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Durability performance evaluation of green geopolymer concrete

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ABSTRACT

The present manuscript is a state-of-the-art review, which examines the most recent stages in the developments of the class of eco-efficient green geopolymer concrete technology in the light of its history of research, more specifically, focusing on its unsettled durability criterion. The objective of this article is not merely to review it's on hand literature but also to focus on durability attribute on establishing it as a perspective cost-effective and sustainable universal building material. According to some researchers, durability related characteristics of GPC such as alkali-silica reaction; resistances to acid attack, Sulphate attack, freeze-thaw conditions, corrosion; water absorption, permeability, porosity, sorptivity, Chloride penetration, Chloride migration test techniques, Carbonation, drying shrinkage and efflorescence necessitate more elucidations to prove its capability as durable edifice material. The suggestions mentioned in this article will be helpful for future research work on long-drawn-out durability. Although a little challenge viz., curing hurdles, practical confronts of utilization at times, restricted supply chain, and a call for vigilant command of mixture design for its manufacturing, are standing in its pathway for a quid pro quo replacement of OPC-concrete from the construction industries. Ultimately, the paper identifies research challenges, promotion and relevant discussions for this promising novel type of building material.

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Waste; green house gas; environmental pollution; environment; affordable; durability; geopolymer concrete

1. Introduction

An overshoot of the human population and revolutionary development of industries have piloted to a gigantic exigency for residential and infrastructures. Therefore, more and more construction and infrastructural developments are essential for accommodation. This, in turn, had resulted in the titanic demand for concrete – an essential construction material with vast usage since Romans. Consequently, the essential ingredients for concrete manufacturing viz., OPC as a binder along with fine and coarse natural materials are needed. The existing process of production of OPC necessitates Limestone as raw material along with natural coals for achieving higher energy at high temperatures by setting them on fire. This blame-worthy process does not merely devour natural ingredients but, unfortunately, also emits primary gas CO₂ embodied with Limestone during its calcination at elevated temperatures. Some of the built-up OPC-concrete structures over the last few decades are found disintegrated (Luhar et al., 2018b). Production of a one-ton quantity of OPC emits an almost equal amount of CO₂ into the atmosphere (Luhar et al., 2016). This is a threat to environments and a boost to the dilemma of global warming. Consequently, humanity

waits keenly for the emergence of a new-fangled binder which will expectantly substitute the customary OPC not only to favour sustainable environments but also provide a guarantee for durable concrete structures. To deal with this, quite an alarming situation researchers are attracted towards the sustainable alternative construction material free from OPC through employing a range of pozzolanic [supplementary materials](#) viz., meta-kaolin, Fly ashes, Slag, Silica fumes, etc. The diverse types of wastes and by-products etc. can also be utilized to serve the purpose. Looking to the natural fine and course ingredients, they are found to be quarried in a haphazard manner owing to the lack of stringent regulations (Luhar et al., 2018a; Luhar et al., 2019a, 2019b, Luhar, Cheng et al., 2019a, 2019b; Luhar and Gourav, 2018). Therefore, their conservation is badly needed to protect them from degradation. By global footprint network, 'currently, mankind is using the equal to 1.5 planets to furnish the sources we are utilizing and consume our wastes'. Environmentalist, Jeremy Rifkin accounted that 'the mushrooming population and metropolitan way of life have bought at the cost of immense eco-systems and habitations'. Hence, on the one hand, the reduction in the use of natural aggregates is highly desirable while, on the other hand, various wastes and some other discarded materials are easily accessible from their landfills to apply them as a replacing material for either OPC or natural fine and/or course ingredients or at times both, in manufacturing a range of green concretes. These heaps of superfluous wastes materials are not merely useful as a [supplementary material](#) to incorporate with concrete but also lend a hand to resolve the predicaments of their disposal too. Moreover, their presence in green concrete has not at all impacted the original significant attributes of concrete within certain fix boundaries proved by investigational studies. On account of these competencies of these wastes, researchers of these days have attracted to apply it more and more in concrete technology. Nowadays, innovative concrete expertise coined as 'geopolymer concrete technology' is very interestingly under investigational studies by researchers. This means construction with required sustainability is possible in the absence of OPC! This concept of construction sans OPC was a dream of past but a reality of today! When the wide range of Alumino-silicates, i.e. precursors, undergo the process of alkali activation popularly known as 'Geopolymerization' – a complex type of chemical reaction kinetics, the production of Geopolymers are taking place by the dissolution of source materials, orientation or moving and subsequent poly-condensation at low temperatures and energy. This formation of geopolymer concrete is analogous to the rock-forming process of geo-synthesis. Furthermore, according to Davidovits et al. (1990), emission of CO₂ during the process of formation of geopolymers is just 0.184 ton (i.e. nine-time less than OPC) per 1-ton production of Geopolymeric cement. That means, nine times more GPC can be produced for the sake of the same emissions than OPC. Weil et al. (2009) have revealed that NaOH and Na₂SiO₃ are answerable for the bulk CO₂ emissions during Geopolymerization. They are very versatile and exhibits excellent attributes of strength and durability. The environmental friendly impact and outstanding characteristics, such as early high strength, resistance to acid, alkali freeze-thaw have motivated researchers to develop these kinds of construction materials in the past too (Juenger et al., 2011; Puertas et al., 2000; Palomo et al., 1999; Singh et al., 2015). The precursors vary regarding accessibility, reactivity and market value globally. Mostly used precursors are Granulated blast furnace slag (Rodríguez et al., 2008), fly ash (Zhu et al., 2014) and metakaolin (Mobili et al., 2016) while the activators such as caustic alkali, silicate, carbonate and Sulphate, etc. are predominant. Geopolymeric materials are generally classified as high calcium system that is dominated by calcium-alumina silicate-hydrate (C-A-S-H) gels having a structure similar to Tobermorite, eg. Slag based Geopolymeric materials and the other is low calcium system, where alkali aluminosilicate (N-A-S-H) gels having Pseudo structures analogous to Zeolites are found as the chief products, e.g. Fly ash-based Geopolymeric materials. Both, the kinds of gel systems could co-exist as a one blended system of C-A-S-H and N-A-S-H gels (Ismail et al., 2014; Yip et al., 2005). Geopolymer concrete has demonstrated acceptable outcomes in building structures, road paving and waste solidification. Still, the concerns exist for its widespread applications concerning, costing of raw materials (McLellan et al., 2011) and unsolved durability attribute (San Nicolas et al., 2014). Moreover, there is a little systematic or prognostic data concerning techniques or heuristic processes through which activator can be match-best possibly to the precursor. At present, this is obtained mostly by testing parameters which still need to be improved. Though their application is best suited to prefabricated concrete structures but can be employed for in situ constructions or in other circumstances whereby alkaline activators can be aptly handled, and cautious control for curing is feasible. So far, research studies (Pacheco-Torgal et al., 2008a, 2008b; Li et al., 2010) carried out in context to their developments had displayed that eco-friendly alternative to OPC is emerging in the form of Geopolymer cement. Pacheco-Torgal et al. (2009, 2008c, 2008d, 2008e) have demonstrated that Geopolymer mortar

can be accessible with seven times less cost than OPC repair mortar that establishes it as a feasible option of OPC. On the other hand, Juenger et al. (2011) believe that durability is the main unsolved question in their application and development. Similarly, Van Deventer has also accounted for the durability issue as the chief obstruction to its acceptance for structural constructions.

2. Durability of green GP-concrete (GGPC)

The durability of green geopolymer concrete is the most critical attribute that assesses its life circle. An exposure of GGPC to outer milieu is one of the significant features that specify its durability. The researchers of the universe are still unable to take a unanimous decision on the durability attribute of Geopolymer edifice materials. Hence, in this critical review of the durability of GGPC, its most significant durability parameters viz., alkali-silica reaction; resistances to acid attack, Sulphate attack, freeze-thaw conditions, and corrosion of steel reinforcement; along with, water absorption, permeability, porosity, sorptivity, Chloride penetration, Chloride migration test techniques, Carbonation, drying shrinkage and efflorescence have been accounted in detail to comprehend these vital issues. The characteristics of lesser absorption of water, lower permeability and low down porosity; better resistance to corrosion, alkali-silica reaction, sulphate attack, acid attack, chloride attack, and vigorous environmental attack are prerequisites to produce a highly dense microstructure concrete. Thomas et al. (2012) accounted that amalgamation of pozzolans is advantageous as it has proved to be capable enough to withstand degradation in antagonistic environmental circumstances and also enhancing the durability. Nevertheless, there exist hullabaloo concerning permeability and water absorption properties of Geopolymer construction materials (GPCMs). On the one hand, Mithun and Narasimhan (2016) argued that the water permeability of Na_2SiO_3 -activated slag-GGPC was inferior to that of OPC-concrete while on the other hand, Bernal et al. (2010) have claimed that both the permeability and water absorption of the same, i.e. Na_2SiO_3 -activated slag-GGPC were superior to OPC-concrete! Furthermore, Albitar et al. (2017) revealed that fly ash and slag based GGPC-concrete have a higher rate of both water absorption and sorptivity than OPC-concrete. Even though the equivalent grade of strength is employed, a comparison between GPCMs and OPC-construction materials devoid of a standard mix specification of manufacturing may escort to perplexities. The kind of activators and precursors along with the age of specimen and techniques of the test and so many other criteria may influence permeability and water absorption of GGCMs (Ismail et al., 2013). Though the durability of both the types of materials can be influenced by their permeability of the matrix and water absorption, their mechanisms of wear and tear are dissimilar. For instance, in carbonation, products of the reaction of GPCMs may get reacted with the dissolved CO_2 of pore solution could resulting not only in a decrease of pH of a solution of pore but also enhancing the jeopardy of corrosion of steel reinforcement owing to depassivation. It was made known that the rate of natural carbonation of GGPC is a little faster than OPC-concrete (Bakharev et al., 2001b; Byfors et al., 1989). This is answerable for the imperfect representation of natural carbonation attitude of GCMs through the accelerated carbonation tests used for OPC (Bernal et al., 2012, 2013, 2015a, 2014b). The rebar corrosion is caused by chiefly due to Chloride ingress (Della et al., 2000; Elfmarkova et al., 2015; Neville, 1995). When reinforced concrete is exposed to the oceanic milieu, they are vulnerable to chloride attack which normally less damage the matrix of concrete but corrode away steel reinforcement through the process of depassivation resulting in diminution of the bearing competence of structure. In general, GPCMs possess low chloride diffusion coefficient than OPC (Adam, 2009; Mithun & Narasimhan, 2016) and exhibit healthier resistance to chloride (Fernandez-Jimenez et al., 2007), on account of peculiar their chemistry (Della et al., 2000) and structures of the pore (Bondar et al., 2012) resulting in a belief to consider rapid chloride penetration test (RCPT) for chloride migration utilized for OPC as incongruous for GPCMs. This is because of unlike chemistry of pore solution. Hence, in such a situation, Non-steady state migration (NSSM) of chloride test appears to be more steadfast (Vance et al., 2014) provided further verifications favours it. Also, Sulphate attack is an imperative issue that degrades structures of concrete. Sulphates exist in brine, soil, and groundwater as well as found as salt crystals that can react with Hydroxides and aluminates of Calcium of OPC (Aye & Oguchi, 2011; Manu et al., 2003) resulting in a boost of the volume of concrete and owing to the formation of Gypsum and Ettringite. Consequently, the strength of and stability of OPC structures may be affected, adversely creating solemn predicaments. While on the other side, in the case of GPCMs the mechanism of sulphate attack is quite dissimilar owing to the complete absence of $\text{Ca}(\text{OH})_2$ and presence of low Calcium or Silicon of C-(N)-A-S-H. The resistance to sulphate attack by GPCMs depends on kind of cations, concentration and gel chemistry (Bakharev,

2005; Bakharev et al., 2002; Mithun & Narasimhan, 2016; Pan et al., 2003). Malviya and Goliya (2014) have observed that the GGPC concrete manufactured by Geopolymerization of NaOH and Na₂SiO₃ have not only demonstrated enhanced resistance to acid and Sulphate attack but also exhibited higher durability and superior corrosion resistance as compared to OPC-concrete (Bastidas et al., 2008; Olivia & Nikraz 2011). According to Thokchom et al. (2009), the low alkali-containing specimens displayed much greater values of porosity, absorption, and sorptivity of water. Regrettably, higher sodium and silica-containing FA based Geopolymer mixtures have represented a higher drying shrinkage. The length change rate of FA and slag based Geopolymer composite was enhancing with the increase in age and liquid to binder ratio as examined by Chi et al. (2015). Rashad (2013) have found a boosting tendency of drying shrinkage on adding up more quantity of slag in the mix. Adam (2009) have reported that FA based GGPC demonstrated better results as far as the sorptivity and chloride penetration tests are concerned as compared to all the three, i.e. OPC-concrete, the composite blended concrete of slag and OPC as well as Slag based GGPC. Also, the author worked on Fly ash based GGPC and found higher conductivity values with higher charge passed in examinations of accelerated chloride diffusion and met with a low sorptivity as well as chloride permeability with boosting the quantity of meta-kaolin and activator's concentration. Looking to the other side of a coin, a lessening tendency had been monitored for permeability and compressive strength in the testing of accelerated carbonation. Kim et al. (2014) has accounted for rice husk ash utilized with Sodium hydroxide and Sodium Silicate and has considered it as a potentially great substitute material for OPC. No doubt, the obstacles to establish the durability of GPCMs are debatable issues, but the smokescreen will covert to shining one subsequent to its promotion and fruitful outcomes of future meaningful researches. Table 1 demonstrates some recent researches on the durability properties of alkali-activated, i.e. green geopolymer concrete.

