Chapter 10

Volcanic Scoria as Cement Replacement

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Abstract

Numerous volcanic scoria (VS) cones are found in many places of the world. Many of them have not yet been investigated, although few have been used as binders for a very long time. The use of natural pozzolans as cement replacement could be considered as a common practice in the construction industry due to the related economic, ecologic and performance benefits. This chapter highlights the advantages and disadvantages of the use of volcanic scoria as cement replacement in concrete mixes in terms of fresh and hardened concrete properties. The chemical and mineralogical composition of volcanic scoria samples collected from 36 countries is presented in this chapter, with some further analysis. The effects of using volcanic scoria as cement replacement on some paste, mortar and concrete properties, such as the setting times, the heat of hydration, the compressive strength, the water permeability and the chloride penetrability, have been studied. The improvement in resistance against the chemical attack of volcanic scoria-based cement mortar has also been highlighted. Some estimation equations depending on the data available in literature have also been derived from the analyzed data. The modification of the microstructure of VS-based cement paste has been confirmed, as well.

Keywords: volcanic scoria, blended cement, compressive strength, concrete durability, pozzolan

1. Introduction

Concrete is the most widely used construction material around the world, because of the economic and widespread availability of its constituents, its versatility, its durability and its adaptability [1]. In the year 2000, more than 1.5 billion tons of cement were produced to make, on average, nearly 1 m$^3$ of concrete per capita [2].
Ordinary Portland cement concrete (OPC) is a composite material and its constituents are cement mixed with water, fine-grained aggregate (sand) and coarse-grained aggregate consisting of natural gravel or crushed stones [3]. Cement is a finely pulverized, dry material that by itself is not a binder but develops the binding property as a result of hydration (i.e., from chemical reactions between cement minerals and water) [4]. The considerable amount of carbon dioxide (CO$_2$) liberated during the production of Portland cement, the most commonly used hydraulic cement, is of a greater concern. On average, about 1 ton of CO$_2$ is liberated per ton of Portland cement produced [1].

The use of mineral admixtures such as pozzolans (materials containing reactive silica) in concrete is now widespread due to many economic, ecological and performance-related benefits [4, 5]. Pozzolanic material is “a siliceous or siliceous-aluminous material that in itself possesses little or no cementitious value but will, in finely divided form and in the presence of water, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties” [6]. Pozzolanic supplementary cementitious materials (SCMs) differ from hydraulic SCMs in that hydraulic SCMs can form cementitious products in water, without the presence of calcium hydroxide [6]. The term “pozzolan” comes from the town of Pozzuoli, northeast of Naples in Italy, where red pozzolanic deposits from the volcano Vesuvius were found [7].

Pozzolanic materials can be divided into natural and artificial pozzolans. Natural pozzolans could be considered the first cementing materials used for the production of artificial stones, ancient mortars and concretes, 3000 years ago [8]. For example, according to Jackson et al. [9], the binding pozzolanic mortars of 2000-year-old concretes in the monuments of imperial age Rome contained 40–50 vol. % of scoriaceous volcanic ash. The natural pozzolans may be further divided into two main groups: (1) those derived from volcanic rocks (volcanic scorias, ashes, tuffs, pumices and obsidians) and (2) others derived from rocks and earths, such as the diatomaceous earths (cherts, opaline silica), clays which have been naturally calcined by heat from flowing lava [10].

Volcanic scoria is loose, rubbly, basaltic to andesitic (40–60% SiO$_2$) ejecta that accumulates around Strombolian eruptive volcanic vents, eventually building up as a scoria cone, whose height may range from a few tens of meters to 300 m. The scoria clasts range widely in size, from millimeters to centimeters in size, and have a light, frothy texture, being full of vesicles (Figure 1e). The vesicular nature of scoria is due to the escape of volcanic gases during eruption. Sometimes these vesicles are refilled with minerals like zeolite, calcite and quartz that form from hot water-rich fluids. The scoria clasts are mainly dark gray in color, although when fresh they may be iridescent, but often the scoria oxidizes by reaction with steam escaping from the vent, when it becomes a deep reddish brown [11–13]. The most economically valuable volcanic scoria deposits are late tertiary or quaternary in age [14]. Most of the scorias are composed of glassy fragments and may contain phenocrysts. The word scoria comes from the Greek skōria, rust. An old name for scoria is cinder [15].

With respect to pumice, typical scoria has larger and more interconnected vesicles, is characterized by lower silica content and displays a darker, brown, reddish or black color [16]. Volcanic scoria can be utilized, other than as cement replacement, in several industrial applications including the manufacturing of lightweight concrete, as a heat-insulating material, in addition to other uses such as fillers, filter materials, absorbents and other architectural applications [17].
Although there are numerous studies on using natural pozzolan as cement replacement, few works on studying volcanic scoria were reported in the literature. The present chapter highlights some characteristics of volcanic scoria and their effects on performance-related properties of paste, mortar and concrete. The importance of this chapter is to encourage countries having ample sources of volcanic scoria cones to further investigate the possibility of using it as cement replacement and thus making a greener concrete.

2. Chemical and mineralogical composition of volcanic scoria

Although there are numerous studies on using natural pozzolan as cement replacement, few works on studying volcanic scoria were reported in the literature. The present chapter highlights some characteristics of volcanic scoria and their effects on performance-related properties of paste, mortar and concrete. The importance of this chapter is to encourage countries having ample sources of volcanic scoria cones to further investigate the possibility of using it as cement replacement and thus making a greener concrete.

