



Review

Properties of concrete made with volcanic ash

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ARTICLE INFO

Article history:

Received 28 April 2012

Received in revised form 15 June 2012

Accepted 21 June 2012

Keywords:

Chloride permeability

Compressive strength

Concrete

Electrical resistivity

Hydration

Mortar

Porosity

Sulfate resistance

Volcanic ash

ABSTRACT

Volcanic ash (VA) is formed during volcanic eruptions, and is considered as natural pozzolan as per ASTM C618-93, a standard specification for 'Fly Ash and Raw or Calcinated Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete'. It can be suitably used in cement, mortar, and concrete.

This paper presents comprehensive details of the physical, chemical properties of volcanic ash. It also covers effect of volcanic ash the slump, compressive strength, porosity, permeability, and sulfate resistance of concrete.

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1. Introduction

Volcanic ash (VA) is formed during volcanic eruptions. Ash is generated when solid rock shatters and magma separates into very small particles during explosive volcanic activity. The plum that

is seen above an erupting volcano is composed of ash and steam. These very fine particles of ash are carried away for miles, settling out as a dust-like layer across the landscape. This is called as 'ash fall'. The term for any material explosively thrown out from a vent is tephra, also known as pyroclastic debris. Tephra particles of gravel are called cinders. The size of ash particles falling on the ground decreases with increase in distance from a volcano. The distribution of ash particle sizes can vary widely. The particle size distribution in case of Mount St. Helens 1980 (Johnston, 1997) eruptions is given in Table 1.

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Table 1
Particle size variation with distance (Johnston, 1997).

Distance from the volcano (km)	Mean particle diameter (mm)
0	4.0
54	0.10
150	0.0625
235	0.0380
414	0.0466
621	0.034

1.1. Components of volcanic ash particles

Volcanic ash consists of very small particles composed of varying proportions of: (i) volcanic glass shards; (ii) minerals or crystals; and other rock fragments (lithics).

1.1.1. Volcanic glass shards

Volcanic glass shards are the fragments of the molten part of magma that cools down and solidifies during eruption. Glass shards are remnants of tiny gas bubbles that develop and grow in size during the final ascent toward the surface. Shards formed by phreatomagmatic eruptions generally have angular shape resulting from the violent explosive interaction between magma and water. Scanning electron micrograph (SEM) of vesicular glass shard of ash (just over 0.1 mm long) erupted during in 1980 eruption of Mount St. Helens is shown in Fig. 1, whereas Fig. 2 shows the SEM image of phreatomagmatic glass shards > 0.064 mm (Cas and Wright, 1988).

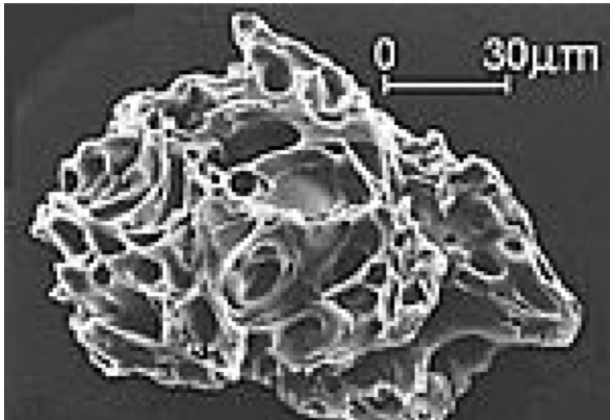


Fig. 1. Scanning electron micrograph (SEM) of a highly vesicular glass shard of ash measuring just over 0.1 mm long, erupted during 18 May 1980 eruption of Mount St. Helens (Johnston, 1997).