3. Alkali-silica reaction (ASR)

The alkali silica reaction (ASR), cancer in concrete, can be defined as a type of protuberance reaction, which is found to crop up over a while in the concrete, among extremely alkaline paste of cement and the amorphous reactive Silica sourced from ingredients, in the presence of adequate dampness. However, the ASR has been extensively studied in context to OPC binders, but the likelihood of it in Geopolymeric binders is an unidentified topic. The reporting of ASR for the first time is done by Stanton (1940) who called for the action of three substances simultaneously to produce: (i) an adequate amount of non-crystalline, i.e. amorphous silica, (ii) water and, (iii) alkaline ions having basic nature. The reactive silica comes from ingredients suffers attack through alkaline ions of cement shaping a soluble and viscously gyroscopic gel of Sodium Silicate Hydrate (N-S-H), that exert a pull on water and begins to swell resulting in a spreading out of the modified ingredient. Ultimately, the swelling of gel and boost in the volume due to absorption of water, mount a pressure roughly around 4MPa on the inner side of Siliceous ingredient answerable for spalling and strength decrease of concrete which at last pilots to its breakdown. This is because the in-house tensions are more significant than the tensile strength of OPC-concrete, escorting to cracking. These grave cracks development directs to crucial structural predicaments that may compel for its devastation. Hence, the consequences of ASR can be considered as a shortcoming of OPC-concrete.

Nevertheless, a belief is also prevailing regarding ASR that merely alkaline ions and amorphous silica along with water are not sufficient enough for taking the place of reaction but the presence of Ca⁺² ions is also equally essential. Some spreading outperformance of Geopolymer binders is lesser than OPC binders as reported by other researchers (Fernandez-Jimenez & Puertas, 2002).

On the other hand, Puertas et al. (2009) has opined that ASR could take place for slag based Geopolymer binders incorporating reactive opala ingredients. While Bakharev et al. (2001a) have matched up the spreading out of OPC and Geopolymer binders and revealed that OPC had greater expansion. This is also evident from the microstructure analysis represented in Figures 1 and 2. García-Lodeiro et al. (2007) displayed that fly ash-based Geopolymers are fewer vulnerable to cause expansion through ASR than OPC.

Further, they also demonstrated that the role of Calcium is vital in spreading out the behaviour of the gels. Recent research works have revealed that siliceous ingredients are more susceptible to ASR than Calcareous ingredients in Geopolymer mixes. Hence, the pathway for more researches about ASR, in Geopolymer binders is not deserted as it can be used minimum for the combinations having Calcium.

Table 1. Recent researches on the durability properties of green geopolymer concrete.

Durability properties	Aluminosilicate	Alkaline activator	Reference
Abrasion resistance	FA	NaOH and Na ₂ SiO ₃	Ramujee and Potharaju (2014)
Sulfate resistance	FA, GGF, GLP	NaOH and Na ₂ SiO ₃	Rashidian-Dezfouli and Rangaraju (2017)
Rapid chloride migration test, rapid chloride permeability, and drying shrinkage	NP, GGBS	NaOH and Na ₂ SiO ₃	Najimi et al. (2018)
Carbonation Resistance	GGBS	NaOH and Na ₂ SiO ₃	Behfarnia and Rostami (2017)
Drying shrinkage, acid attack, water sorptivity	FA and MK	NaOH and Na ₂ SiO ₃	Duan et al. (2015)
Chloride diffusivity	GF and GGBS	NaOH, KOH and Na ₂ SiO ₃	Babaee and Castel (2018)
Chloride-induced corrosion	FA, GGBS and HPA	NaOH and Na ₂ SiO ₃	Babaee and Castel (2016)
Chloride permeability	FA, GGBS	NaOH and Na ₂ SiO ₃	Thomas et al. (2018)
Leaching behaviour	MT	NaOH and Na ₂ SiO ₃	Ahmari and Zhang (2013)
Heating and freezing	CF	NaOH and Na ₂ SiO ₃	Topçu et al. (2014)
Water absorption, abrasion resistance, resistance to chemical attack, the effect of alternate wetting and drying and resistance against chloride ions	FA	NaOH and Na ₂ SiO ₃	Ganesan et al. (2015)
Water absorption, sorptivity, and porosity, sulfate attack, acid attack, heating and freezing	FA, GLSS	NaOH and Na ₂ SiO ₃	Albitar et al. (2017)
Sulfate attack, acid attack	JHK, JSS	NaOH and Na ₂ SiO ₃	Slaty et al. (2015)
Chloride penetration	FA, GGBS	NaOH and Na ₂ SiO ₃	Zhu et al. (2014)
Carbonation, chloride and sulphate ingress	FA	NaOH and Na ₂ SiO ₃	Pasupathy et al. (2017)
Acid resistance	RM, FA	NaOH and Na ₂ SiO ₃	Zhang et al. (2016)
Corrosion performance	FA, GGBS	NaOH, KOH and Na ₂ SiO ₃	Pasupathy et al. (2016)
Sulfate and chloride attack	MK, WS, TR, SBF	NaOH and Na ₂ SiO ₃	Ren et al. (2017)
Acid, sulfate and chloride attack	FA, GGBS	NaOH and Na ₂ SiO ₃	Karthik et al. (2017)
Water absorption, sorptivity	FA	NaOH and Na ₂ SiO ₃	Mermerdaş et al. (2017)
Carbonation	GGBS	NaOH and Na ₂ SiO ₃	Shi et al. (2018)
Rapid chloride ion penetration test	FA	NaOH and Na ₂ SiO ₃	Adak et al. (2014)
Sulfate attack, acid attack, salt attack	FA, silica	NaOH and Na ₂ SiO ₃	Çevik et al. (2018)
Drying shrinkage, rapid chloride penetration, sulfate attack resistance	GGBS	NaOH and Na ₂ SiO ₃	Chi (2012)
Porosity, drying shrinkage, resistances to freezing-thawing cycles, wet-dry cycles, abrasion, sulphuric acid and sulphate attack	POFA, FA, GGBS	NaOH and Na ₂ SiO ₃	Huseien et al. (2018)
Acid resistance	FA, VM	NaOH and Na ₂ SiO ₃	Wiyono and Hardjito, (2015)
Acid resistance	FA, GGBS, HGMW, QP	NaOH and Na ₂ SiO ₃	Zhang et al. (2018)
Sorptivity, chloride diffusion, sulphate resistance	GGBS	NaOH and Na ₂ SiO ₃	Parthiban and Mohan, (2017)
Water absorption, water permeability, air permeability, chloride ingress	FA	NaOH and Na ₂ SiO ₃	Gunasekara et al. (2016)
Sulfate attack	FA, GGBS, SF	NaOH and Na ₂ SiO ₃	Elyamany et al. (2018)
Chloride resistance, pull-off	GGBS, SF, NS	NaOH, KOH and Na ₂ SiO ₃	Ramezaniannpour and Moeini (2018)
Acid resistance, chloride resistance, sulfate resistance	GGBS, SBA	NaOH, KOH and Na ₂ SiO ₃	Pereira et al. (2015)
Sorptivity	FA	NaOH and Na ₂ SiO ₃	Shaikh (2016)
Wet-dry cycle, acid resistance	VA	NaOH and Na ₂ SiO ₃	Djobo et al. (2016)
Drying shrinkage	FA	NaOH and Na ₂ SiO ₃	Punurai et al. (2018)
Water absorption, sorptivity	POFA, GGBS, MK	NaOH and Na ₂ SiO ₃	Kabir et al. (2017)
Sulfate and chloride resistance	GGBS	NaOH and Na ₂ SiO ₃	Heikal et al. (2014)
Sulfate resistance	GGBS	NaOH and Na ₂ SiO ₃	El-Didamony et al. (2012)
Chloride and acid resistance	FA, MK	KOH and K ₂ SiO ₃	Zhuang et al. (2017)
Acid and sulfate resistance	FA, CCR	NaOH and Na ₂ SiO ₃	Hanjitsuwan et al. (2018)
Sulfate attack and shrinkage	LFS	NaOH and Na ₂ SiO ₃	Wang et al. (2016)
Sulfate and acid resistance	lithomarge	NaOH and Na ₂ SiO ₃	Kwasny et al. (2018)
Sulfate resistance	FS	NaOH and Na ₂ SiO ₃	Karakoç et al. (2016)
Acid resistance	FA	NaOH and Na ₂ SiO ₃	Mehta and Siddique (2017b)
Chloride permeability and sorptivity	RHA, GGBS	NaOH and Na ₂ SiO ₃	Mehta and Siddique (2018)
Sulfate resistance	MK, SF, GGBS	NaOH and Na ₂ SiO ₃	Alcamand et al. (2018)

(continued)

Table 1. Continued.

Durability properties	Aluminosilicate	Alkaline activator	Reference
Chloride resistance	GGBS, SF	NaOH and Na ₂ SiO ₃	Rostami and Behfarnia (2017)
Freeze and thaw resistance	GGBS	NaOH and Na ₂ SiO ₃	Shahrajabian and Behfarnia (2018)

FA: Fly ash, GGF: ground glass fiber, GLP: glass-powder, NP: Natural pozzolan, GGBS: ground granulated blast-furnace slag, MK: Metakaolin, GF: Gladstone fly ash, HPA: High-performance ash, MT: copper mine tailings, CF: coal bottom ash, GLSS: granulated lead smelter slag, JHK: Jordanian Hiswa kaolinite, JSS: Jordanian silica sand, RM: red mud, WS: wollastonite, TR: tremolite, SBF: basalt fiber, POFA: palm oil fuel ash, VM: volcanic mud, HGMW: hollow glass microsphere waste, QP: quartz powder, SF: Silica fume, NS: Nano silica, SBA: Sugarcane bagasse ash, VA: Volcanic ash, CCR: calcium carbide residue, LFS: Ladle furnace slag, FS: ferrochrome slag, RHA: Rice husk ash.

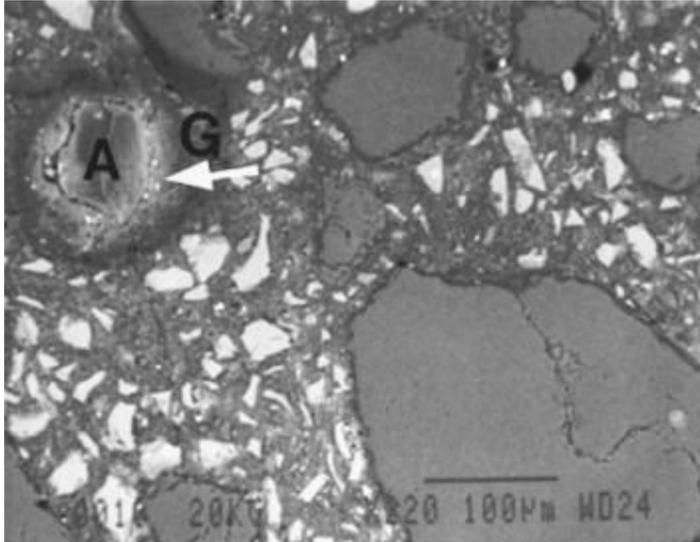


Figure 1. SEM image of AAS concrete (Bakharev et al., 2001a). (A) Reactive aggregate, (G) Alkali-silica gel.