2. Chemical and mineralogical composition of volcanic scoria

The chemical composition of volcanic scoria varies within wide ranges and depends on its sources. Various scoria cones are abundant in many parts of the world, such as Syria, Turkey,
| Source       | SiO<sub>2</sub> | Al<sub>2</sub>O<sub>3</sub> | Fe<sub>2</sub>O<sub>3</sub> | CaO  | MgO  | K<sub>2</sub>O | Na<sub>2</sub>O | TiO<sub>2</sub> | P<sub>2</sub>O<sub>5</sub> | LOI  | SO<sub>3</sub> | R<sub>1</sub> | R<sub>2</sub> | Detected phases          | Ref.  |
|-------------|----------------|----------------|----------------|------|------|-------------|-------------|-------------|----------------|------|-------------|-----------|-----------|-------------------------|------|
| Algeria     | 45.9–47.2      | 16.6–18.9      | 8.4–10.6       | 9.0–10.8 | 2.8–4.4 | 0.2–1.5     | 0.8–4.1    | 4.1         | n.a.          | 3.9–5.8 | 0.4–1.0     | 63–66.1   | 72.4–76.1 | Gl, Ca, Py, Qz, Co, Hm, Ac, Ax, Mn, Il | [18–21] |
| Argentina   | 47.6           | 15.4           | 10.0           | 10.8 | 9.8   | 1.3         | 3.4         | 1.4         | 0.5           | n.a. | n.a.        | 63.0      | 73.0      | Gl, Ol, Pl, CPy, Op          | [22]  |
| Armenia     | 53.6           | 19.6           | 7.5            | 13   | 4     | n.a.        | n.a.        | n.a.        | 73.2          | 80.7 | n.a.        |           |           | n.a.                    | [23]  |
| Cameroon    | 41.4–46.9      | 15.0–16.2      | 12.8–14.5      | 7.9–10.5 | 5.3–8.7 | 0.9–1.6     | 2.2–3.4     | 2.1–3.4     | 0.4–9.3       | 0.01 | 56.8–63.2   | 62.3      | 75.9      | Gl, Pl, CPy, Py, Ol, Qz, Hm, Mg, An, Ma, Mc, SCAS | [24–30]|
| Canada      | 45.7–54.3      | 12.7–16.0      | 11.3–12.2      | 7.1–10.8 | 4.1–12.9 | 3.2–4.6     | 1.6–2.2     | 0.74        | 0.43          | n.a. | 58.4–70.6   | 70.3      | 81.6      | Gl, Pl, Ol, CPy           | [31, 32]|
| Chile       | 46.4           | 18.5           | 12.9           | 6.5  | 3.0   | 1.1         | 3.5         | 1.8         | 0.4           | 6.4  | n.a.        | 64.9      | 77.8      | Gl, CPy, Pl, Mn, Kn        | [33]  |
| China       | 45.1           | 14.7           | 12.4           | 9.3  | 9.2   | 1.8         | 3.6         | 2.0         | 1.8           | 1.5  | n.a.        | 59.8      | 72.1      | Gl, Ol, Mn, Pl, Py         | [34]  |
| Congo       | 46.7           | 15.3           | 13.4           | 11.3 | 8.1   | 3.3         | 2.1         | 3.5         | 0.3           | n.a. | 62.0        | 75.1      |           | Gl, Ol, CPy, Pl, Mn, Le    | [35]  |
| Costa Rica  | 53.3           | 19.7           | 8.1            | 9.8  | 5.0   | 0.6         | 2.9         | 0.7         | 0.2           | n.a. | 72.9        | 81.1      |           | Gl, CPy, Pl, Ho            | [36]  |
| Ethiopia    | 47.2–49.0      | 16.1–16.5      | 12.4–13.7      | 8.2–10.8 | 5.4–6.2 | 0.6–0.9     | 3.0–3.3     | 2.4         | 0.5           | 0.7  | n.a.        | 63.7–65.1 | 76.1–78.8 | n.a.                     | [37, 38]|
| France      | 45.1–56.8      | 15.2–17.7      | 7.0–8.2       | 7.8–8.8 | 3.7–8.8 | 0.9–1.8     | 3.2–3.6     | 0.7–3.6     | 3.0           | n.a. | 60.3–68.5   | 74.5      | 81.5      | Gl, CPy, Py, Pl, Ol, Mn, Am, CPy, Pl, Mn, Am | [39, 40]|
| Germany     | 45.5–47.9      | 6.4–15.4       | 7.4–14.8      | 8.2–12.7 | 6.5–12.6 | 0.03–0.5    | 0.6–1.2     | 1.2         | 6.05          | n.a. | 51.9–63.3   | 78.1      |           | Gl, Ol, Pl, CPy, Py, Am, Mi | [41, 42]|
| Indonesia   | 55.1–56.7      | 18.0–18.5      | 82.8–8.8     | 8.1–9.2 | 3.7     | 0.8–1.4     | 2.9–3.1     | 0.6–3.1     | 0.2           | 0.0            | 73.6–74.7 | 82.4–82.9 | Gl, Pl, Py, CPy, Mn          | [43, 44]|
| Iran        | 48.0–48.3      | 12.3–16.4      | 9.4–11.4      | 9.6–9.8 | 4.4–7.7 | 1.3–2.7     | 3.3–5.6     | 1.8–2.6     | 1.1           | 1.1          | 60.3–64.7 | 69.7–76.1 | Gl, Py, Ol, Mn, CPy         | [45, 46]|
| Italy       | 50.6           | 19.7           | 9.1           | 6.2  | 3.8   | 2.3         | 0.7         | 1.0         | 0.3           | 7.2  | n.a.        | 70.3      | 73.9      | n.a.                    | [47]  |
| Japan       | 54.3           | 15.6           | 13.7           | 9.5  | 3.9   | 0.5         | 2.0         | 1.2         | 0.1           | n.a. | 70.0        | 83.7      |           | Gl, Ol, CPy, Pl            | [48]  |
| Jordan      | 41.7           | 10.6           | 8.9            | 12.8 | 6.3   | 1.4         | 1.1         | 2.3         | 0.4           | n.a. | 52.3        | 61.2      |           | n.a.                    | [49]  |
| Madagascar  | 44.6           | 13.0           | 12.5           | 12.1 | 9.6   | 1.3         | 2.4         | 2.3         | 0.7           | n.a. | 57.7        | 70.2      |           | Gl, Pl, Mn, CPy, Ol         | [50]  |
| Mexico      | 54.2–56.0      | 15.5–18.0      | 7.1–14.7      | 7.1–7.7 | 5.3–9.5 | 0.9–1.1     | 3.4–4.8     | 0.8–1.0     | 0.2–0.3        | 0.01 | 69.7–73.9   | 81.0–84.5 |           | Gl, Pl, Ol, Py, CPy        | [51, 52]|

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| Source                      | SiO₂  | Al₂O₃ | Fe₂O₃ | CaO  | MgO  | K₂O  | Na₂O | TiO₂ | P₂O₅ | LOI  | SO₃  | R₁    | R₂    | Detected phases                    | Ref.       |
|---------------------------|-------|-------|-------|------|------|------|------|------|------|------|------|-------|-------|------------------------------------|------------|
| New Zealand               | 46.3– | 11.5– | 10.8– | 8.4– | 9.2– | 0.8– | 13–  | 2.9– | 0.6  | n.a. | n.a. | 58.8– | 69.6– | Gl, Ol, CPy, Pl, Fe-Ti oxides       | [53, 54]   |
| Nicaragua                 | 56.4  | 18.0  | 7.8   | 7.3  | 2.2  | 1.2  | 3.0  | 0.8  | 0.6  | n.a. | n.a. | 74.5  | 82.3  | Gl, Pl, Ol, CPy, Mn                 | [55]       |
| Papua New Guinea          | 47.5  | 14.0  | 3.5   | 6.5  | 5.0  | n.a. | n.a. | 1.4  | 0.02 | 61.5 | 65.0 | n.a.  | n.a.  |                                     | [56]       |
| Peru                      | 57.4  | 17.9  | 6.2   | 4.6  | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 75.3 | 81.5  | n.a.  | [57]       |
| Philippines               | 53.2  | 18.5  | 8.9   | 8.5  | 4.4  | 0.95 | 3.4  | 0.7  | 0.3  | 0.2  | n.a. | 71.7  | 80.6  | n.a.                              | [58]       |
| Romania                   | 46.1  | 18.8  | 9.9   | 10.4 | 7.2  | 1.7  | 3.2  | 1.6  | 1.1  | n.a. | 64.9  | 74.8  | n.a.  | [59]       |
| Russia                    | 52.6  | 14.4  | 9.7   | 8.0  | 4.2  | 2.1  | 3.7  | 1.5  | 0.5  | n.a. | 70.0  | 79.7  | n.a.  | [60]       |
| Saudi Arabia              | 42.0– | 13.1– | 11.1– | 7.8– | 2.5– | 0.6– | 1.5 | 0.2– | 2.1– | 0.3– | 0.9– | 0.02– | 58.0– | 69.4– | Gl, Pl, Ol, CPy, Py, Qz             | [61–65]    |
| Southern Pacific Ocean    | 43.9  | 10.8  | 12.6  | 13.1 | 12.9 | 1.5  | 1.4  | 3.1  | 0.5  | n.a. | 54.7  | 67.3  | n.a.  | [66]       |
| South Africa              | 47.3  | 15.7  | 13.1  | 8.7  | 5.5  | 1.0  | 4.2  | 3.7  | 0.7  | n.a. | 62.9  | 76.0  | Gl, Ol, CPy, Pl                    | [67]       |
| Spain                     | 44.3– | 14.2– | 10.0– | 8.8– | 4.5– | 9.0– | 1.7– | 2.1– | 2.7– | 0.7– | n.a. | 59.2– | 70.9– | Gl, Ol, CPy, Mn, Pl, Le            | [68–70]    |
| Syria                     | 44.9– | 13.0– | 8.6–  | 9.4– | 8.9– | 9.1– | 0.8– | 1.8– | 2.1– | 0.9  | n.a. | 59.5– | 70.5– | Gl, Ol, Pl, Ca, CPy, Fu            | [71, 72]   |
| Tanzania                  | 40.0  | 13.0  | 13.9  | 9.6  | 4.6  | n.a. | n.a. | n.a. | n.a. | 10.8 | n.a. | 53.0  | 66.9  | n.a.                              | [73]       |
| Taiwan                    | 51.5  | 18.8  | 11.1  | 10.0 | 4.7  | 0.4  | 2.8  | 0.9  | 0.1  | 1.4  | n.a. | 53.0  | 66.9  | Gl, Ol, Pl, Py                     | [74]       |
| Turkey                    | 54.9– | 16.9– | 6.6–  | 6.5– | 2.0– | 5.1– | 1.2– | 1.9– | 2.2– | 0.3– | 0.9  | 0.29  | 71.8– | 79.8– | Gl, Pl, Py, CPy, Qz, Ho            | [75–77]    |
| USA                       | 48.0  | 16.7  | 11.8  | 8.6  | 5.9  | 1.8  | 3.5  | 2.0  | 1.2  | n.a. | 64.8  | 76.6  | Gl, Ol, Pl                        | [78]       |
| Yemen                     | 48.5  | 16.5  | 12.2  | 8.6  | 5.7  | 1.0  | 3.6  | 1.9  | 0.4  | 1.8  | n.a. | 65.1  | 77.3  | n.a.                              | [79]       |