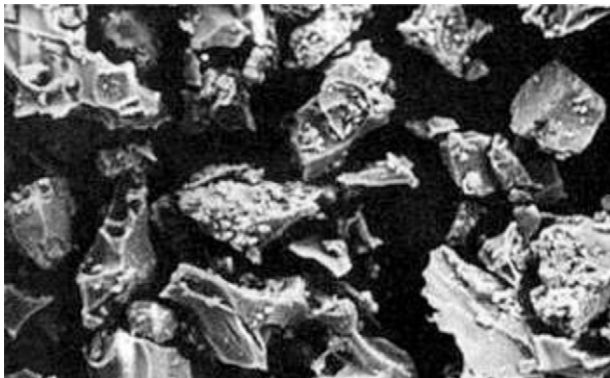


Fig. 2. SEM image of phreatomagmatic glass shards > 0.064 mm (Cas and Wright, 1988).

Table 2
Physical properties of volcanic ash (Hossain, 2003).

Physical properties	Volcanic ash
Fineness, m ² /kg	242
Bulk density, kg/m ³	2450
Residue on 75 μm sieve	42

1.1.2. Minerals or crystals

Minerals are primarily derived from the magma. These minerals crystallized and grew within the magma while it was below the earth's surface. The type of minerals within an ash deposit depends upon the chemistry of the magma.

1.1.3. Lithics

These non-magmatic rock fragments are found in varying abundances within ash deposits and often have a shape and texture distinctly different than glass shards.

2. Properties of volcanic ash

ASTM C618-93, a standard specification for 'Fly Ash and Raw or Calcinated Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete' can be used to evaluate the physical and chemical properties of a volcanic ash.

2.1. Physical properties

2.1.1. Density

Shiple and Sarna-Wojcicki (1982) have reported that density of particles vary between 700 and 1200 kg/m³ for pumice, 2350–2450 kg/m³ for glass shards, 2700–3300 kg/m³ for crystals, and 2600–3200 kg/m³ for lithic particles. Physical properties of volcanic ash reported by Hossain (2003) are given in Table 2.

2.2. Chemical composition

Chemical composition of volcanic ash depends upon the chemistry of the source magma. Volcanic glass is rich in silica compared to mineral crystals, but relatively low in non-silica elements. Hossain (2003) have reported the chemical composition of volcanic ash (Table 3).

Hossain (2005a) reported the XRD analysis of Portland cement (PC) and blended cements with 20% volcanic ash (VA) and 20% volcanic pumice powder (VPP) as cement replacement. The fineness of VA and VPP were 285 and 298 m²/kg, respectively. The phase composition of these materials is presented in Table 4.

3. Applications of volcanic ash

Applications of volcanic ash are based on its particle size, angularity of particles, friability, light color, and chemical properties. It could be used in the following ways.

Table 3
Chemical properties of volcanic ash (Hossain, 2003).

Chemical compounds	Amount (%)
Silica (SiO ₂)	59.32
Alumina (Al ₂ O ₃)	17.5
Iron oxide (Fe ₂ O ₃)	7.06
Calcium oxide (CaO)	6.10
Sodium oxide (Na ₂ O)	3.80
Magnesia (MgO)	2.55
Potassium oxide (K ₂ O)	2.03
Sulfur trioxide (SO ₃)	0.71
Loss on ignition	1.0

Table 4
Potential phase composition of the cementing materials from X-ray diffraction (Hossain, 2005a).

Phase	PC (%)	PVAC (PC blended with 20% VA) (%)	PVPC (PC blended with 20% VPP) (%)
C ₃ S	68.1	46.3	46.8
C ₂ S	14.1	9.5	9.6
C ₃ A	5.9	5.1	5.3
C ₄ AF	9.2	6.4	6.4
Other	2.4	5.2	5.1
Total	99.7	72.5	73.2

- In ceramics.
- As abrasive.
- In light weight aggregates, cellular blocks, and concrete.
- In glass and vitreous enamels.