4. Resistance to acid attack

An acid attack is the most intimidating parameter of durability. Some researchers are of the view that resistance to chemicals is more remarkable in Geopolymeric binders than OPC. Davidovits et al. (1990) have revealed that mass losses of 6% and 7% for Geopolymeric binders submerged into 5% concentrated HCl and H₂SO₄ all through four weeks of the period were encountered. Also, keeping the constant conditions, they accounted that OPC-concrete, regrettably, exhibited mass losses among 78% and 95%. Palomo et al. (1999) have investigated on metakaolin mixes activated by Sodium hydroxide and water glass when subjected to H₂SO₄ having pH of 3, Na₂SO₄ with pH of 6, and water of sea containing pH of 7 for 90 days. They have monitored analogous performances as the number of acids are displaying, i.e. a trivial decline from 7 to 28 immersion days in flexural strength while between 28 and 56 days long immersion it has demonstrated an augment but again went on reducing from 56 to 90 days, however, beyond 90 days of immersion it was found to ascend. They did not find non-reacted-Na particles in the structure of toughened material hinting to be leftover in as a solution. Consequently, they are leaked when there was a contact with a solution resulting in a diminution of mechanical strength and a boost in the porosity of the binder. An augment of strength after three months signals that the process of reaction is progressing still, along with the development of Zeolite, namely Faujasite, causing boosting of strength and lower down of porosity. Shi and Stegemann (2000) have matched up to the acid resistance of several binders like slag based Geopolymeric materials, OPC binders, lime or fly ash binders and cement rich in alumina. When submerged in solutions of HNO₃ with pH of 3 and an acetic acid having

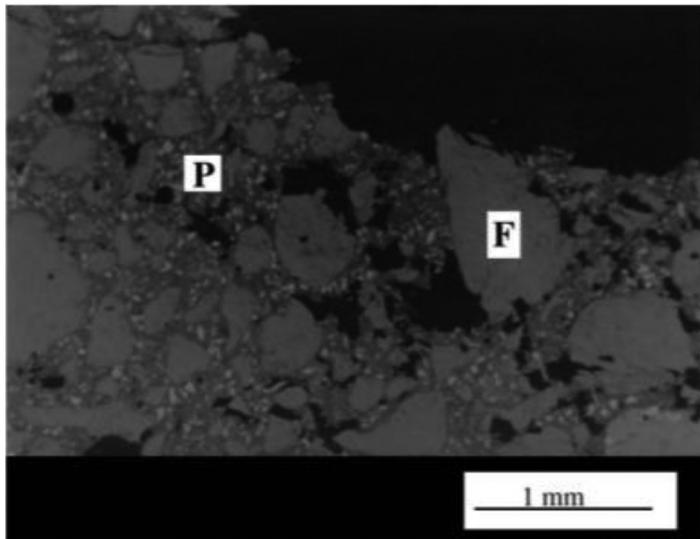


Figure 2. SEM of AAS concrete after exposure to acid (Bakharev et al., 2001a).

pH of 3 to 5, the OPC binders represented greater mass losses as compared to fly ash and slag based binders whereas AC pastes were found dissolved totally. Furthermore, they added that OPC pastes possess more porous nature than geopolymeric one but at the same time exhibit less porosity than FAL-pastes. That means the attack of chemicals is more affected by the behaviour of products of hydration as compared to porosity. Astonishingly, acids with low pH are capable enough for the highest chemical attack as per their report! Also, Bakharev et al. (2002) have weighed OPC for resistance to sulphate attack against slag based GGPC and revealed that the earlier demonstrated an inferior strength reduction, which could be owing to chemical differences concerning binder structure. Also, Bakharev et al. (2003) have studied OPC and slag based Geopolymer concretes with NaOH as an activator accompanied with water glass solution, submerged into a solution of an acetic acid having pH of 4 for one year. Following their report, 47% loss in strength for OPC and 33% for Geopolymer concrete. They further made known that the strength loss is affected by the content of Calcium as 64% for OPC and just 39% for slag based GGPC. Slag incorporated materials exhibit low Ca:Si molar ratio and have proved to be steadier in acidic condition. While, Calcium compounds of OPC-concrete, possess high Ca:Si molar ratios and when react with acetic acid, they form highly soluble acetic calcium compounds. In their conclusion, they accounted that concretes having less free Calcium represent a better presentation in acidic circumstances. SEM image of the specimen after exposure of acid solution shown in Figures 3 and 4. High resistance to chemicals is also confirmed by Song et al. (2005) for fly ash based GGPC when submerged in a 10% concentrated solution of H_2SO_4 for eight weeks, and the mass and strength losses reported were of 3% and 35% respectively. Gourley and Johnson (2005) have established that OPC-concrete having a life of fifty years demonstrates the loss of 25% of its mass subsequent to merely eighty cycles of immersions into a solution of H_2SO_4 with pH of 1 while a GGPC necessitates 1400 to lose the same mass! That means 18 times more service life, i.e. 900 years, of GGPC than OPC-concrete! Pacheco-Torgal et al. (2010) have also talked about a middling loss of mass for GGPC to just 2.6% subsequent to exposure to the attack of all three notable acids viz., HCl, H_2SO_4 , and HNO_3 for twenty-eight days, whereas the mass loss for OPC-concrete is more than double of this value.

In an acidic medium, Topçu and Canbaz (2015) have monitored the formation of salt due to a reaction among acid and AAB. This salt contains water in high quantity and, therefore, developments of cracks in binders initiate which at last dissolve the binders wholly. The authors have studied on resistance to acid attack by GBFS that was activated through three modes, i.e. by Sodium Hydroxide and Sodium Carbonate ($NaOH + Na_2CO_3$), by Sodium Hydroxide and Sodium silicate ($NaOH + Na_2SiO_3$), as well as only by Sodium silicate (Na_2SiO_3). On account of acidic impact, micro-structure of GBFS-mortar which was activated by Sodium Hydroxide and Sodium Carbonate ($NaOH + Na_2SiO_3$), had found to lose its bonding phase in Sand and hence, to convert to granules. Whereas, in the case of activation of the same with

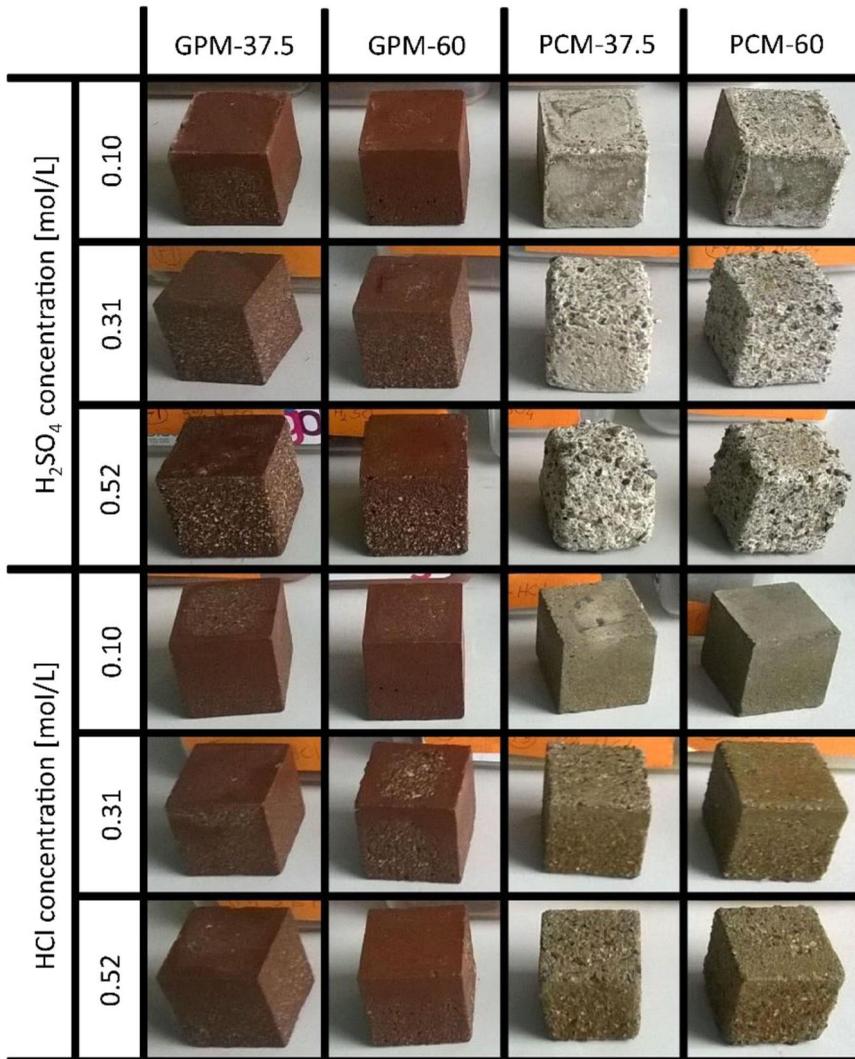


Figure 3. The visual appearance of specimens after exposure to H₂SO₄ and HCl concentration solutions (Bakharev et al., 2003).

sodium Hydroxide and Sodium silicate (NaOH + Na₂SiO₃), the microstructure of it had displayed micro-cracks occurred owing to the trivial formation of sphere-shaped particles along with bonding dissolution phase in acid medium. They have observed a boost concerning the development of pores and cracks with the dissolution of C–S–H gel structure of binder. After some time, the said dissolution results in a dwindle of sticking together both – sand and binder. In the microstructure of GBFS mortars, which were activated with only Sodium silicate, the white coloured sphere-shaped structures were monitored on account of the development of cracks encircling the ingredient because of acid impact. They reported further about the said formation of pores that this has happened simply because of the shattering of the C–S–H gel structure of binders. Following them, GBFS – binders that were activated with both Hydroxide and Silicate of Sodium (NaOH + Na₂SiO₃) have displayed not only superior resistance to attack of acid but also enhanced durability by employing a high quantity of AAS. AA GBFS has impacted optimistically in acidic medium but, on the contrary, pessimistic effects have been monitored in case of microstructures of AAS-concretes within the same medium, according to Bakharev et al. (2003). On account of acid influence, Chang et al. (2005) have encountered an advancement concerning setting time as well as drying shrinkage but oppositely a slimming tendency of strength for AAS-paste in an acidic environment. While

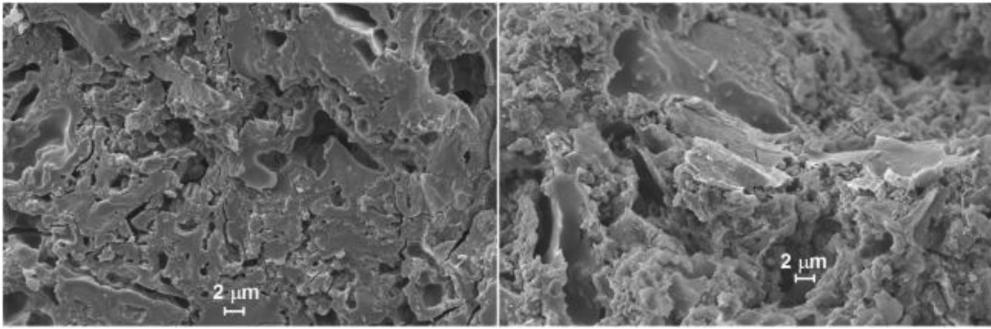


Figure 4. SEM images of samples after immersed in water-immersion (left) and after exposure to acid (right) (Bakharev et al., 2003).

an inferior resistance to acid attack for AAB following an immersion for 90 days into acid was visually observed and the loss of strength of binders was also measured by Khater (2014). Kim et al. (2014) have experimented to develop AAR HA-based activated-concrete using Hydroxide and Silicate of Sodium (NaOH and Na_2SiO_3) as activators. RHA incorporated mortars are having a ratio of sand as 1:2, as well as 7 to 10 M., concentrated Sodium Hydroxide (NaOH) employed whereas the ratio of Sodium Silicate to Sodium Hydroxide has maintained as 2.5 percentage by mass. Resistance to acid attack test was conducted in the presence of acid solutions like H_2SO_4 and HCl . The outcomes of the investigation (Kim et al., 2014) have demonstrated the weight loss greater than 8 and 22 percentages in solutions of HCl and H_2SO_4 in that order which has been ascribed to the attendance of Calcium Hydroxide ($\text{Ca}(\text{OH})_2$). Whereas, AA-mortar had exhibited excellent resistance to acid attack owing to the nonexistence of Calcium Hydroxide ($\text{Ca}(\text{OH})_2$). The findings of researchers (Abdulkareem et al., 2013; Rashad & Zeedan, 2011) were based on the exposure of activated mortars to acid that resulted in again of the weight of maximum 2.5 percentage because of scale occurrence in acid subsequent to the revelation of 28 days. The investigations on immersion have revealed that AA-mortars were found with superior resistance to acid. Furthermore, Malviya and Goliya (2014) have accounted that the specimens of OPC-concrete have exhibited a boost in a weight loss of 1.15 and 3.4 percentages than specimens of fly ash based activated-concrete when immersed into a solution of five percent concentrated H_2SO_4 for the period of one and two months correspondingly. The losses in strength exhibited by OPC-concrete as 4.51 and 2.74 percentages were greater than the values represented by specimens of activated-concrete. When the solution of five percent concentrated H_3PO_4 was employed to immerse these specimens, the specimens of OPC-concrete have demonstrated more loss of weight by 0.71 and 1.97 percentages than the specimens of activated-concrete as well as also 5.22 and 1.36 percentages more compressive strength than those specimens of activated-concrete after one and two months in that order. The authors have finally summarized their investigation on AAFA concrete with the conclusion that activated-concrete had displayed superior durability to acid as compared to OPC-concrete. An analogous opinion has also been put forward by Thokchom et al. (2009). The authors have monitored that specimens of activated-mortar manufactured employing fly ash and alkali activators continued to be integral structurally without any noticeable modification of colour by the effect of a solution of H_2SO_4 , but it appeared somewhat yellow when subjected to a solution of HNO_3 . On examining using an optical microscope, damage of surface observed due to corrosion after some time. As a final point, they have suggested that alkalinity loss was depending upon the content of alkali. Immersion in solutions of H_2SO_4 as well as HNO_3 has represented that specimens possessing lesser content of Sodium oxide (Na_2O) have suffered the loss of alkalinity swifter than high of its volume specimens. Nevertheless, the de-alkalization rate appeared quicker with a solution of HNO_3 . The specimens have suffered a loss in weight from 0.21 to 1.64 percentages when exposed to the said H_2SO_4 and HNO_3 solutions. The highly alkaline specimens have exhibited more loss of weight with a solution of H_2SO_4 . Though, the specimens possessing lesser Sodium Oxide (Na_2O) when exposed to the solution of HNO_3 , demonstrated an augmented loss of weight. On immersing Sodium and Potassium Hydroxides (NaOH plus KOH) activated specimens of fly ash-based concrete in three percent concentrated solution of HCl , there found to occur a considerable loss of weight as investigated by Raijiwala et al. (2012).