LOI: Loss On Ignition; n.a.: Not available.
Gl: Glass; Pl: Plagioclase; Ol: Olivine; Py: Pyroxene; CPy: Clinopyroxene; Mu: Muscovite; Qz: Quartz; Ma: Managoalcite; An: Anatase; Mc: Microcline, SCAS: Sodium calcium aluminum silicate; Co: Cordierite; Ac: Analcime; Ax: Axinite; Mn: Magnetite; Ca: Calcite; Hm: Hematite; Il: Illite; Mr: Montmorillonite; Ho: Hornblende; Mg: Maghemite; Fu: Fujasite; Am: Amphibole; OP: Opaque minerals; Mi: Mica; Kn: Kaolinite; Le: Leucite

Table 1. Chemical composition of some different scoria samples quarried from 36 countries.
Saudi Arabia, Cameroon, Ethiopia, Jordan, Libya, Algeria, Spain and others [18–79]. Harrat Al-Shaam volcanic field, for example (Figure 1a), is a basaltic province, extends widely at the Arabian plate (over 50,000 km²), covers the south of Syria, northeast of Jordan, north of Saudi Arabia and contains hundreds of volcanic scoria cones [80, 81]. The chemical analysis of some volcanic scoria reported for 36 countries [18–79] is presented in Table 1.

Figure 2. Different oxides versus silica content in the volcanic scoria (R₁: sum of SiO₂ and Al₂O₃; R₂: sum of SiO₂, Al₂O₃ and Fe₂O₃) [18–79].
Table 1 shows that most of the volcanic scoria samples are relatively rich in silica (40–60%) and alumina (10–20%). The next oxides are iron (5–16%), calcium (5–13%) and magnesium (2–13%) oxides. The alkali content is not high but may vary between 1 and 7%. Loss on ignition is generally low but may reach 10% in some pozzolans. Harker variation diagrams (Figure 2), using SiO$_2$, show a general increase of Al$_2$O$_3$ and alkalis with increasing SiO$_2$. However, the elements such as Fe$_2$O$_3$, MgO, CaO and TiO$_2$ display inverse relationships with SiO$_2$. The author attempted to derive an equation in order to estimate R$_1$ (sum of SiO$_2$, Al$_2$O$_3$ and Fe$_2$O$_3$) and R$_2$ (sum of SiO$_2$, Al$_2$O$_3$ and Fe$_2$O$_3$) from the knowledge of SiO$_2$ content (Figure 2).

The mineralogical composition of volcanic scoria also varies depending upon their sources. Owing to their formation process, volcanic scoria consists of crystalline and noncrystalline particles as glassy particles. The most detected minerals are plagioclase, olivine, pyroxene and clinopyroxene.

3. Reactivity of volcanic scoria

Volcanic scoria as a pozzolanic material has high silica (SiO$_2$) and alumina (Al$_2$O$_3$) content with a glassy/amorphous structure for reactivity with lime or cement [82]. Reactive silica content can react with portlandite (CH) liberated from the hydration of C$_3$S and C$_2$S in cement. This reaction forms additional calcium silicate hydrates (C-S-H). The principal reaction is:

$$\text{CH (Portlandite)} + \text{Si (reactive silica)} + \text{H (Water)} \rightarrow \text{C-S-H (Calcium silicate hydrates)}$$

The composition of C-S-H is not very different from that formed in regular hydration, although generally the C/S molar ratio is slightly lower [83]. Analogously to reactive silica, reactive alumina present in volcanic scoria can react with CH to form calcium aluminate hydrates (C-A-H) [83]. This reaction which is frequently called the pozzolanic reaction is slow, portlandite consuming and very efficient in filling up capillary spaces [4]. It depends on several factors, such as the glassy phase content in volcanic scoria and the fineness of volcanic scoria.

3.1. Glassy phase in volcanic scoria

ASTM designation C618 (2012) [84] requires that for a material to be accepted as a natural pozzolan, the sum of SiO$_2$, Al$_2$O$_3$ and Fe$_2$O$_3$ should have a minimum value of 70% and the strength activity index should exceed 75% of the control mortar’s compressive strength at either 7 or 28 days. The strength activity index (SAI) gives an indication of the reactivity of volcanic scoria by comparing the compressive strength of mortar cubes made with 80 wt.% cement and 20 wt.% volcanic scoria to the compressive strength of the control mortar cubes made with only cement. In addition, EN 197–1(2000) [85] requires a reactive silica content of more than 25% for volcanic scoria to be accepted as natural pozzolan.

3.2. Fineness of volcanic scoria

An increase in fineness that exposes more surface area of the volcanic scoria may accelerate the early pozzolanic reactivity [86, 87]. The specific surface area of volcanic scoria, which is the area
of a unit mass, is measurable by different techniques. The most common is the Blaine-specific surface area technique, which measures the resistance of compacted particles to an air flow. A laser particle size analyzer can also be used for the determination of the specific surface area of volcanic scoria [88, 89]. Al-Swaidani et al. [89] reported an increase of about 145% in the early compressive strength when the Blaine fineness of 2-day-cured volcanic scoria (VS)-based cement increased from 240 to 510 m²/kg at replacement levels ranging from 25 to 35% by mass, as shown in Figure 3. The authors also concluded that an increase of about 5 MPa can be expected for every 1000 cm²/g increase in Blaine fineness for VS-based binder mortars at all curing times [89]. Similar results were obtained by other researchers [90, 91]. This reactivity enhancement was explained by the effect of grinding which breaks the vitreous body, decreases the particle size and increases dissolution rate and solubility of volcanic scoria, which will accelerate pozzolanic reaction rate and the strength development of mortar containing volcanic scoria [89, 90, 92].

4. Properties of VS-based cement paste

4.1. Setting times

Most of the studied scoria samples showed an increase, ranging from slight to significant, in setting times of the VS-based cement paste with the increase in volcanic scoria content. This can be explained by the reduction of hydration heat on the binder system with the presence of VS [91]. A significant relationship (R² = 0.9) between initial and final setting times was obtained by the author depending on data collected from other papers [20, 62, 71, 72, 75, 79, 89, 91], as clearly shown in Figure 4. So, knowing initial setting time, the final setting time of the VS-based cement paste can be predicted by using the equation shown in Figure 4. It is worth to note that among all the investigated volcanic scoria compiled with the standard requirements in terms of the initial setting time, most of them met the requirements in terms of final setting times (i.e., initial setting time ≥ 45 min and final setting time ≤ 420 min), according to ASTM C595 [93].
4.2. Heat of hydration

The hydration of cement paste is accompanied by the liberation of heat that raises the temperature of the concrete mix. Because of the slower pozzolanic reaction, the partial replacement of cement by volcanic action results in a release of heat over a longer period of time enabling the heat to dissipate and the overall concrete temperature to remain lower. This is of great importance in mass concrete where cooling, following a large temperature rise, can lead to cracking. As shown in Figure 5, a volcanic scoria from Syria reduced the heat of hydration [94]. Similar results were also reported by Alhozaimy et al. [95] who concluded that the heat of hydration of VS-based cement pastes liberated in the first 72 h was, on average, 85% of the control mix.