4. Influence of volcanic ash on the properties of concrete

4.1. Compressive strength

Hossain and Lachemi (2004) reported the results of residual compressive strength of concretes made with 0 to 40% of volcanic ash (VA) as cement replacement by mass, subjected to high temperatures up to 800 °C. Chemical composition of volcanic ash was calcium oxide (6.1%), silica (59.3%), alumina (17.5%), iron oxide (7%), sulfur trioxide (0.7%), magnesia (2.6%), sodium oxide (3.8%), LOI (1%), and its fineness was 285 m²/kg. Initial tests for air content, slump and 28-day compressive strength were conducted and the results are given in Table 5. Residual compressive strength results of volcanic ash concrete (VAC) are shown in Fig. 3. It was observed that (i) from 25 to 200 °C, the VAC with 20–40% VA showed an increase in strength. The strength gain was probably due to the formation of tobermorite, which was formed by reaction between unhydrated VA particle and lime at high temperature (Nasser and Marzouk, 1979). The strength of control OPC however was reduced by 14%. No visible cracking or spalling was absorbed at this temperature range; (ii) from 200 to 400 °C, a significant decrease in strength (19–33%) was observed in VAC. This reduction was due to the pore structure coarsening in such concretes (Chan et al., 1996); (iii) severe loss (59–73%) in strength was observed in 400–600 °C temperature range. The VAC performed better and showed no cracking except hairline cracks. The better performance of VAC in temperature was due to reduced amount of Ca(OH)₂, which otherwise resulted in strength loss and disintegration; (iv) at 800 °C, all the concretes showed severe deterioration due to the decomposition of C–S–H

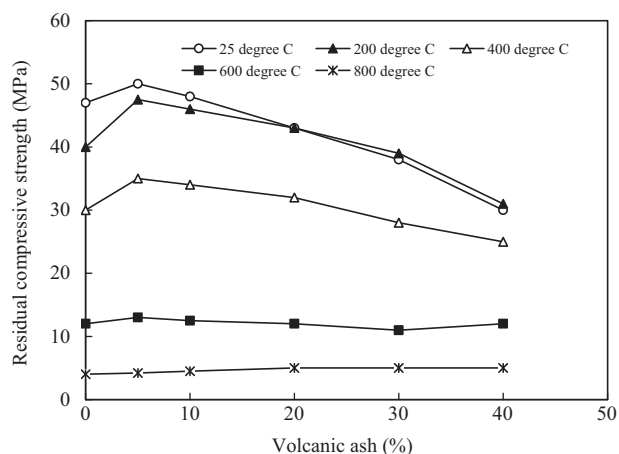


Fig. 3. Residual compressive strength as function of volcanic ash for different temperature levels (Hossain and Lachemi, 2004).

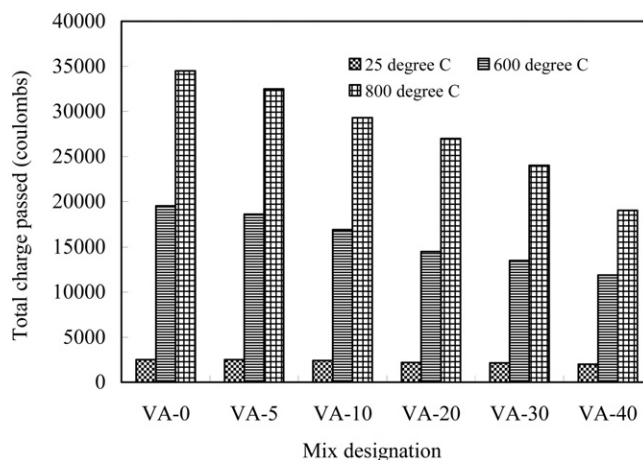


Fig. 4. Effect of high temperature on chloride-ion resistance of volcanic ash concretes (Hossain and Lachemi, 2004).

gel (Lin et al., 1996); and (iv) generally, strength loss decreased with the increase of VA content when the temperature was varied from 200 to 800 °C. This was an indication of better performance of VAC in retaining the strength at evaluated temperature as compared to control OPC concrete. The deterioration of strength at evaluated temperature for such concretes were due to the coarsening of pore structure and increase in pore diameter. The beneficial effect of pozzolanic VA was more pronounced at temperatures below 600 °C. Spalling was observed in 10% of controlled OPC concrete specimens while VAC only showed visible network of fine structure cracks.