5. Resistance to sulphate attack

'A chemical process whereby water enclosing dissolved sulphate ions (SO_4) come into contact with concrete and penetrates it by attacking its exterior surface resulting in a deterioration of the concrete, is known as Sulphate attack'. This is a general form of worsening of concrete. Hence, the concrete must be competent enough to resist it to establish itself as a durable one. It is a critical crisis in context to the recital of concrete and mortar that causes extreme spreading out and strength decline (Atahan & Dikme, 2011). El-Sayed et al. (2011) have reported that the durability attribute of slag which is water-cooled and activated in the ratio of 3:3 of both sodium hydroxide plus sodium silicate mix and immersed in five percent concentrated Magnesium Sulphate (MgSO_4) had demonstrated superior micro-structure and towering resistance to sulphate attack. The mortar and concrete incorporated with pozzolan enhance resistance to sulphate attack in comparison to C_3A possessing OPC-mortars and concretes (Bondar, 2009). Analogous findings were encountered to Malviya and Goliya (2014) concerning both NaOH and Na_2SiO_3 activated FA based-concrete. They accounted that samples of OPC-concrete experienced more loss in weight by 0.23 and 0.26 percentages as well as more loss of compressive strength by 3 and 1.36 percentages than the specimens of activated concrete on their immersion in five percent concentrated solutions of Na_2SO_4 for 30 and 60 days correspondingly. They also accounted that specimen of OPC-concrete immersed in Magnesium Sulphate solution had demonstrated more loss in weight by 0.36 and 0.46 percentages, as well as more loss in compressive strength 1.11 and 0.92 percentages than the specimens of activated concrete for 30 and 60 days correspondingly. Bakharev (2005) had worked on resistance to sulphate on class-F FA based binder which has been activated by all three, i.e. Na_2SiO_3 , KOH and NaOH. Here, the specimens have been subjected to immersion in five percent concentrated mixture solution of MgSO_4 together with Na_2SO_4 and also in a mixture solution of five percent concentrated Na_2SO_4 plus MgSO_4 for 150 days. The factors such as loss of compressive strength, visual examinations, mass modifications, and analysis of microstructures have been investigated concerning resistance to Sulphate attack. He has monitored the highest deterioration in a solution of Na_2SO_4 due to the remarkable feature of alkali migration into the solution. Whereas, a dispersal of Magnesium (Mg^{2+}) and Calcium (Ca^{2+}) ions on the surfaces and alkali migration into the solution was monitored in the solution of MgSO_4 . This phenomenon was especially found more pronounced for the samples with activation through Na_2SiO_3 plus a mix of KOH + NaOH was found with more eminently. A least modify concerning strength was observed in the samples subjected to immersion in solution mix of five percent concentrated Na_2SO_4 plus MgSO_4 . XRD and SEM image of specimens after 5% sulfate solution are present in Figures 5 and 6, respectively. XRD analysis shown Ch = chabazite, P = gismondine, N = hydro-sodalite, E = ettringite, Q = quartz, M = mullite, H = hematite are present in samples. They have accomplished with the findings that NaOH activated samples were found with the best performance. This is attributed to its everlasting polymer structure having cross-bonding aluminosilicate. Bakharev (2005) have also reported that specimens of AA FA and slag cement immersed in the MgSO_4 solution and activated by activators other than alkali silicates have displayed a superior resistance to sulphate attack. Furthermore, specimens cured by heat and activated through sodium silicate (modulus of 1 to 3) had displayed a decline of resistance to sulphate attack as compared to ambiently cured specimens. The research investigations of El-Sayed et al. (2011) on an attack of MgSO_4 to slag pastes, which was water-cooled employing diverse alkali activators viz., NaOH plus Na_2SiO_3 . They have made known that the strength declines with the period of immersion maximum to 180 days. The compressive strength pattern reveals the greater effectiveness of Sodium Hydroxide and Sodium Silicate (in a proportion of 3:3) than any other dosages of Sodium Hydroxide (NaOH) in standing firm against the impact of sulphate ions. The strength of six percent concentrated NaOH activated concrete which was cured at the usual condition of 38°C and complete (100%) relative humidity is very near to concrete activated with both NaOH and Na_2SiO_3 activators, particularly at later on maturity. Chi (2012) thought that resistance to sulphate by AAS-concrete is superior to OPC-concrete. Additionally, Bakharev (2005) have accounted that the reduction in compressive strength of a maximum 20 percent for OPC-concrete while 15 percent for AAS-concrete on account of immersing it in five percent concentrated solution of MgSO_4 following 90 days. Hawa et al. (2013) have examined sulphate spreading out in MK based mortars which activated and produced through partial replacement of MK by POFA with 0, 5, 10 and 15 percentages by weight. A spreading out of mortars which were activated had been controlled at the various period of heat curing 1, 2 and 4 h were immersed in five percent concentrated mix solution of Na_2SO_4 and MgSO_4 correspondingly. Nevertheless, activated mortars put on display a dissimilar

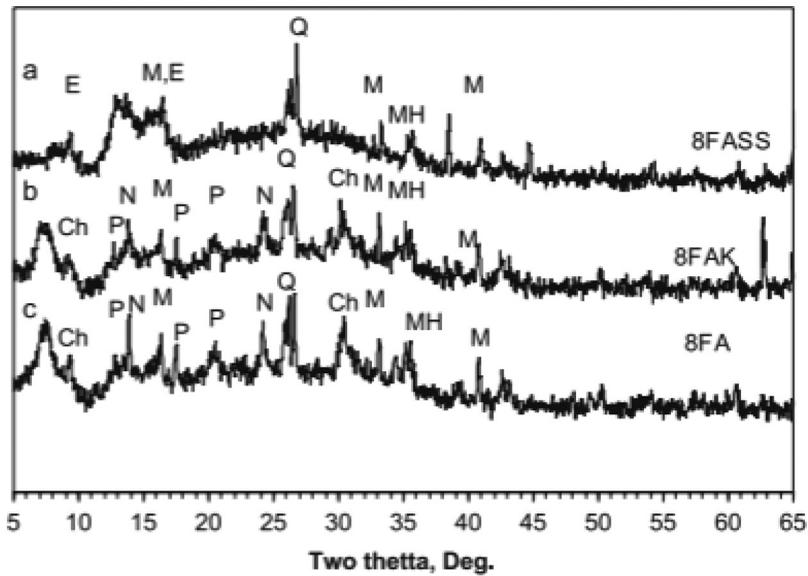


Figure 5. XRD analysis of the geopolymer materials after exposure to 5% sodium sulfate solution, Bakharev et al. (2005).

mechanism. They have accounted that mortars which were activated in the course of study have great compressive strength and suppress sulphate spreading out in the presence of solutions of Na and Mg. Kim et al. (2014) have described that the specimens of mortar of RHA based AAB have demonstrated a gain of weight maximum to 2.5 percent when exposed for 28 days. This was attributed to the white powder deposition on the exterior surface of samples on when exposed to sulphate attack. No doubt, there existed some debates among researchers on the issue of resistance to sulphate by AAB but it can ultimately be concluded that AAB is competent enough to resist appreciably the attack of sulphate.

5.1. Sulphate resistance of calcium systems

Sulphate resistance to Calcium composites can be divided into two systems such as high calcium and low calcium:

5.1.1. Resistance to sulphate with high calcium system

Among alkali-activated materials, the most studied a topic in context to high Calcium-activated system is Alkali-activated slag. In alkali-activated slag or fly ash incorporations, the gel behaviour depends powerfully upon the ratio of slag or fly ash. The is recognise as the N-A-S-H gel is recognized as the key product of binders incorporating 50 percent slag (Ismail et al., 2014). Rodríguez et al. (2008) have concluded in favour of Slag based Geopolymer concrete subsequent to a comparative study with OPC-concrete concerning the resistance to Sulphate that the compressive strength of former was constant on immersion in a solution of five percent concentrated Sodium Sulphate for ninety days whereas the later one had suffered severe deterioration. This is assigned to the development of Ettringite and Gypsum. In this case, the loss of strength of OPC-Concrete was very high, figuring to 43 percent while the value of expansion was noted as six times of Slag based Geopolymer Concrete. Also, Komljenović et al. (2013) have met with the same findings on examining better resistance of Slag based Geopolymeric material than the OPC based to Sodium Sulphate solution owing to the presence of Aluminium and absence of Hydroxides of Calcium $[Ca(OH)_2]$ in the former causing inhibition of Ettringite and Gypsum developments. Heikal et al. (2014) have monitored better durability by Slag cement activated with Sodium Silicate in comparison to OPC. On immersing the specimens into five percent concentrated solution of Magnesium Sulphate ($MgSO_4$) for six months, the rate of penetration of Sulphate ions (SO_4) trimmed down with the curing time. This is because of the formation of products of hydration which filled up some pores. However, given there, in particular, No dilapidation has monitored in the specimens of alkali-activated Slag with a

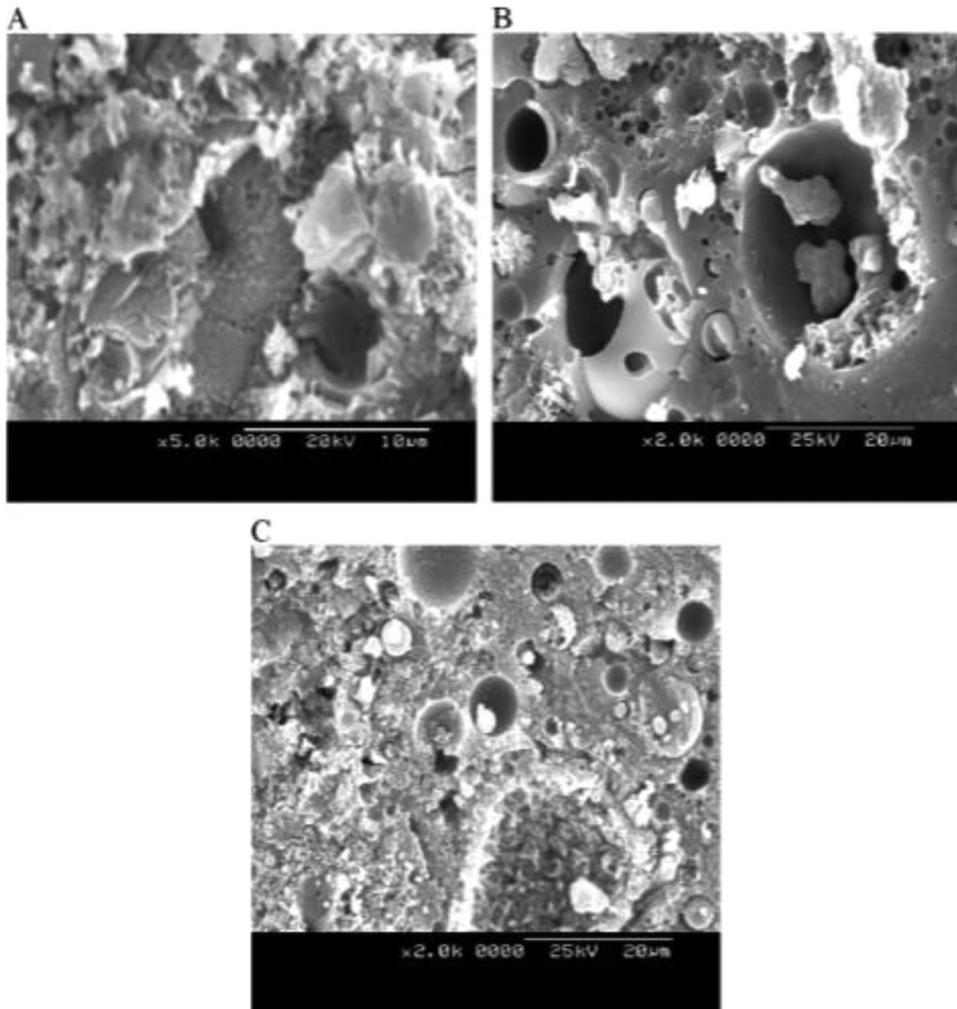


Figure 6. SEMimage of samples after exposure to sodium sulfate solution, Bakharev et al. (2005).