4.3. Microstructure

The presence of volcanic scoria leads to the disappearance of portlandite crystals and the appearance of the condensed type of C-S-H crystals, as shown in Figure 6. This type of condensed C-S-H results from the interaction of pozzolanic material with portlandite. Condensed

![Figure 4. Relationship between initial and final setting times.](image)

![Figure 5. Influence of different SCMs on the heat of hydration of the mixtures [94].](image)
C-S-H fills the micropores, reduces the porosity and consequently improves the impermeability and the compressive strength. The enhancement in the microstructure in the mixtures with volcanic scoria can be attributed to the formation of additional C-S-H, which generally fills in the pores, creates denser hydration products and accordingly reduces the permeability [63]. Similar observations were also reported in the literature [71, 72].

5. Properties of VS-based cement mortar/concrete

5.1. Compressive and flexural strength

All the results reported in the literature [18–20, 30, 56, 62, 63, 71, 72, 75, 79, 89, 91, 96, 97] show that the compressive strength of VS-based cement mortars/concretes increases with the curing age and decreases with the replacement level of volcanic scoria content (Figure 7). This reduction in the compressive strength is attributed mainly to slower pozzolanic activity at room temperature of volcanic scoria as natural pozzolan [71, 83]. This ascertainment is explained by the interaction between the reactive silica which is in the glassy portion of the addition and the Ca(OH)$_2$ released by the hydration of the cement. It has also been noted that the mortars containing volcanic scorias exhibit compressive strength comparable to those of the control mortar starting from the period of 90 days.

The author attempted to derive an equation in order to reasonably estimate the relative compressive strength of VS-based mortars. This prediction equation could be written as follows:

\[
RCS = (0.176\ln t - 1.343) \times VS + 1.01 \quad (R^2=0.81)
\]

where RCS is the relative compressive strength, $t$ is the curing age (day) and VS is the volcanic scoria content (%). This prediction equation having a relatively high coefficient of determination ($R^2 = 0.81$) was obtained through the regression analysis of literature data (Figure 8). The variants in the equation are the curing age and the volcanic scoria content. So, knowing the
curing age and the volcanic scoria content and the compressive strength of the control sample (i.e., without volcanic scoria), the compressive strength of VS-based cement and mortar could be reasonably estimated.

It is worth to mention that, in contrast to previous literature, studying the effect of total alkali content (Na$_2$O and K$_2$O) and K$_2$O on the compressive strength of VS-based cement mortars did not give definite correlations (Figure 9).

A similar behavior was observed by many researchers in terms of flexural tensile strength of VS-based cement mortars. An attempt to predict the flexural strength based on the compressive strength, with a reasonable coefficient of determination ($R^2 = 0.83$), is clearly shown in Figure 10.

5.2. Drying shrinkage

Drying shrinkage represents the strain caused by the loss of water from the hardened material. The shrinkage is believed to originate in the C-S-H and its associated porosity [83].
Figure 9. Effect of total alkali content (a and b) and $K_2O$ content (c and d) on compressive strength of VS-based cement mortars at 7 and 28 days curing.

Figure 10. Relationship between compressive and flexural strengths of VS-based cement mortars.
The increase of drying shrinkage with the cement replacement level [99] might be due to: (1) the pozzolanic reaction, generating an additional CSH, resulting in the decrease in spacing of CSH particles; (2) the transportation of large pores into fine pores (pore size refinement) increasing capillary tension [99–103]; (3) the higher water demand of scoria-based cements [99, 102]; (4) the porous microstructure of scoria [104] (Figure 1d). However, this increase was lower than the maximum 0.03% allowed by ASTM C618 (Figure 11) [99].

**Figure 11** shows the results of drying shrinkage of VS-based cement mortars.

### 5.3. Sulfate attack

The sulfate attack on the cement mortar is a complex process involving the hydration products produced by Portland cement. The damage caused by sulfate attack may involve cracking and expansion of mortar as a whole, as well as softening and disintegration of cement paste [83]. Cements with a high C₃A content will be subject to sulfoaluminate corrosion in which ettringite is formed, as displayed in Eq. (3) [83, 105].

\[
\begin{align*}
\text{C}_4\text{A}_8\text{H}_{12} \text{(Monosulfate)} + 2\text{C}_2\text{H}_2 \text{(Gypsum)} + 16\text{H} \text{(Water)} & \rightarrow \text{C}_6\text{A}_3\text{H}_{32} \text{(Ettringite)} \\
\end{align*}
\]

This type of corrosion is initiated by the reaction between sulfate ions and calcium hydroxide (CH):

\[
\text{CH} \text{(Calcium hydroxide)} + \text{SO}_4^{2-} \text{(aq) (Sulfate ion)} \rightarrow \text{C}_2\text{H}_2 \text{(Gypsum)} + 2\text{OH}^{-} \text{(aq)}
\]

This reaction can be described as gypsum corrosion. Both reactions are accompanied by an expansion in solid volume causing internal stresses and ultimately lead to cracking [83].

---

*Figure 11. Drying shrinkage values of prismatic mortar specimens [99].*
The beneficial effects of using volcanic scoria on the sulfate resistance of mortar as reported by many authors [5], Figure 12, may be ascribed to a number of mechanisms [5, 106–108], including:

- reduced permeability,
- dilution of the C₃A phases and CH (both participants in reactions with sulfates) as a result of the partial replacement of Portland cement,
- consumption of CH by pozzolanic reaction and
- alteration of hydrated aluminate phases, making them more resistant, for example, the presence of reactive silica may favor the formation of strätlingite (C-A-S-H).

### 5.4. Acidic attack

Sulfuric acid, among other aggressive acids such as HCl, HNO₃ and CH₃COOH, is very damaging to mortar as it combines an acid attack and a sulfate attack [109]. At the first stage, deterioration of Ca(OH)₂ results in an expansive gypsum formation. The gypsum then reacts with C₃A in the aqueous environment and forms a more expansive product called ettringite. These very expansive compounds cause internal pressure in the mortar, which leads to the formation of cracks [110] and the transformation of the mortar into a mushy or a noncohesive mass [111]. Sulfuric acid may also cause the decalcification of calcium silicate hydrates C-S-H and will ultimately transform the C-S-H into amorphous hydrous silica. The following equations express these reactions [110]:

\[
\text{Ca(OH)}_2 + \text{H}_2\text{SO}_4 \rightarrow \text{CaSO}_4.2\text{H}_2\text{O (Gypsum)} \quad (5)
\]

\[
3(\text{CaSO}_4.2\text{H}_2\text{O}) + 3\text{CaO.Al}_2\text{O}_3.12\text{H}_2\text{O} + 14\text{H}_2\text{O} \\
\rightarrow 3\text{CaO.Al}_2\text{O}_3.3\text{CaSO}_4.32\text{H}_2\text{O}_3 \quad (\text{Ettringite}) \quad (6)
\]

\[
\text{CaO.SiO}_2.2\text{H}_2\text{O} + \text{H}_2\text{SO}_4 \rightarrow \text{CaSO}_4 + \text{Si (OH)}_4 \quad (\text{Hydrous silica}) + \text{H}_2\text{O} \quad (7)
\]

The white gypsum, which covers the surface of mortar, can potentially lead to the blocking of pores on the surface, leading to a slower rate of attack initially. However, this effect lasts only temporarily [112].