Hossain (2005b) investigated concretes made with different plain (ASTM I, II, and V) and blended cements incorporating different percentages of volcanic ash (VA) up to 30% as cement replacement. Concretes were exposed to marine environment for a period of 1 year. Tests were conducted for compressive strength under three different curing conditions; ordinary water ordinary water (OWOW), sea water sea water (SWSW), and ordinary water sea water (OWSW). He concluded that (i) compressive strength of concrete decreased in a marine environment and the strength loss increased with the age of exposure; (ii) use of Types I and II blended cements with VA (between 10 and 20%) increased concrete resistance against seawater attack; (iii) use of VA in combination with Portland cements with very low C₃A content such as ASTM Type V, did not result in a level of resistance equal to or greater than that of Types I or II Portland cements in marine environments; (iv) pre-casting is beneficial in marine environments in all three types of plain and blended cements; (v) the blending of VA in Type I cement was observed to be more beneficial than the blending in Types II or V cements against marine environments in both simulated precast and cast in situ situations.

4.2. Chloride permeability and porosity

Hossain and Lachemi (2004) reported the chloride-ion resistance (permeability) and porosity of concretes made with 0–40% of volcanic ash (VA) as cement replacement. Chloride permeability tests were conducted as per ASTM C1202 (1997) whereas porosity was measured by using MIP on specimens subjected to 25 °C, 600 °C, and 800 °C temperatures. Chloride-ion resistance and porosity results of volcanic ash concrete (VAC) are shown in Figs. 4 and 5, respectively. Based on the results, they reported (i) a clear relationship between the residual compressive strength and concrete permeability, as more permeable specimens showed more pronounced loss of compressive strength. As the temperature was increased, a severe loss in impermeability was observed, possibly due to loss ranged from 500 to 2000%. The ASTM C1202 (1997)

Table 5
Mixture details of volcanic ash concrete (Hossain and Lachemi, 2004).

Mixture ID	VA (%)	w/b	Cement (kg/m ³)	Aggregates (kg/m ³)		Air content (%)	Slump (mm)	28-Day compressive strength (MPa)
				FA	CA			
VA-0	0	0.45	400	760	1020	2.5	80	41.4
VA-05	5	0.45	380	755	1020	2.5	80	42.9
VA-10	10	0.45	360	751	1020	2.6	90	40.8
VA-20	20	0.45	320	743	1019	2.8	110	35.2
VA-30	30	0.45	280	734	1019	2.9	86	30.7
VA-40	40	0.45	240	725	1018	3.1	85	25.2

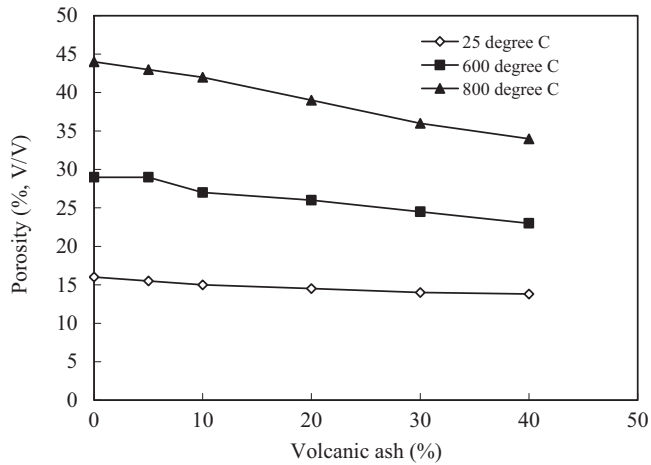


Fig. 5. Porosity of volcanic ash concrete as function of volcanic ash content for different temperature levels (Hossain and Lachemi, 2004).