short testing period of exposure, signalling to its 'superior durability'. Also, Puertas et al. (2002) observed that Slag based Geopolymer mortars had demonstrated a great resistance to the solution of Na_2SO_4 . They have revealed that resistance to Sulphate has a relation with the nature of activators, largely owing to the chemistry and structural diversity of the C-S-H gel product developed. The comparison of both slag mortars activated one with Na_2SiO_3 and another with NaOH possessing greater structural order, reduced Geopolymerization and an elevated ratio of Ca:Si is more sensible to the attack of Sulphates. Here, the minor decline of strength has observed owing to the development of and Ettringite and Gypsum. The reduction in porosity, enhancement in compressive strength and improvement in the resistance to Sulphate attack were demonstrated by Sodium silicate activated slag or fly ash when the dose of activators was boosted (Wang et al., 2015). As well, fine Silicious powder of Pumice, glass Sand and Silica fumes have also been employed to enhance resistance to Sulphate, owing to the boost of C-S-H gel. Bakharev et al. (2005) have reported the compressive strength of Slag based Geopolymer concrete activated with Sodium Silicate and conventional OPC-concrete that a decline of 17 percent for former whereas 25 percent for the later one was observed when immersed in five percent concentrated solution of Na_2SO_4 for one year, nevertheless, immersion in five percent concentrated solution of MgSO_4 has displayed the strength decline by 23 percent for earlier and by 37 percent for the later. The obliteration of C-S-H is a significant mechanism of corrosion during the attack of Sulphate ions from the solution of

MgSO₄ on AASC, and Gypsum is the key product of this reaction. The impact of the kind of cations, Na⁺¹ as well as Mg⁺², present in solutions of Sulphate on resistance to Sulphate by AAS was claimed in another investigation. Generally, the higher percentages of Calcium containing alkali-activated materials represent more resistant to Sulphate solutions of Sodium than of Magnesium. Mithun and Narasimhan, (2016) have found that the compressive strength of AASC specimens has enhanced by 10% solution of Na₂SO₄ subsequent to immersion for one year, displaying better resistance to Sulphate attack than OPC-Concrete. Nevertheless, the compressive strength of specimens of AASC immersed in 10 percent concentrated solution of MgSO₄ was found declined, and the loss in strength was also more than OPC-concrete. They have assigned the bulky loss in strength to the crack development persuaded due to the reaction among C–S–H and Mg²⁺ ions resulting in a formation of M–S–H along with Gypsum. The analogous outcomes were also monitored in Slag mortars activated with alkali (Gourley & Johnson 2005). Ismail et al. (2013) have accounted the physical attributes of fly ash: slag as 1: 1 mix activated by Na₂SiO₃ and concluded that severe deterioration caused by its immersion five percent concentrated solution of MgSO₄ for 90 days. The phase of C–S–H has suffered decomposition and Gypsum was formed, but there was an absence of the formation of Ettringite due to lesser accessibility of aluminium as the same was supposed to play a part in the development of N–A–S–H gels. On account of the chemical structure of chief gel products fundamentally unaffected, it is possible that the binder carried on stabilizing and developing into the solution of Na₂SO₄. Valencia Saavedra et al. (2016) have appraised the resistance to Sulphate by inferior class fly ash or slag (80:20) concrete activated by alkali in five percent concentrated Sulphate solutions of Na and Mg. The investigations utilizing MgSO₄ have deteriorated at highest levels of signalling at greater fierceness by MgSO₄, owing to the development of new-fangled crystalline phases, chiefly Gypsum formation.

5.1.2. Resistance to sulphate with low calcium system

In general, low Calcium alkali-activated system exhibits brilliant resistance to Sulphate attack. As per (Fernandez-Jimenez et al., 2006), when fly ash-based geopolymer mortar kept immersed in 4.4 percent concentrated solution of Na₂SO₄ for even after a prolonged period of 365 days, there was not found any sign of degradation. Also, the fly ash (Hardjito et al., 2004) and kaolinite clay-based geopolymer concrete (Slaty et al., 2015) have represented the first-rate resistance to Sulphate in the solution of five percent concentrated Na₂SO₄. Duan et al. (2016) have experimented on partly replacement of Metakaolin (MK), i.e. 5 to 20 percentages, in fly ash-based geopolymer with Na₂SiO₃ as an activator could mitigate the loss of strength in five percent concentrated solution of Na₂SO₄. The impact was more obvious when change-over of MK was gone beyond 15 percent. The loss of compressive strength was directly related to the Vickers hardness of surface which was exposed. The attack by Sulphates could diminish the Vickers hardness of the exposed surface. On immersion of the fly ash-based geopolymer where NaOH plus CaO were employed as activators into ten percent concentrated solution of MgSO₄, Hu et al. (2009) have accounted that the supplementation of Zeolite could improve the strength and resistance to Sulphate by geopolymeric materials. This was attributed to the development of the steadier structure of Zeolite. Contrasting to high Calcium alkali-activated system, the low calcium alkali-activated systems demonstrate, generally, superior resistance to MgSO₄ than the degree of resistance to Na₂SO₄. Bakharev (2005) have probed the resistance to Sulphate of Class F fly ash-based geopolymer which was subjected to immersion into merely Na₂SO₄ solution, the only solution of MgSO₄ and mixed solutions of Na₂SO₄ + MgSO₄, all are with five percent concentration, for 150 days. The upshots of compressive strength of geopolymer activated by Na₂SiO₃ were found declined by 18 percent concentrated in the solution of merely Na₂SO₄ while specimen with activation of mix solution of NaOH plus KOH has displayed a decrease of 65%, but it was encountered with four percent increase in case of specimen activated by only NaOH. Conversely, in context to the solution of MgSO₄, the compressive strength of specimens with activation by only NaOH and by mix solutions of NaOH plus KOH have been obtained with an augment of 12 and 35 percentages correspondingly. However, the geopolymer with Na₂SiO₃ activation provided a decrease of 24 percent on immersing in Na₂SO₄ plus MgSO₄ solutions, both having a concentration of five percent. On the one hand, OPC specimens have exhibited severe deterioration, while on the other hand, the geopolymers had displayed a slight modification concerning mass and strength. They further had considered the relocation of cations of alkali into the contacting solution is the most momentous grounds of loss in strength when a solution of Na₂SO₄ was employed in some of the cases of geopolymers proving that the

alkali loss is also a matter of concern (Albitar et al., 2017). This is a diverse case from that of Ettringite formation, which is answerable to the corrosion of specimen into solutions containing Sulphates. Hitherto, the impacts of the loss of alkalis on the durability of geopolymers have not been studied in details, and hence, further future studies on the topic are highly sought-after. Also, incorporation of fly ash and Metakaolin type supplements with low Calcium alkali-activated materials displayed superior resistance to Sulphate attack than the OPC materials. Sata et al. (2012) have investigated that the length modifications of specimens of Lignitic bottom ash-based geopolymer were only 65 to 121 μm subsequent to immersion in five percent concentrated solution of Na_2SO_4 for 365 days, whereas amalgamated cement mortars were met with 595 and 648 μm . Nevertheless, on account of the development of Ettringite and Gypsum, the OPC-mortar exhibited the greatest value (7600 μm) of expansion. The enhanced presentation by Geopolymers in case of Na_2SO_4 is owing to the steadier cross bonding of alumino-silicate polymeric products in comparison with the products of hydration of OPC. When natural pozzolans based Geopolymer concrete subjected to immersion into mix solution of Na_2SO_4 plus MgSO_4 both having concentration of 2.5 percent as investigated by Bondar et al. (2015), the value of utmost expansion of specimens was reported only 0.074% even after 180 days. At this juncture, the loss in compressive strength accounted was 19.5 percent after a prolonged period of two years, representing superb resistance to Sulphate. Further, the Ferro-chrome type slag based geopolymer concrete was studied by Karakoç et al. (2016) on immersion into three dissimilar kinds of MgSO_4 solutions with 3, 5 and 7 percentage concentration for 180 days, the exterior of Geopolymer concretes remained unchanged with the length change of less than 0.1% which was lesser than OPC counterpart. As the concentration of MgSO_4 was increasing, the compressive strength was found trimming down. Yusuf, (2015) have observed that the alkali-activated mortar incorporating palm oil fuel ash has suffered severe deterioration subsequent to six months of immersion in five percent concentrated solution of Na_2SO_4 , the result was a reduction of mass by 6.3 percent, and merely 16 percent was the residual compressive strength. Nevertheless, in five percent concentrated solution of MgSO_4 , the withholding of strength was 76.8 percent. The research work of them represented superior strength preservation in the specimens of MgSO_4 owing to the development of surficial deposits and crystalline Anhydrites (CaSO_4). The leaking of dynamically active element viz., Ca, Al and Mg, have piloted to the deterioration into Na_2SO_4 . Also, Salami et al. (2017) have found that the specimens of palm oil fuel ash mortar subjected to five percent concentrated solutions of MgSO_4 for a longer period of 270 days has displayed superior durability results than the specimens immersed into five percent concentrated Na_2SO_4 . It would be valuable to report that specimens which were subjected to immersion into the five percent concentrated solution of Na_2SO_4 had mostly lost their alkalinity and those immersed into five percent concentrated MgSO_4 had lost only slight alkalinity, as well as the resistance to Sulphate attack that could be witnessed by their higher residual strength.

6. Resistance to freeze-thaw conditions

When waters from surroundings incessantly seep or enter into pores and cracks present in concrete constructions during warmer daytime and freeze in extremely colder night owing to severe environmental conditions, especially in colder regions. This is repeatedly melting and freezing, i.e. expansion and contraction, escort to spread out the cracks resulting in an ultimate breaking of structures in the long run. This type of phenomenon may sometimes be answerable to great catastrophe. Hence, the concrete should be capable enough to withstand these changes by retaining its strength. That means, it is an attribute of concrete to resist cyclic freezing and melting processes owing to vigorous weather to prove it serviceable. Following Yunsheng and Wei (2006), fly ash based Geopolymer composites are 2.2 times more competent to resist freeze-thaw cycle in comparison to OPC-concrete of analogous compressive strength. The loss of merely 30 percent was reported by Dolezal et al. (2007) in context to freeze-thaw resistance of fly ash based Geopolymer binders subsequent to 150 freeze-thaw cycle's exposure. Bortnovsky et al. (2007) have scrutinized the said resistance by slag-waste shales based Geopolymer binders and reported a high compressive strength even subsequent to one hundred freeze-thaw cycles. Slavik et al. (2008) have attained higher resistance to freeze-thaw in fluidized bed combustion bottom ash based Geopolymer binders. Brooks et al. (2010) have corroborated the higher resistance to freeze-thaw of the Geopolymer binders through their experiments. A quite recent study by Fu et al. (2011) on slag based Geopolymer concrete has revealed an outstanding resistance to freeze-thaw.