The better performance of VS-based cement mortars in terms of the acid attack, as shown in Figure 13 [99], can be due to the pozzolanic reaction [5, 113, 114]. This reaction between scoria and calcium hydroxide liberated during the hydration of cement [5, 114] leads to a refinement of the pore structure resulting in a highly impermeable matrix [5, 113]. The pozzolanic reaction also fixes Ca(OH)₂, which is usually the most vulnerable product of the hydration of cement insofar as the acid attack is concerned [115]. In the study by al-Swaidani and Aliyan [5],...
the number of days needed to register a 10% loss in weight was considered in their evaluation. As shown in Table 2, the 10% weight loss was obtained with 35% VS-based cement mortars up to 6.2 and 6.70 days of exposure to sulfuric acid and 4.6 and 5.2 days of exposure to hydrochloric acid at 28 and 90 days curing, respectively. In addition, none of the mixtures containing 25% volcanic scoria and more lost 10% weight even after 100 days of exposure to nitric and acetic acids.
5.5. Permeability

Permeability of concrete to water is closely related to the durability of concrete. Permeability is the rate at which aggressive agents penetrate through concrete [115].

5.5.1. Water permeability

Water penetration depth can be considered as an indication of permeable and impermeable concrete [115]. A depth of less than 50 mm classifies the concrete as impermeable and a depth of less than 30 mm as impermeable under aggressive conditions [115]. The water penetration depth test results for concretes containing VS-based cement concretes show their lower permeability when compared with plain Portland cement, particularly at late ages (Figure 14) [98].

5.5.2. Chloride penetrability

Although chloride ions in concrete do not directly cause severe damage to the concrete, they contribute to the corrosion of steel bars embedded in concrete that is considered as the factor causing most premature deterioration of reinforced concrete (RC) structures worldwide, especially in the marine environments. Therefore, the study of chloride penetrability is important for evaluating reinforcing steel corrosion in RC structures. This has prompted the search for economic methods of extending the service life of structures. One of these methods was the use of pozzolan such as volcanic scoria [5].

The improvement in resistance of volcanic scoria-based cement concretes to chloride penetration which was frequently noted in the literature may be related to their refined pore structure and their reduced electrical conductivity [71]. This refinement in pore structure is due to the
secondary-contributing pozzolanic reaction that makes the microstructure of concrete denser [71]. Figure 15 clearly shows such improvement with the increase of volcanic scoria content and curing age.

Analyzing the results of chloride penetrability gathered from different works [19, 62, 63, 98, 116, 117], an estimation equation with strong correlation ($R^2 \approx 0.86$) can be derived (Figure 16). The estimation equation is:

$$RCP = (-0.3\ln t - 0.68) \times VS + 1.06 \quad (8)$$

Figure 14. Water penetration depths of VS-based cement concretes prepared with different w/c ratios and cured for different ages [98].

Figure 15. Chloride ion penetrability of VS-based cement concretes as reported by al-Swaidani [98].
where, RCP is relative chloride penetrability, t is curing age and VS is volcanic scoria content (% by mass). So, the chloride penetrability of VS-based cement concrete can be predicted from knowledge of curing time and volcanic scoria content.

6. Conclusion

- Volcanic scoria has been used in construction since ancient times in pozzolan-lime concrete providing durable structures that survived over 2000 years.
- The SiO$_2$ content for all sources are within the range of 40–60%; Al$_2$O$_3$ and Fe$_2$O$_3$ are within the ranges from 10 to 20% and from 5 to 16%, respectively.
- Incorporation of volcanic scoria in concrete has significant effects on the properties of concrete, particularly durability-related properties.
- The chloride permeability of VS-based cement concrete demonstrated better performance as compared to plain concrete, especially at the curing age of 28 days and longer.
- The wide availability of volcanic scoria in many countries, its low cost and the drive toward more sustainable construction have resulted in renewed interest in volcanic scoria as natural pozzolan for concrete. Historically, various types of volcanic scoria were successfully used in dams and aqueducts, where the strength demand is not high but the durability and thermal cracking control are of major concerns.
- Estimation equations for predicting the investigated concrete properties (i.e., compressive strength, water penetration depth and chloride penetration) incorporating the effect of curing time and the replacement level of volcanic scoria were derived. These equations permit the concrete properties of VS-based cement concretes to be predicted with a relatively high degree of accuracy ($R^2 \geq 0.8$).
- Investigating the volcanic scoria cones that have not been yet invested is highly recommended. In addition, making more sustainable and durable concrete using volcanic scoria is highly encouraged.
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References

[1] Aitcin PC, Mindess S. Sustainability of Concrete. 1st ed. London, UK: Spon Press; 2011
[2] Aïtcin PC. Binders for Durable and Sustainable Concrete. London, UK: Taylor & Francis; 2008
[3] Brandt AM. Cement-Based Composites: Materials, Mechanical Properties and Performance. 2nd ed. London, UK: Taylor & Francis; 2009
[4] Mehta PK, Monteiro PJM. Concrete: Microstructure, Properties and Materials. 3rd ed: New York, USA: McGraw-Hill; 2006
[5] al-Swaidani AM, Aliyan SD. International Journal of Concrete Structures and Materials. 2015;9:241. DOI: https://doi.org/10.1007/s40069-015-0101-z
[6] ASTM C125. Standard Terminology Relating to Concrete and Concrete Aggregates. West Conshohocken, Pennsylvania, United States: American Society for Testing and Materials; 2007
[7] Jahren P, Sui T. Concrete and Sustainability. Boca Raton, Florida, USA: CRC Press; 2014
[8] Dedeloudis C, Zervaki M, Sideris K, Juenger M, Alderete N, Kamali-Bernard S, Villagrán Y, Snellings R. Natural pozzolans. De Belie N et al, editors. In: Properties of Fresh and Hardened Concrete Containing Supplementary Cementitious Materials. 2018. RILEM State-of-the-Art Reports 25. https://doi.org/10.1007/978-3-319-70606-1_6
[9] Jackson M, Deocampo D, Marra F, Scheetz B. Mid-Pleistocene pozzolanic volcanic ash in ancient roman concretes. Geoarchaeology. 2010;25(1):36-74
[10] Hammond AA. Pozzolana Cements for Low Cost Housing. Japan: Building and road research institute; 1983
[11] Dictionary of Earth Sciences. A Dictionary Edited by Michael Allaby. 3rd ed. Oxford, UK: Oxford University Press; 2008
[12] Lefond SJ. Industrial Minerals and Rocks. Society of Mining Engineers. New York: American Institute of Mining, Metallurgical and Petroleum Engineers, Inc. Vol. 2; 1983:723-1446
[13] Sen G. Petrology: Principles and Practice. Berlin Heidelberg: Springer-Verlag; 2014
[14] Mathers SJ, Harrison DJ, Mitchell CJ, Evans EJ. Exploration, Evaluation and Testing of Volcanic Raw Materials for Use in Construction, British Geological Survey; 2000. 116p

[15] Jackson JA, Mehl J, Neuendorf K. Glossary of Geology. Alexandria, Virginia: American Geological Institute; 2005. 800 pp

[16] Taddeucci J, Edmonds M, Houghton B, James MR, Vergniolle S. Hawaiian and Strombolian Eruptionsthe encyclopedia of volcanoes. Elsevier Inc; 2015. DOI: 10.1016/B978-0-12-385938-9.00027-4

[17] Hossain AKM. Resistance of Scoria-based blended cement concrete against deterioration and corrosion in mixed sulfate environment. Journal of Material Civil Engineering. 2009:299-308. 10.1061/(ASCE)0899-1561(2009)21,7(299)

[18] Senhadji Y, Escadeillas G, Mouli M, Khelafi H, Benosman. Influence of natural pozzolan, silica fume and limestone fine on strength, acid resistance and microstructure of mortar. Powder Technology. 2014;254:314-323