specifies the concrete as highly permeable if the charge that passes through it is more than 4000 Coulombs. Because all the specimens showed values higher than 4000 Coulombs after fire, such concretes can be considered as no durable depending upon the situation, even if they retain a higher proportion of their compressive strength; and (ii) MIP test results clearly indicated an increase in porosity with the increase in temperature. This effect can be related to the coarsening of pore structure possibly due to micro cracks formed due high temperature (Chan et al., 1996) and was responsible for the strength and permeability loss. A significant decrease in porosity was observed in VAC by the addition of pozzolanic VA as compared with the control OPC concrete even at elevated temperatures.

Hossain (2005b) studied the porosity of concrete mixtures made with different plain (ASTM I, II, and V) and blended cements incorporating different percentages of volcanic ash (VA) up to 30% as cement replacement. The specimens were exposed to marine environment for a period of 1 year. Tests were conducted for porosity and rapid chloride permeability under three different curing

conditions. Curing conditions were; ordinary water ordinary water (OWOW), sea water sea water (SWSW), and ordinary water sea water (OWSW). Based upon the experimental study, he concluded that blending Type I cements with 20% VA produced the best performance showing lower porosity and higher chloride ion resistance under both OWOW (precast) and SWSW (cast in situ) situations. This indicated that a Type I blended VA cement is a potential choice for the construction of marine structures. In view of the high chloride combining capacity of high C₃A Type I cement; and (vii) the use of precasting in place of casting in situ will further increase the resistance of concrete against marine environments.

Hossain and Lachemi (2006) evaluated the performance of volcanic ash (VA) and finely ground volcanic pumice (VP) based ASTM Type I and Type V (low C₃A) blended cement concrete mixtures. 0 and 20% VA or VP were used in blended cement for preparing concrete mixtures with two (0.35 and 0.45) water-to-binder ratio. Tests were conducted for density, compressive strength and rapid chloride permeability, and porosity. Table 6 summaries strength and density (at 28 days) of concrete mixtures as well as test results of RCP and, MIP tests conducted at 56 day. They concluded that (i) 28-day density of concrete mixtures varied between 2360 and 2410 kg/m³; (ii) Type I/V VA/VP based blended concrete showed lower strength, higher chloride ion resistance and lower porosity/average pore diameter than Type I/V plain concrete: this can be attributed to the fact that the strength gain of VA/VP based pozzolanic concrete is not merely related to lowering of porosity, (iii) concrete mixtures with higher W/B showed lower strength, lower chloride ion resistance and higher porosity/average pore diameter and (iv) use of type V cements showed slightly better chloride ion resistance and lower porosity with no visible strength gain compared to Type I and (iv) VP based concrete showed lower chloride ion resistance and higher porosity compared with VA based concrete with no significant 28-day strength difference.

4.3. Sulfate resistance

Hossain and Lachemi (2006) compared the performance of volcanic ash (VA) and finely ground volcanic pumice (VP) based ASTM

Table 6
Strength, durability and micro-structural properties of concrete (Hossain and Lachemi, 2006).

Mixtures	28-Day density (kg/m ³)	28-Day compressive strength (MPa)	RCPT (C) at 56 days	Porosity (%)	Average pore diameter (μm)
W/B = 0.45					
Type I	2401	38	2850	16.46	0.0464
Type V	2403	37	2805	16.39	0.0461
20VA-I	2384	32	2210	14.95	0.0435
20VP-I	2380	31	2186	14.89	0.0428
20VA-V	2365	31	2321	15.40	0.0444
20VP-V	2360	30	2316	15.35	0.0438
W/B = 0.35					
Type I	2410	49	2350	15.10	0.0432
Type V	2408	48	2306	15.03	0.0427
20VA-I	2401	41	1920	13.20	0.0402
20VP-I	2398	40	1905	13.11	0.0395
20VA-V	2372	42	1985	13.60	0.0413
20VP-V	2370	41	1966	13.51	0.0403

Table 7
Weight loss, corrosion potential and polarization resistance after 48 months of exposure (Hossain and Lachemi, 2006).