7. Corrosion of steel reinforcement

For steel-reinforced concrete, the corrosion of reinforcing bars in concrete is a significant crisis for its durability. To get better-quality resistance to corrosion by the concrete is forever a vast concern merely next to its mechanical attribute. A range of methods has been employed to defend the reinforcing steel bars in opposition to corrosion inside the concrete. The durability of Geopolymer concrete was investigated by copious researchers (Bastidas et al., 2008; Fansuri et al., 2012; Olivia & Nikraz 2011; Patil & Allouche, 2012). In context to steel reinforced OPC-composites, the steel reinforcement along with some entrenched metals gets corroded away through the chemical process of corrosion, which is a principal reason to deteriorate OPC-structures. The resulting rust owing to the corrosion of steel covers a larger volume than the steel itself. This spreading out is responsible for creating tensile stresses inside the concrete. Sooner or later it becomes a root cause for crack development, spalling, and delamination, i.e. splitting apart into layers. In short, corrosion is a chemical or electrochemical degradation. It is one of the reasons that affect the structural competence of elements of concrete. The corrosion of reinforcing steel bars is a solemn threat since they are very close to the surface of the concrete and are very susceptible to corrosion. The higher alkalinity of Ca(OH)_2 lend a hand to protect steel bars by a passivity coating in case of OPC based constructions. This passivity layer may be destroyed when the pH of water mitigates, making it acidic that favours oxidation process. It may result in corrosion of steel bars and starts destroying them. The carbonation or chloride ingress may also help the corrosion of the steel structures. It takes place because of an electrochemical type of action when dissimilar natured metals are connected electrically in the presence of oxygen and water. The course of action of the process consisting in anodic Iron dissolution while positive (+ve) charge-carrying ions of Iron move into the solution and a surplus of negative (-ve) charge bearing electrons pass to steel through the cathode. Here, the same is soaked up by a component of electrolyte which results in a formation of ions of 'Hydroxyl'. The said ions again unite with ions of Iron and the consequential product would be 'Ferrichydroxide or Hydrated ferric oxide' having the molecular formula as FeH_3O_3 or Fe(OH)_3 or $\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$. This, in turn, alters to rust finally by dehydration. An augment of volume occurs owing to the development of rust around steel bars which escorts to the formation of cracks along with spalling of the exterior surface of the concrete structure. While, on the other hand, the literature to study its capacity to resist corrosion of reinforced steel in case of Geopolymer binders is very petite. However, little investigations about Chloride diffusion favoured Geopolymer binders for their ability to put a stop to the doorway for damaging constituents that could initiate corrosion of steel. The upshots of a comparative study carried out by Roy et al. (2000) on Chloride diffusion concerning OPC as well as Geopolymer binders have revealed that Geopolymers has represented merely a half of value of Chloride diffusion of OPC-binders. Saraswathy et al. (2003) have investigated fly ash-based geopolymer mixes and accounted for resistance to steel corrosion analogous to OPC-binders. Miranda et al. (2005) have represented that Fly ash-based geopolymer binders possess better conditions of pH than OPC-binders. Further, they disclosed that pH declined with the progression of the reaction of hydration. Nevertheless, the condition of alkalinity has maintained even subsequent to five years as the carbonation incident had not taken place. Aperador et al. (2009) have explained that slag based Geopolymer concrete was found with a pitiable display of resistance to the carbonation, which is a core driver for steel reinforcement corrosion. Bernal et al. (2010) have made obvious that the activation of Granulated Blast Furnace Slag incorporated with Metakaolin possesses inferior resistance to carbonation. Further, they Bernal et al. (2011) clarified that slag based Geopolymer concrete represents a little vulnerability to the carbonation that relies on the content of the binders. Lloyd et al. (2010) have divulged that Geopolymer cement is inclined to the leaking of alkali which pilots to a diminution of pH necessitate stopping happening of corrosion of steel. Nevertheless, they have shed a light on the presence of calcium by considering it as an essential element to get 'durable steel-reinforced concrete'. This can be regarded as a drawback of aluminium and Silicon-containing Geopolymeric composites. Therefore, further research works on corrosion of reinforced steel are highly desirable considering alkalinity stability plus time for curing, resistance to carbonation as well as chloride diffusion as the significant parameters. Miranda et al. (2005) have reported the resistance to corrosion by Fly Ash-based Geopolymer mortar with the employment of the 8 M and 12.5 concentrated solutions of NaOH in their experiment and accounted an identical resistance to corrosion by OPC-mortar. Also, Bastidas et al. (2008) have reported an analogous resistance to corrosion by Fly Ash based Geopolymer mortars to its OPC counterpart by using a solution of 12.5 M NaOH. Oliva and Nikraz (2011) have investigated on the resistance to corrosion with utilizing two Geopolymer concrete mixtures where the use of 14 M solution of NaOH with

acceleration in the caustic medium has made. The better-quality resistance to corrosion by both Geopolymer concrete was exhibited as compared to OPC-concrete with the same compressive strength in their research work. Also, Reddy et al. (2011) have monitored the resistance to corrosion by Geopolymer concretes by applied 8 M and 14 M solution of NaOH with a very high outer DC potential of 30 V employed to bar with 13 mm diameter and 500 mm length entrenched with the specimens of concrete under a highly favourable medium for corrosion. They have accounted for a superior resistance to corrosion by Geopolymer concrete in context to lower down corrosion current than OPC-concrete. Currently, Patil and Allouche (2012) have revealed an advanced resistance to corrosion by Geopolymer concrete with 14 M solution of NaOH. Generally, a greater concentration of the solution of NaOH for a provided quantity of Na_2SiO_3 improves the reaction of Geopolymerisation consequential in an augment about the compressive strength of concrete. Fansuri et al. (2012) have made public that the concentrations of a solution of NaOH and the quantity of Na_2SiO_3 influence the attributes of Geopolymer concrete. Shaikh (2014) have reported the impacts of a solution of NaOH with higher molar like 14 M and 16 M with activators ratios as Na_2SiO_3 : NaOH of 2.5, 3 and 3.5 on the resistance to corrosion by Geopolymer concretes. They have employed a technique of half-cell potential measurement for examining the decay, but it has provided merely the likelihood of activities of corrosion. The observations obtained from the half-cell potential that exists based on the reference electrode of Copper or CuSO_4 . Geopolymer concrete has demonstrated superior resistance to corrosion in context to lower negative potential observations than relevant OPC-concrete. The potential reading of all Geopolymer concrete has found boosted to more negative readings as time progressed. Therefore, the rate of corrosion of Geopolymer concrete was more decelerator than in case of OPC-concrete. The geopolymer concrete developed employing 16 M solution of NaOH has represented superior resistance to corrosion concerning inferior values of negative potential than developed with 14 M solution of NaOH. Following ASTM C876, the minor negative potential readings point to a low-down likelihood of steel corrosion in concrete. The phenomenon of mitigation of negative potential readings was attributed to a boost in the ratio of Na_2SiO_3 :NaOH. The rate of augmenting of values of the negative potential of Geopolymer concrete with a ratio of Na_2SiO_3 :NaOH of 3.5 was very sluggish but achieved a stable rate with the use of 16 M NaOH. This was because of a concurrent augment in molarity of NaOH and the amount of Na_2SiO_3 solutions in Geopolymer concrete. Chaparro et al. (2011) have utilized embedded bars of steel in AASconcrete and have examined on immersion of specimens into 3.5 percent concentrated solution of NaCl. The specimens of OPC were also examined on immersion in the permanent solution for comparative study objectives. To monitor the nature of corrosion of bars of the steel, an 'Open circuit potential' was observed, and an Electrochemical Impedance Spectroscopy (EIS) was employed. Subsequent to exposure intervals of 0, 3, 6, 9 and 12 months, the attitude of corrosion was examined for AAS and OPC-concretes. Corrosion of passive nature was monitored for specimens of AAS-concrete in an initial three-month period as per the data noted by electrochemical measurement. The Chlorides found present in steel and AAS-interface are answerable to trimming down of the tendency to resist corrosion which was met with after three months. Likelihood of the ten percent corrosion was reported on 28th day curing for both AAS and OPC-concrete. An analogous attitude of corrosion was witnessed in the cases of both AAS and OPC-concrete subsequent to the immersion of 90 days period during which the active potentials were found ranging between -0.2 to -0.6 V signalling to the likelihood of corrosion for about 90 percent. OPC-concrete corrosion potential was unchanged subsequent to 180 days while specimens of AAS exhibited the most negative values of corrosion potential after an identical period shown in Figure 7. The pitiable resistance to carbonation demonstrated by AAS concrete was a key factor for corrosion of its reinforcing bars of steel as revealed by Aperador et al. (2009). Bernal et al. (2010) have monitored a low resistance to carbonation of Slag plus MK blended Geopolymers. Lloyd et al. (2010) have accounted for that AAB is responsible for the leaking of alkali, which causes mitigation of value of pH that, successively, accountable for resistance to corrosion of steel. Also, they have described that the tough steel reinforced concrete can be developed by high Calciumbased AAB. A range of conceptions concerning corrosion resistance can be quoted from a variety of earlier investigations. Consequently, numerous advanced researches on the nature of corrosion of reinforced steel AAS binder are gravely looked-for.

8. Water absorption and permeability

'Water absorption' is the quantity of water absorbed under a definite state of affairs by concrete, whereas, permeability depends notably upon the permanence, dimension and distribution of pores and

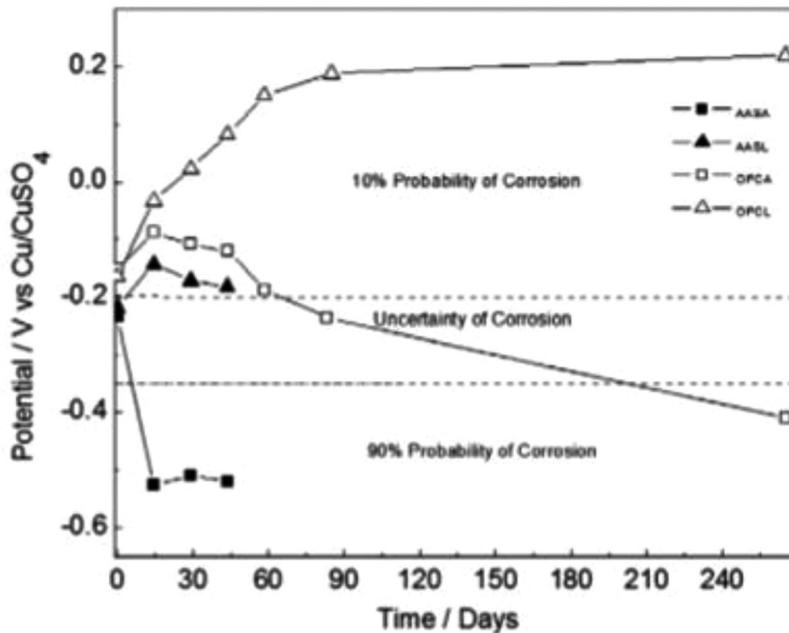


Figure 7. Corrosion resistance for AAS (Chaparro et al., 2011).

differs as to the ratio of water (W): cement (C) of concrete. Bernal et al. (2011) have monitored water absorption of specimens of AAS and OPC with identical contents of binder on both 28th and 90th days. They have encountered a lower downvalues of absorption of water by specimens of AAS as compared to OPC-specimens having even identical values for porosity. According to researchers, this has been assigned to the presence of fine, meandering and closed pores in specimens of AAS in which water is not able to go through with ease (Bernal et al., 2011). In their opinion, it may be due to the absorption of little water in OPC-binder particularly for a low ratio of water as to cement to draw to a close the left-over course of hydration. Troconis de Rincon, (2000) have exemplified that concrete with less than ten percent value of porosity plus less than three percent values of absorption of water demonstrated the durability of the brilliant level. Also, they explained that high durability possessing AAS-concrete could be developed by employing five hundred and four hundred kilograms per cubic meter Slag for curing of three months. A yet another investigation on volume analysis of pores plus the absorption of water, Bernal et al. (2012) have accounted that solid, dense gel structure entirely relied upon time for AAS binder, but the examination was wholly diverse for the incorporated Slag with a greater amount of Meta Kaolin illustrated in Figure 8. Qureshi and Ghosh (2013) have divulged a slimming down tendency in context to water absorption for specimens with water curing with a comparison to specimens which are cured in an oven in the company of alkali presence varying from 6.41 to 10.41 percent. The smallest quantity of absorption of water as 6.38 percent was monitored for specimens cured by water possessing alkali content of 10.41percent signalling structure of the matrix as more homogenous and compacted. Furthermore, Qureshi and Ghosh (2013) have displayed affiliation between the content of SiO_2 , apparent porosity, and absorption of water by AAS-paste. A greater apparent porosity plus the absorption of water were monitored for Silica varying from 1.6 to 4.8 percent demonstrate in Figure 9. After that, an unexpected decline in both was detected at 6.4 percent Silica content. The specimens of AAS with low Silica of 1.6–4.8 percent exhibited a greater absorption of water, indicating the larger content of void. When Silica content was 6.4 and 8 percent, the absorption of water was recorded 6.06 and 9.37 percent in that order, which had pointed out that the amalgamation of soluble Silicates escorted to homogeneous and thicker micro-structure. Chi et al. (2015) have reported about absorption of water by Fly Ash plus Slag based Geopolymer mortars (AAFS) with their reference OPC-mortars. They have divulged lower values of absorption of water for the former in comparison to the later one. By maintaining an identical ratio for the liquid to the binder, greater absorption of water was noticed in Fly Ash-based geopolymer mortars in comparison with Fly Ash plus Slag based Geopolymer mortars. By using a liquid to binder ratio of 0.35

