand (fineness modulus of 2.55, apparent density of 2,581 kg/m^3 and water absorption rate of 1.89%), whereas the coarse aggregate was gravel (fineness modulus of 6.38, nominal size of 12.7 mm, apparent density of 2,544 kg/m^3 and water absorption rate of 2.01%). The latest generation of superplasticizer (SP) SIKAPLAST 326 (specific gravity of 1,130 kg/m^3 and pH of 5) was used in compliance with ASTM C494 [7] types A and F.

2.2. Selected SCC mixtures

The methodology proposed by the ACI committee 237R-07 [1] was considered for the design of the self-compacting concrete (SCC). A slump flow greater than 650 mm was selected; therefore, a cement content of 480 kg/m^3 was established. Five concrete mixtures were developed (see Table 2) based on Burgos [14]. One standard mixture and four mixtures based on volcanic materials incorporating 20% MVT, 30% MVT, 20% MVT + 10% MVP and 20% MVT + 10% MVB as a cement replacement (by mass). All the design parameters (see Table 2) were determined to reach the target slump flow >650 mm) and to comply with the Self-Compacting Concrete European Project Group [48]. However, the SP content was determined by the volcanic material type in the mixture.

2.3. Self-compactability tests

The self-compactability tests performed on each of the trial mixtures included tests of the slump flow, T_{50}, V-funnel for filling ability and L-box for passing ability. These tests were conducted in accordance with the guidelines provided by the 2005 European guide for SCC.

2.4. Tests of the properties of hardened SCC

A test of the compressive strength was conducted to evaluate the mechanical properties of the SCC mixtures. The durability indices of the SCC mixtures evaluated included the rate of absorption (sorptivity) of water and the chloride resistance. Additionally,