Mixtures	Concrete weight loss (%)	Corrosion potential, SCE (mV)	Polarization resistance ($k\Omega\text{ cm}^2$)	Corrosion initiation (months)
W/B=0.45				
Type I	1.34	-434	51	44
Type V	1.51	-372	69	44
20VA-I	15.4	-749	22	44
20VP-I	14.6	-704	22	44
20VA-V	11.1	-738	8	44
20VP-V	10.9	-701	8	44
W/B=0.35				
Type I	5.7	-245	630	No corrosion
Type V	3.3	-203	347	No corrosion
20VA-I	11.6	-784	25	44
20VP-I	11.0	-753	26	44
20VA-V	7.7	-736	40	44
20VP-V	7.5	-707	41	44

Type I and Type V (low C_3A) blended cement concrete mixtures. 0 and 20% VA or VP were used in blended cement for preparing concrete mixtures with two (0.35 and 0.45) water-to-binder ratio. Concrete mixtures were immersed in magnesium-sulfate solution for period up to 48 months. They determined weight loss and corrosion resistance. Results are given in Table 7. They concluded that (i) Type I/V VA/VP based blended cement concrete specimens showed higher and faster rate of deterioration than those of Type I/V plain cement concrete specimens. The higher deterioration in Type I and Type V VA/VP based blended cement concretes in sulfate environment compared to Type I and Type V plain Portland cement concretes can be attributed to the presence of Mg^{2+} cations associated with $MgSO_4$. The consumption of portlandite ($Ca(OH)_2$) by the pozzolanic reaction in VA and VP blended cements causes Mg^{2+} cations to react directly with the calcium silicate hydrate (C-S-H) gel converting it to cohesion less, porous, reticulated magnesium silicate hydrate (M-S-H) gel; (ii) use of Type V cements reduced the deterioration of VA/VP based concrete specimens compared with those of Type I possibly due to lower C_3A content. However, Type I/V VA/VP based blended cement concrete specimens exhibited weight loss which were more than the 2.5% failure criterion; (iii) Type I/V VA/VP based blended cement concretes showed inferior performance compared with Type I/V plain cement concretes in terms of corrosion resistance. This could be attributed to the advance stage of deteriorations (in Type I/V VA/VP based blended concretes) at this period whereby a weight loss that ranged between 7.47% and 15.4% which is higher than 2.5%, was observed. High degree of deterioration in blended cement concrete mixtures could not preserve the integrity of the internal structure and enabled the SO_4 ions to diffuse to the steel, leading to corrosion of reinforcing steel; (iv) on the contrary, the specimens made with plain Type I/V cements exhibited better resistance to sulfate attack, especially specimens with W/B of 0.35 where reinforcing steels were not found to be in active state of corrosion (polarization resistance $N87\text{ k}\Omega\text{ cm}^2$) after 48 months of exposure. This might be attributed to the mechanism of $MgSO_4$ attack as well as to the diffusion of SO_4 ions; and (v) Initial polarization resistance on steel in various concrete mixtures was very high (ranging between 5200 and 6400 $k\Omega\text{ cm}^2$ for concrete mixtures with w/b 0.45; between 3600 and 5600 $k\Omega\text{ cm}^2$ for concrete mixtures with w/b 0.35). The polarization resistance decreased significantly (rate of decrease seems to be higher in Series A with W/B of

0.45 compared to Series B with W/B of 0.35) in an immersion period of 48 months.

5. Conclusions

Volcanic ash satisfies the requirements of ASTM C618 for pozzolanic materials. It has physical and chemical properties which clearly indicate that it could be suitable used as partial replacement of cement, paste and mortar. Published literature on the effect of volcanic ash indicates. Therefore, it can also be used in blended cement and concrete manufacturing.

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