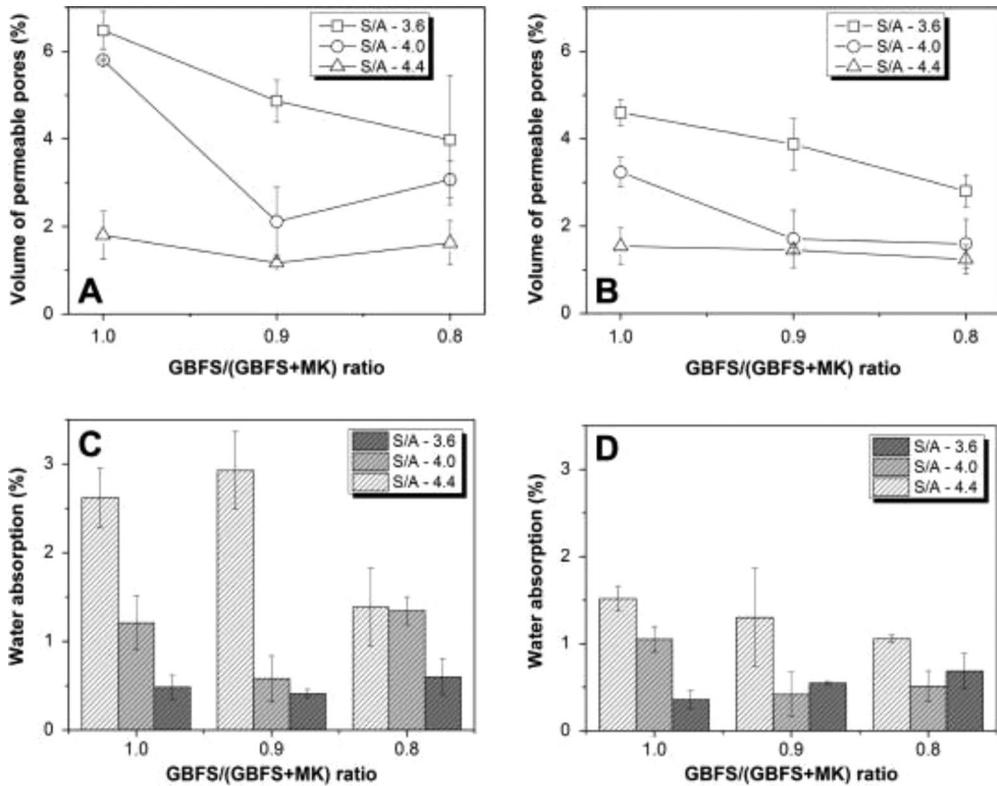


Figure 8. Total porosity (see Fig. A and B) and water absorption (see Fig. C and D) of GBFS and MK based alkali-activated concretes (Bernal et al., 2012).

and 0.5, they achieved a water absorption range of Fly Ash-based geopolymer mortars from 2.5 to 3.8% and 1.3 to 6.1%, whereas 6.1 and 7.5% with their matching OPC-mortars respectively. An increase in water absorption by Fly Ash plus Slag based Geopolymer mortars from 2.6 to 9% was found when the liquid to binder ratio was enhanced from 0.5 to 0.65. Thokchom et al. (2009) have accounted that Geopolymer mortars developed with higher alkali amount have provided a low absorption of water but greater compressive strength. On the contrary, an amalgamation of rice husk bark ash and Fly Ash when employed as a binder with $\text{NaOH} + \text{Na}_2\text{SiO}_3$ activation, Wongpa et al. (2010) have found a boosting tendency of coefficients of water permeability for 28 to 90 days as a contrast with values of the compressive strength. Also, they have encountered a prolonged shrinkage of the said mixture where a declining propensity of compressive strength was monitored throughout 28 to 90 days. Simultaneously, an escalating leaning of the coefficient of water permeability was also recorded. Finally, they have wrapped up that shrinkage resulted in cracks was the key accountable factor for amplified permeability of water as well as declined compressive strength. Also, Karim et al. (2014) have met with advanced values of absorption of water for Geopolymer composite binder which was developed by blending of Slag, POFA and rice husk ash than OPC-binders. They employed an ambient curing technique where pozzolans were NaOH-activated.

8.1. Effects of precursors on water absorption and permeability

Water absorption and permeability of Geopolymeric materials depend upon a lot of factors. The precursors and their chemistry play a significant role in this regard. In Slag based Geopolymer concrete, Bernal et al. (2011) have found that boosting of Slag content could drastically diminish capillary sorptivity. Following Bernal et al. (2011), in case of Slag and Metakaolin intermingles activated by alkalis, the replacement of metakaolin up to fix limit can trim down the absorption of water and permeability. In Slag and fly ash mixes, a boosting in replacement of fly ash enhances porosity Gao et al. (2016) while

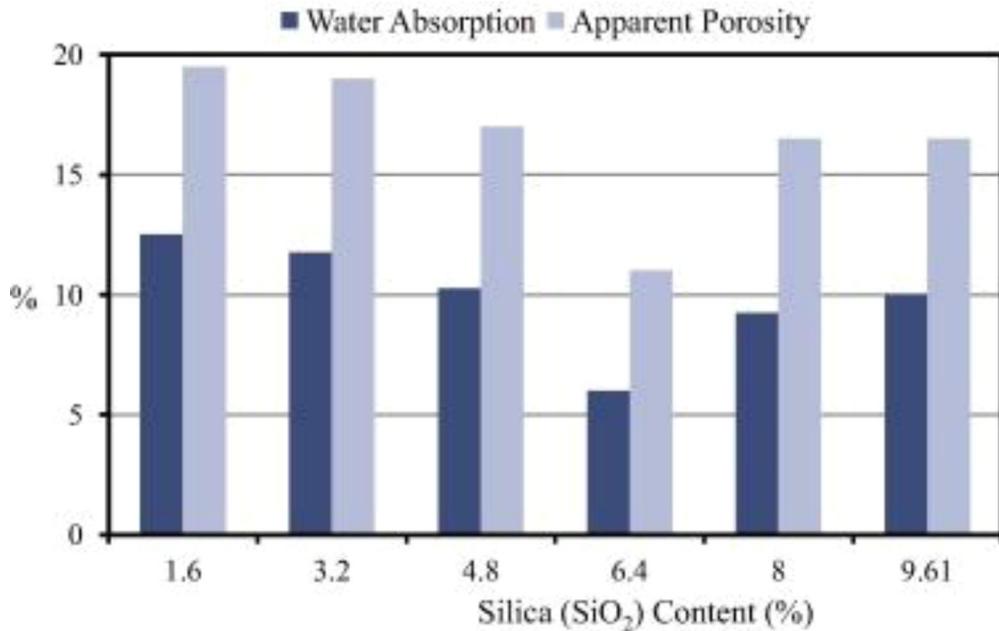


Figure 9. Effect of silica on water absorption and apparent porosity (Qureshi & Ghosh, 2013).

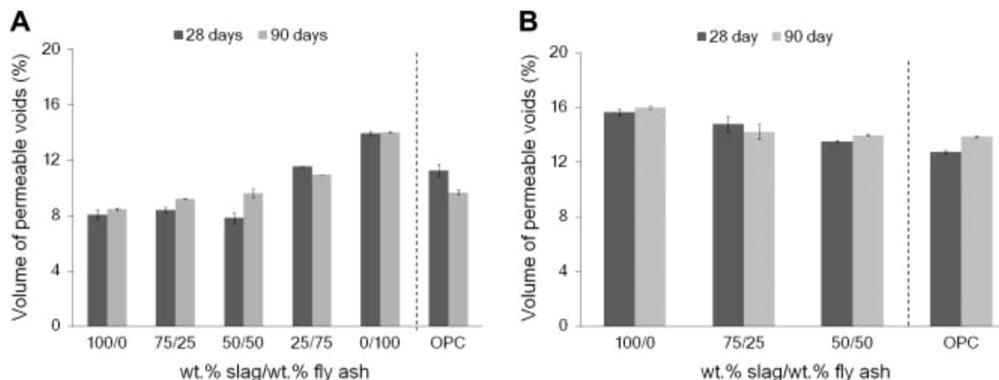


Figure 10. The volume of permeable voids of (A) mortars and (B) concretes (Ismail et al., 2013).

declines tortuosity of the structure of pore. Ismail et al. (2013) had monitored a petite change in the Volume of Permeable Voids (VPV) of Slag and fly ash based Geopolymer mortars when less than 50% quantity of fly ash employed as shown in Figure 10. Nevertheless, while the amount of fly ash used had gone beyond 50%, the boost in VPV encountered on account of the porous nature of N–A–S–H gel (Ismail et al., 2014). Moreover, the VPV of Slag and fly ash based Geopolymer concrete was greater than OPC counterpart when slag content was less than 50 percent. By constantly maintaining slag and fly ash ratio, Chi and Huang (2013) have also derived that the absorption of water by Slag and fly ash based Geopolymer mortars was inferior to OPC or Fly ash based Geopolymer mortars. Additionally, the substitution of slag with ten percent micro-silica could decrease the early and overall absorption of water by Slag based Geopolymer concrete (Rostami & Behfarnia, 2017), as met with in upshots of Behfarnia and Rostami (2017) for the water penetration depth by 49%. Deb et al. (2016) have reported that the coefficient of sorptivity found trimmed down on employing two percent nano-silica with fly ash based Geopolymer mortar mixtures. Ultimately, they have winded up that the joint filling impact of nano-silica through the packing of particles and the supplementary products of reaction developed a denser fastening matrix, which was responsible for a reduction of the sorptivity and porosity.

8.2. Effects of activators and ratio of water to binders on water absorption and permeability

With this regard, the concentration and modulus of activators have also been found affecting the absorption of water by Geopolymer composites (Law et al., 2009). Adam (2009) and Law et al. (2012) have boosted the modulus of activators from 0.75 to 1.00 in the case of Slag and fly ash based Geopolymer concrete and observed mitigation in the absorption of water. The Fly Ash-based Geopolymer concrete has demonstrated a slight decrease while Slag based Geopolymer concrete has displayed an advanced noticeable decline with context to absorption of water when the modulus of activators enhanced from 1.00 to 1.25. However, when the modulus of activators was 1.00, Slag based Geopolymer concrete recorded the uppermost compressive strength plus least absorption of water. The optimum modulus of activators of the said Geopolymer concrete was confirmed to be 1.25. The mixes designated as G1–G5 when subjected gradual boost in modulus of activators from 0.75 to 1.22, the capillary sorptivity found enhanced as the augment in the content of silicate. An escalating alkali and silica content of fly ash activated by alkali have resulted in low total porosity and a fine structure of pore. Therefore, greater alkali and silica content considerably trim down the permeability of water Ma et al. (2013). Water permeability of Geopolymeric composite materials is affected by water and binders, which are in the form of solid precursors. The greater ratio of water: binder in MK based Geopolymer resulted in the swifter rate of water absorption. This is assigned to the bigger volume of and pore size and pores (Okada et al., 2009). In case of low calcium-containing Fly Ash based Geopolymer concrete, the absorption of water also found enhanced with an augment of total water/binder (Olivia & Nikraz 2011). The rice husk bark ash incorporated fly ash based Geopolymer concrete has been investigated when the water/binder was highest, it was found that the water permeability was also the maximum which relies on the number of cracks and pores present inside the micro-structures.