[19] Ghrici M, Kenai S, Meziane E. Mechanical and durability properties of cement mortar with Algerian natural pozzolana. Journal of Materials Science. 2006;41:6965-6972

[20] Mebrouki A, Cyr M, Belaribi NB. Enhancing value of local materials in developing countries, case of an Algerian pozzolan. European Journal of Environmental and Civil Engineering. 2009;13(10):1263-1278

[21] Laoufi L, Senhadji Y, Benazzouk A, Langlet T, Mouli M, Laoufi I, Benosman AS. Evaluation de la durabilité de mortiers pouzzolaniques exposés à une attaque chimique (Assessment of pozzolanic mortars sustainability exposed to chemical attack). Journal of Material Environmental Science. 2016;7(5):1835-1845

[22] Bertotto GW, Hirch MH, Ponce AD, Orihashi Y, Sumino H. Petrology and geochemistry of Toscales basaltic eruptive center. Extra-Andean back-arc zone of Mendoza province. Revista de la Asociacion Geologica Argentina. 2016;73(3):330-340

[23] Kuperman AM, Gorbatkina YA, Goreenberg AY, Ivanova-Mumzhieva VG, Zakharova TY, Lebedeva OV, Solodilov VI, Petrosyan GK. Physical-mechanical properties of fibers made from scoria and materials based on them. Glass and Ceramics. 2009;66(7-8)

[24] Juimo WT, Cherrad LA, Oliveira L. Characterisation of natural pozzolan of :Djoungo (Cameroon) as lightweight aggregate for lightweight concrete. International Journal of GEOMATE. 2016;11(27):2782-2789

[25] Billong N, Melo UC, Njopwouo D, Louvet F, Bonnet JP. Physicochemical characteristics of some Cameroonian Pozzolans for use in sustainable cement like materials. Materials Sciences and Applications. 2013;4:14-21

[26] Tchakouté HK, Kong S, Djobo JNY, Tchadjité LN, Njopwouo D. A comparative study of two methods to produce geopolymer composites from volcanic scoria and the role of structural water contained in the volcanic scoria on its reactivity. Ceramics International. 2015;41(10):12568-12577. DOI: 10.1016/j.ceramint.2015.06.073
[27] Djobo JNY, Tchadjie LN, Tchakoute HK, Kenne BBD, Elimbi A. Synthesis of geopolymer composites from a mixture of volcanic scoria and metakaolin. Journal of Asian Ceramics Societies. 2014;2(4):387-398

[28] Tchamdjoua WHJ, Grigolettoc S, Michelec F, Courardc L, Abediac ML, Cherradia T. An investigation on the use of coarse volcanic scoria as sand in Portland cement mortar. Case Studies in Construction Materials. 2017;7:191-206

[29] Bidjocka C. Conception de bétons légers isolant s porteurs. Applications aux pouzzolanes naturelles du Cameroun, Thèse de doctorat. Vol. 1990. INSA de Lyon; 1990 167p

[30] Tchamdjou WHJ, Cherradi T, Abidi ML, Pereira de Oliveira LA. Influence of different amounts of natural pozzolan from volcanic scoria on the rheological properties of Portland cement pastes. Energy Procedia. 2017;139:696-702

[31] Wong LJ, Larsen JF. The middle scoria sequence: A Holocene violent strombolian, subplinian and phreatomagmatic eruption of Okmok volcano, Alaska. Bulletin of Volcanology. 2010;72:17-31. DOI: 10.1007/s00445-009-0301-y

[32] Eiche GE, Francis DM, Ludden JN. Primary alkaline magmas associated with the quaternary alligator Lake volcanic complex, Yukon territory, Canada. Contributions to Mineralogy and Petrology. 1987;95:191-201

[33] Amigo Á, Lara L, Smith V. Holocene record of large explosive eruptions from Chaitén and Michinmahuida volcanoes, Chile. Andean Geology. 2013;40(2):227-248. DOI: 10.5027/andgeoV40n2-a03

[34] Ogura T. Volcanoes in Manchuria. In: Ogura T, editor. Geology and Mineralogy of the Far East. University of Tokyo Press; 1969. pp. 373-413

[35] Smets B, Kervyn M, d’Oreye N, Kervyn F. Spatio-temporal dynamics of eruptions in a youthful extensional setting: Insights from Nyamulagira volcano (D.R. Congo), in the western branch of the east African rift. Earth-Science Reviews. 2015;150:305-328. http://dx.doi.org/10.1016/j.earscirev.2015.08.008

[36] Parat F, Streck MJ, Holtz F, Almeev R. Experimental study into the petrogenesis of crystal-rich basaltic to andesitic magmas at Arenal Volcano. Contributions to Mineralogy and Petrology. 2014;168:1040. DOI: 10.1007/s00410-014-1040-4

[37] Siebug M, Gemon TM, Bull JM, Keir D, Barford DN, Taylor RN, et al. Geological evolution of the Boset-Bericha volcanic complex, main Ethiopian rift: 40Ar/39Ar evidence for episodic Pleistocene to Holocene volcanism. Journal of Volcanology and Geothermal Research. 2018;351:115-133. DOI: 10.1016/j.jvolgeores.2017.12.014

[38] Tessema AET. Concrete Production and Quality Control in Building Construction Industry of Ethiopia: Addis Ababa, November 2005, Master of Science in Construction Technology and Management, pp. 148

[39] Bourdier JL, Gouragaud A, Vincent PM. Magma mixing in a main stage of formation of Montagne Pelee: The Saint Vincent-type scoria flow sequence (Martinique, F.W.I.). Journal of Volcanology and Geothermal Research. 1985;25(1985):309-332
[40] Jannot S, Schiano P, Boivin P. Melt inclusions in scoria and associated mantle xenoliths of Puy Beaunit volcano, Chaine des Puys, massif central, France. Contributions to Mineralogy and Petrology. 2005;149:600-612. DOI: 10.1007/s00410-005-0670-y

[41] Cools S, Juvigne E, Pouclet A. Composition of tephra of the Goldberg volcano (west Eifel, Germany) and search for its dispersion. International Journal of French Quaternary Association. 2011;22(1):47-60

[42] Büchner J, Tietz O, Viereck L, Suhr P, Abratis M. Volcanology, geochemistry and age of the Lausitz volcanic field. International Journal of Earth Sciences. 2015;104:2057-2083. DOI: 10.1007/s00531-015-1165-3

[43] Bourdier JL, Pratomo I, Thouret JC, Boudon G, Vincent PM. Observations, stratigraphy and eruptive processes of the 1990 eruption of Kelut volcano, Indonesia. Journal of Volcanology and Geothermal Research. 1997;79:181-203

[44] Handley HK, Macpherson CG, Davidson JP. Geochemical and Sr–O isotopic constraints on magmatic differentiation at Gede volcanic complex, west java, Indonesia. Contributions to Mineralogy and Petrology. 2010;159:885-908. DOI: 10.1007/s00410-009-0460-z

[45] Seyfi S, Azadmehr AR, Gharabaghi M, Maghsoudi A. Usage of Iranian scoria for copper and cadmium removal from aqueous solutions. Journal of Central South University. 2015;22:3760–3769. DOI: 10.1007/s11771-015-2920-0

[46] Asiabanh A, Bardintzeff JM, Sara Veysi S. North Qorveh volcanic field, western Iran: Eruption styles, petrology and geological setting. Mineral and Petrology. 2017;20. DOI: 10.1007/s00710-017-0541-z

[47] Marra F, Deocampo D, Jackson MD, Ventura G. The Alban Hills and Monti Sabatini volcanic products used in ancient roman masonry (Italy): An integrated stratigraphic, archaeological, environmental and geochemical approach. Earth-Science Reviews. 2011;108:115-136. DOI: 10.1016/j.earscirev.2011.06.005

[48] Nakano S, Yamamoto T. Chemical variations of magmas at Izu-Oshima volcano, Japan: Plagioclase-controlled and differentiated magmas. Bulletin of Volcanology. 1991;53:112-120

[49] Al-Zboon KK, Al-Zou’by J. Effect of volcanic tuff on the characteristics of cement mortar. European Journal of Environmental and Civil Engineering. 2015. http://dx.doi.org/10.1080/19648189.2015.1053151

[50] Rajaonarison EF, Gacoin A, Randriana J, Ranaivoniarivo VG, Bam Haja Nirina Razafindrabe BHN. Effect of scoria on various specific aspects of lightweight concrete. International Journal of Concrete Structures and Materials. 2017;11(3):541-555. DOI: 10.1007/s40069-017-0204-9

[51] Erlund EJ, Cashman KV, Wallace PJ, Pioli L, Rosi M, Johnson E, Granados HD. Compositional Evolution of Magma from Paricutin Volcano. Mexico: The tephra record, Journal of Volcanology and Geothermal Research; 2009. DOI: 10.1016/j.jvolgeores.2009.09.015
[52] Siebe MNGC, Agustín-Flores J. Eruptive style of the young high-mg basaltic-andesite Pelagatos scoria cone, southeast of México City. Bulletin of Volcanology. 2009; 71:859-880. DOI: 10.1007/s00445-009-0271-0

[53] McGee. New Zealand, Lucy Emma McGee, Melting Processes in Small Basaltic Systems: The Auckland Volcanic Field. New Zealand, PhD thesis: University of Auckland; 2012. p. 210

[54] Smith IEM, Blake S, Wilson CJN, Houghton BF. Deep-seated fractionation during the rise of a small-volume basalt magma batch: Crater Hill, Auckland, New Zealand. Contributions to Mineralogy and Petrology. 2008; 155:511-527

[55] Hradecky P, Rapprich V. Historical tephra-Tratigraphy of the Cosiguina volcano (western Nicaragua). Revista Geológica de América Central. 2008; 38:65-79

[56] Hossain KMA, Julkarnine KMY, Anwar MS. Evolution of strength and durability of scoria concrete in sea environment. Journal of Multidisciplinary Engineering Science and Technology. 2015; 2(6):1268

[57] Lechtman H, Moseley ME. The scoria at CHAN CHAN; non-metallurgical deposits, Ñawpa Pacha. Journal of Andean Archaeology. 1972; 10(1):135-170. DOI: https://doi.org/10.1179/naw.1972.10-12.1.008

[58] Castillo PR, Newhall CG. Geochemical constraints on possible subduction components in lavas of Mayon and Taal volcanoes, southern Luzon, Philippines. Journal of Petrology. 2004; 45(6):1089-1108. DOI: 10.1093/petrology/egh005

[59] Halmagyi T, Mosonyi E, Fazekas J, Spataru M, Goga F. Characterization of cements from Dominantly volcanic raw materials of the Carpathian bend zone. Hungarian Journal of Industry and Chemistry. 2016; 44(2):135-139. DOI: 10.1515/hjic-2016-0017

[60] Ermakov VA, Gontovaya LI, Senyukov SL. Tectonics and magma chambers of the recent Tolbachik fissure eruption (Kamchatka peninsula). Atmospheric and Oceanic Physics. 2014; 50(8):745-765

[61] Celik K, Meral C, Mancio M, Mehta PK, Monteiro PJM. A comparative study of self-consolidating concretes incorporating high-volume natural pozzolan or high-volume fly ash. Construction and Building Materials. 2014. DOI: 10.1016/j.conbuildmat.2013.11.065

[62] Khan MI, Alhozaimy. Properties of natural pozzolan and its potential utilization in environmental friendly concrete. Canadian Journal of Civil Engineers. 2011; 38:71-78. DOI: 10.1139/L10-112

[63] Fares G, Alhozaimy A, Abdalla Alawad O, Al-Negheimish A. Evaluation of powdered scoria rocks from various volcanic lava fields as cementitious material. Journal of Materials in Civil Engineering. 2016; 28(3):9. Paper nr. 04015139. DOI: 10.1061/(ASCE) MT.1943-5533.0001428

[64] Surour AA, Moufti MR, Nassief MO, Abu Saeda Y. Chemical characteristics of black scoria and their influence on economic use as industrial rock: A case study from harrat Rahat, Saudi Arabia, ISESCO Journal of Science and Technology, Nr. 23. 2017; 13(23): 48-59
[65] Bakhsh RA. The Harrat Al-Birk basalts in southwest Saudi Arabia: Characteristic alkali mafic magmatism related to Red Sea rifting. Acta Geochimica. 2017;36(1):74-88. DOI: 10.1007/s11631-016-0126-2

[66] Thompson GM, Malpas J, Smith IEM. Volcanic geology of Rarotonga, southern Pacific Ocean. New Zealand Journal of Geology and Geophysics. 1998;41(1):95-104. DOI: 10.1080/00288306.1998.9514793

[67] le Roux AP, Chevallier L, Verwoerd WJ, Barends R. Petrology and geochemistry of Marion and Prince Edward Island, Southern Ocean: Magma chamber process and source region characteristics. Journal of Volcanology and Geothermal Research. 2012;223-224:11-20

[68] Traglia FD, Cimarelli C, de Rita D, Torrente DG. Changing eruptive styles in basaltic explosive volcanism: Examples from Croscat complex scoria cone, Garrotxa volcanic field (NE Iberian peninsula), Journal of Volcanology and Geothermal Research. 2009;180:89-109. DOI:10.1016/j.jvolgeores.2008.10.020

[69] Krockert J, Buchner E. Age distribution of cinder cones within the Bandas del Sur Formation, southern Tenerife, Canary Islands. 2009;146(2):161-172. DOI: https://doi.org/10.1017/S001675680800544X

[70] Albert H, Perugini D, Joanmarti. Fractal analysis of enclaves as a new tool for estimating rheological properties of magmas during mixing: The case of Montana Reventada (Tenerife, Canary Islands). Pure and Applied Geophysics. 2015;172(2015):1803-1814

[71] al-Swaidani AM. Production of more durable and sustainable concretes using volcanic scoria as cement replacement. Materiales De Construccion. 2017;67(326):e118. DOI: 10.3989/mc.2017.00716

[72] al-Swaidani et al. Improvement of the early-age compressive strength, water permeability, and sulfuric acid resistance of scoria-based mortars/concrete using limestone filler. Advances in Materials Science and Engineering. 2017;2017. article ID 8373518, 17 pages. https://doi.org/10.1155/2017/8373518

[73] Amboya HA, King’ondo CK, Njau KN, Mrema AL. Measurement of pozzolanic activity index of scoria, pumice, and rice husk as potential supplementary cementitious materials for Portland cement. Advances in Civil Engineering. 2017. p. 15. ID 6952645, DOI: 10.1155/2017/6952645

[74] Wang KL, Chung SL, O’reilly SY, Sun SS, Shinjo R, Chen CH. Geochemical constraints for the genesis of post-collisional magmatism and the geodynamic evolution of the northern Taiwan region. Journal of Petrology. 2004;45(5):975-1011. DOI: 10.1093/petrology/egh001

[75] Depci T, Efe T, Tapan M, Ozvan A, Aclan M, Uner T. Chemical characterization of Patnos Scoria (Agri, Turkey) and its usability for production of blended cement. Physicochemical Problems of Mineral Processing. 2011;48(1):303-315

[76] Ozvan A, Tapan M, Erik O, Efe T, Depci T. Compressive strength of scoria added Portland cement. Gazi University Journal of Science. 2012;25(3):769-775
[77] Gonca Gencalioglu-Kuscu G. Geochemical characterization of a quaternary monogenetic volcano in Erciyes volcanic complex: Cora maar (central Anatolian Volcanic Province, Turkey). International Journal of Earth Science (Geol Rundsch). 2011;100:1967-1985. DOI: 10.1007/s00531-010-0620-4

[78] Perry FV, Straub KT. Geochemistry of the Lathrop Wells Volcanic Center, Los Alamos, New Mexico, UC-8021996. p. 19

[79] Al Naaymi TA. Assessment of pumice and scoria deposits in Dhamar-Rada’ volcanic field SW- Yemen, as a pozzolanic material and lightweight aggregates. International Journal of Innovative Science, Engineering & Technology. 2015;2(9):386

[80] al-Kwatli MA, Gillot PY. A New Method in Volcano-Morphology to Investigate the Tectonic Constraints on the Volcanism, Case Study of Harrat Al Sham Volcanic Field, Arabia Plate: The Interest of GIS and Relational Database, COM. Geo, June 21-23, Washington, DC, USA; 2010. p. 2010

[81] Ilani S, Harlavan Y, Tarawneh K, Rabba I, Weinberger R, Ibrahim K, Peltz S, Steinitz G. New K–Ar ages of basalts from the Harrat ash Shaam volcanic field in Jordan: Implications for the span and duration of the upper-mantle upwelling beneath the western Arabian plate. Geology. 2001;29:171-174

[82] Swamy RN. Design for durability and strength through the use of fly ash and slag in concrete. ACI Special Publication. 1987;171

[83] Mindess S, Young JF, Darwin D. Concrete. 2nd ed. USA: Prentice Hall; 2003. NY 07458

[84] ASTM C618. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. West Conshohocken, Pennsylvania, United States: American Society for Testing and Materials; 2012

[85] EN 197-1 (2000). Cement. Part 1: Composition, Specifications and Conformity Criteria for Common Cements. European Standards

[86] ACI 232.1R-12, Report on the Use of Raw or Processed Natural Pozzolans in Concrete, American Concrete Institute

[87] Lea FM, Hewlett PC, editors. Lea’s Chemistry of Cement and Concrete. 4th ed. Oxford, UK: Butterworth-Heinemann, Elsevier Ltd.; 1998

[88] Ramezanianpour AK. Cement Replacement Materials: Properties, Durability, Sustainability. Springer-Verlag Berlin Heidelberg; 2014. p. 345. DOI: 10.1007/978-3-642-36721-2

[89] al-Swaidani A, Aliyan S, Adarnaly N. Mechanical strength development of mortars containing volcanic scoria-based binders with different fineness. Engineering Science and Technology, An International Journal. 2016;19:970-979

[90] Shi C. An overview on the activation of the reactivity of natural pozzolans. Canadian Journal of Civil Engineers. 2001;28(2001):778-786
[91] Tchamdjou WHJ, Cherradi T, Abidi ML, Pereira-de-Oliveira LA. The use of volcanic scoria from Djoungo (Cameroon) as cement replacement and fine aggregate by sand substitution in mortar for masonry. European Journal of Environmental and Civil Engineering. 2017. DOI: 10.1080/19648189.2017.1364298

[92] Chen W. Hydration of Slag Cement, Ph.D. Thesis. Netherland: University of Twente; 2007

[93] ASTM C 595. Standard specification for blended hydraulic cements. West Conshohocken, Pennsylvania, United States: American Society for Testing and Materials; 2002

[94] Al-Chaar GK, Yaksic DA, Kallemeyn LA. The Use of Natural Pozzolan in Concrete as an Additive or Substitute for Cement. 2011. ERDC/CERL TR-11-46

[95] Alhozaimy A, Fares G, Alawad OA, Al-Negheimish A. Heat of hydration of concrete containing powdered scoria rock as a natural pozzolanic material. Construction and Building Materials. 2015;81:113-119. DOI: 10.1016/j.conbuildmat.2015.02.011

[96] Moufifi et al. Assessment of the industrial utilization of scoria materials in central Harrat Rahat, Saudi Arabia. Engineering Geology. 2000;57:155-162

[97] Fares G, Alhozaimy A, Alawad OA, Al-Negheimish A. Evaluation of powdered scoria rocks from various volcanic lava fields as cementitious material. Journal of Materials in Civil Engineering. 2015. DOI: 10.1061/(ASCE)MT.1943-5533.0001428

[98] Al-Swaidani. Prediction of compressive strength and some permeability-related properties of concretes containing volcanic scoria as cement replacement. Romanian Journal of Materials. 2016;46(4):505-514

[99] Al-Swaidani A, Aliyan S, Adarnaly N, Hanna B, Dyab E. Influence of volcanic scoria on mechanical strength, chemical resistance and drying shrinkage of mortars. Building Research Journal. 2014;61(3):pp. 143-150

[100] Meddah MS, Tagnit-Hamou A. Effect of mineral admixtures on shrinkage measured on massive concrete elements. In: Tanabe et al., editors. Creep, Shrinkage and Durability Mechanics of Concrete and Concrete Structures. London: Taylor & Francis Group; 2009

[101] Rao GA. Long-term drying shrinkage of mortar—Influence of silica fume and size of fine aggregate. Cement and Concrete Research. 2001;31:171-175

[102] South W. A study of the compressive strength and drying shrinkage of cementitious binders prepared using natural pozzolans, PhD Thesis. Australia: University of Wollongong; 2009

[103] Touttanji HA, Bayasi Z. Effect of curing procedures on the properties of silica fume concrete. Cement and Concrete Research. 1999;29:497-501

[104] Massazza F. Pozzolanic cements. Cement and Concrete Composites. 1993;15:185-214

[105] Marchand J, Odler I, Skalny JP. Sulfate Attack on Concrete. CRC Press; 2002
[106] Thomas M. Supplementary Cementing Materials in Concrete. Taylor & Francis Group; 2013. p. 195

[107] Irassar EF, Gonzalez MA, Rahhal V. Sulfate resistance of type V cements with limestone filler and natural pozzolan. Cement & Concrete Composites. 2000;22(5):361-368

[108] al-Amoudi OSB. Attack on plain and blended cements exposed to aggressive sulfate environments. Cement & Concrete Composites. 2002;24:304-316

[109] Attiogbe EK, Rizkalla SH. Response of concrete to sulfuric acid attack. ACI Materials Journal. 1988;85:481-488

[110] Monteny JE, Vincke A, Beeldens A, De Belie N, Taerwe L, Van Gemert D. Chemical, microbiological, and in situ test methods for biogenic sulfuric acid corrosion of concrete. Cement and Concrete Research. 2000;30:623-634

[111] Al-Dulaijan SU, Maslehuddin M, Al-Zahrani MM, Sharif AM, Shameem M, Ibrahim M. Sulfate resistance of plain and blended cements exposed to varying concentrations of sodium sulfate. Cement & Concrete Composites. 2003;25:429-437

[112] Biczok I. Concrete Corrosion and Concrete Protection, Chemical Publishing Co. Inc. New York; 1967

[113] Cao HT, Bucea I, Ray A, Yozghatlian S. The effect of cement composition and pH of environment on sulfate resistance of Portland cements and blended cements. Cement & Concrete Composites. 1997;19(2):161-171

[114] Aydın S, Yazıcı H, Yigiter H, Baradan B. Sulfuric acid resistance of high-volume fly ash concrete. Building and Environment. 2007;42:717-721

[115] Neville AM. Properties of Concrete. 5th ed. London, UK: Pearson Education; 2011

[116] Hossain KMA. Blended cement and lightweight concrete using scoria: Mix design, strength, durability and heat insulation characteristics. International Journal of Physical Sciences. 2006;1(1):005-016

[117] Ghrici M, Kenai S, Said-Mansour M, Kadr EH. Some engineering properties of concrete containing natural pozzolana and silica fume. Journal of Asian Architecture and Building Engineering. 2006;5(2):349-354