8.3. Some extra effects on water absorption and permeability

The influence of interface of aggregates of past and age of specimens is significant factors to be considered for the water permeability of geopolymer materials. The absorption of water by Slag and fly ash pastes was found quicker than the paste with only 100% fly ash. However, this rule cannot be taken as granted clearly in case of mortars because of the impact of the interface of past aggregates Rodríguez et al. (2008). The outcomes of the study of Ismail et al. (2013) have represented that there was significant differentiation among concretes and mortars concerning the development of VPV value. The coefficient of capillary absorption of concretes was found greater than mortars. Though the mortars had greater paste volume fraction, and it may be associated with the impact of the diverse interface of paste aggregate (see Figure 11). The value of capillary absorption is greater owing to more interface in concretes. A prolonged period of heat-curing is advantageous for the refinement of the structure of pore in alkali-activated fly ash. This could trim down significantly the permeability of water (Ma et al., 2013). With the boosting age of curing, the chemistry of Ca and Al of Slag and Metakaolin gels could reduce the absorption of water owing to the lesser consistent pores in matured gels. Furthermore, specimens with inferior alkalinity necessitate a prolonged time of 90 days to achieve a proportional micro-structure development, and the disparity of absorption of water among 28 and 90 days was more momentous than strength and total porosity Bernal et al. (2012). Consequently, the impact of maturity of the sample should desirably be investigated in the days to come. Above and beyond, the factors tested and talked about, the upshot of permeability and absorption of water by Geopolymer materials are to a great extent affected by severe conditions for pre-drying when the test of permeability conducted. Following Collins and Sanjayan, (2008), the absorption of water is still susceptible to the process of pre-drying at a prolonged period for water-bath type curing. The values for higher absorption of water by Geopolymer materials are supposed to be connected to the cracks persuaded by the pre-drying at 105 °C (Tanzer, 2010). The report of Ismail et al. (2013) suggested that the C–A–S–H gel dried out and the porosity enhanced even at 60 °C. Consequently, the test standards of permeability and absorption of water employed for OPC do not suit to Geopolymer material composites. Nevertheless, the only technique to guarantee is the similar early water content of specimens following ‘dried to constant weight’ in dry condition. To resolve the said predicament, drying at 40 °C for ten days was advocated for tests of durability (Al-Otaibi, 2008).

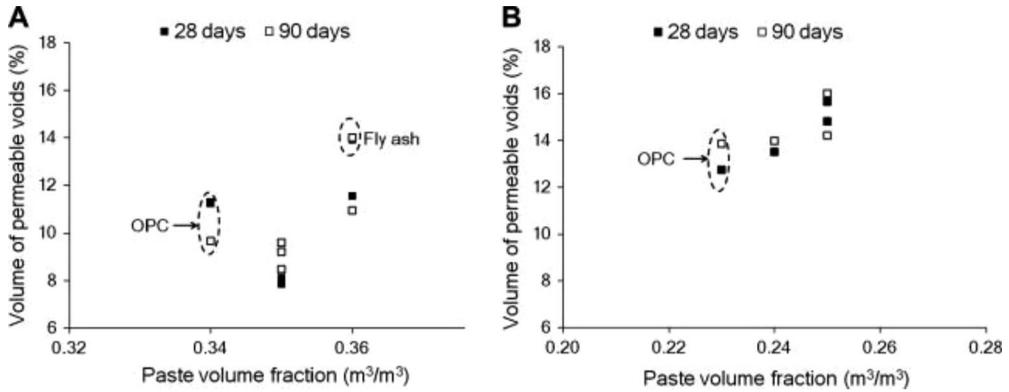


Figure 11. The volume of permeable voids of (A) mortars and (B) concretes with paste volume fraction (Ismail et al., 2013).

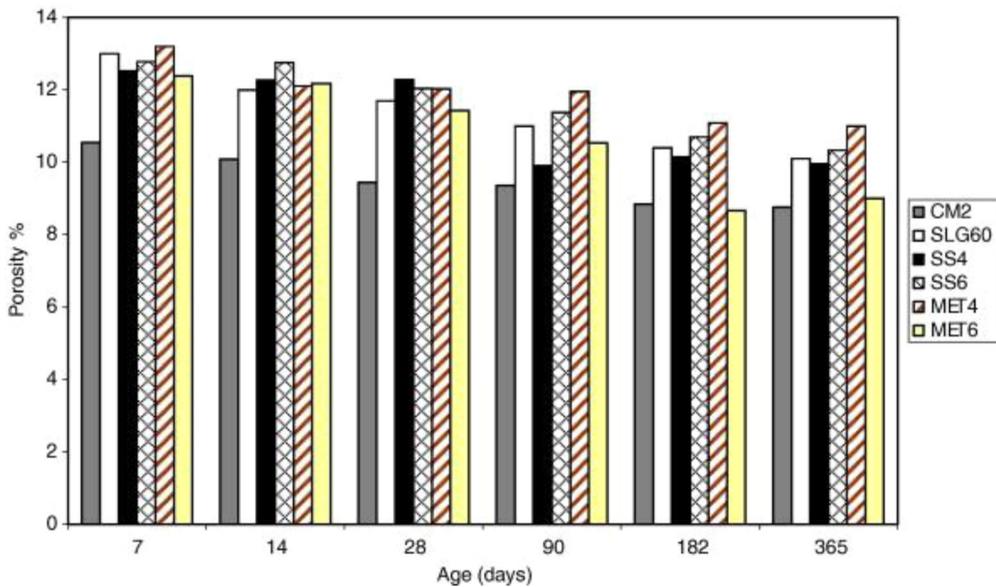


Figure 12. Porosity of concrete (Al-Otaibi, 2008).

9. Porosity and sorptivity

It is the excellence of concrete being absorbent or jammed of petite holes. The pore size, distribution, microstructure and the hydration characteristics of Slag based Geopolymer binders rely upon chemistry and physical attributes of GBFS as well as the attitude of alkaline activator (Tanzer, 2010). Based on examinations of micro-structure and a study of form, shape or structure, i.e. morphology, of the developed phases, He has accounted that no formation of Portlandite – a common product of the hydration of OPC in the form of $\text{Ca}(\text{OH})_2$, was found to occur and microstructure of the binders with Hydroxide and Silicate of Sodium was porous and enormous. Nevertheless, Al-Otaibi (2008) have evidence that microstructure of binder along with an activator Potassium Silicate (K_2SiO_3) was opaque having visibly closed surface devoid of any ability to be seen pores. This was owing to precipitation of silica gel that cross-linked the particles of slag and filling of vacant holes. Also, Al-Otaibi (2008) have monitored greater values of porosity of Slag based Geopolymer concrete as compared to OPC-concrete. He has recorded 13 to 10 percent values of porosity in 7 days to one year for Slag based Geopolymer concrete. On the other side, for an identical period, 10.4 to 8 percent values of porosity were evidenced for OPC-concrete (see Figure 12). Qureshi and Ghosh (2013) have investigated in context to the porosity of Slag based Geopolymer paste with water cured specimens at an ambient 28°C temperature and also samples

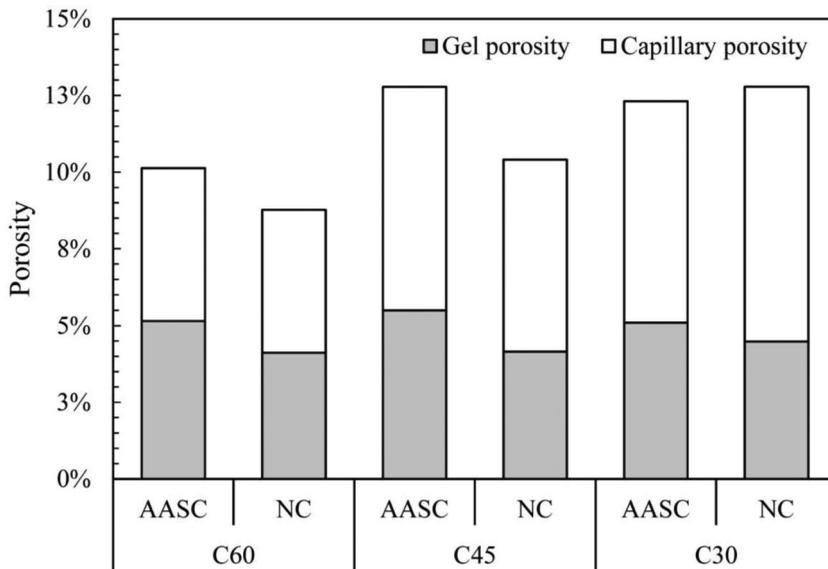


Figure 13. The porosity of AASC and NC concrete (Chen & Brouwers, 2007).

subjected to heat curing at 40, 50 and 60 °C. They have encountered a diminish in apparent porosity concerning specimens with water curing in comparison with specimens of oven curing with a range of content of alkali from 6.41 to 10.41 percent. After that, there was observed a boost in apparent porosity with 12.41 percent content of alkali. Also, a similar tendency was noted for all other kinds of conditions of curing. The least apparent porosity obtained for specimens which undergone water curing was 10.10 percent with the content of alkali as 10.41 percent designating a more compact and homogeneous matrix structure. Bernal et al. (2011) have witnessed a lessening cleaning in whole porosity slag based geopolymer concrete than the corresponding OPC-concrete subsequent to curing of three months. On the other side, Chen and Brouwers (2007) have wrapped up that Slag based geopolymer binder possesses a higher porosity of C–S–H gel produced through hydration comparison with OPC-binder and greatest quantity of pores monitored were gel pores for toughened Slag based Geopolymer binder. As a result, they accounted that Slag based Geopolymer paste demonstrates a fine microstructure in comparison with OPC-paste. Yang and Lee (2013) have investigated a logical mixture design of foamed Geopolymer concrete in which GBFS was employed as raw material and activated by two kinds of alkali activators namely, 10 percent concentrated $\text{Ca}(\text{OH})_2$ + 4 percent concentrated $\text{Mg}(\text{NO}_3)_2$, and 2.5 percent $\text{Ca}(\text{OH})_2$ + 6.5 percent Na_2SiO_3 . The critical parameters of the test were ratios of water to binder (W: B) and the replacement echelon of Fly Ash for GBFS. They have made known that the number of micro-capillaries and non-natural air pores boosted with an augment in ratios of Water: Binder escorting to dwindle in compressive strength. Also, they have described that the quantity of bigger pores declined with more substitution up to 10 percent in Fly Ash, but beyond this level, it was found enhanced. The porosity of diverse concrete is represented in Figure 13. Karim et al. (2014) have also kept an eye on greater values of porosity for Geopolymer composite binder developed incorporation with Slag, POFA and rice husk ash than OPC. They have applied an ambient curing technique where pozzolan was subjected to activation by NaOH. Thokchom et al. (2009) have revealed that specimens of activated mortar developed with a higher content of alkali passed on least values of porosity and greater compressive strength.

9.1. Sorptivity

It is a measure of the capability of the concrete to soak up fluid or water by the process of 'capillarity'. That means it articulates the propensity of concrete to absorb and pass on water and liquids through capillary action. The conduct of porous specimen can be judged by measuring the rate of absorption of water via capillary soaking by specimens which are unsaturated and held immersed into water sans any water head. The said attribute of concrete is known as 'sorptivity', and its assessments have a

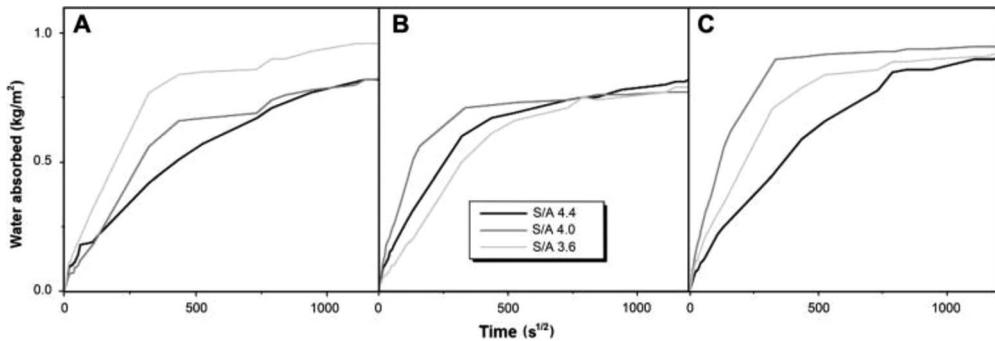


Figure 14. Sorptivity of GGBFS and MK based concretes different binder ratio (Bernal et al., 2011).

fundamental insinuation in reviewing the durability of Geopolymer binders (Kushal & Partha, 2012). The investigation of Bernal et al. (2011) was on sorptivity through capillarity of specimens of Slag based Geopolymer, and OPC-concrete developed with a range of quantity percentage of the binder for twenty-eight days curing (see Figure 14). Fagerlund (1982) have studied the kinematical action of capillarity soaking and has revealed that it relies entirely upon the capacity to resist the infiltration of water, indicate as 'm', along with the coefficient of capillary absorption, designate as 'k'. 'Sorptivity curves' land a hand to obtain the said two parameters. Keeping the content of the binder as constant, the values of the coefficient of capillary absorption (k) for OPC-concretes were recorded very high with a comparison to Slag based Geopolymer concretes. Whereas a slight disparity has monitored concerning values of 'm', i.e. resistance to penetration by water, among both Slag based Geopolymer concretes and OPC-concretes. Nevertheless, the specimens manufactured with 500 kg/m^3 of Slag in both AASand OPC have demonstrated a declining tendency of values of 'm' pointing towards a diminution concerning confrontation to the entry of invasive agencies into samples. Furthermore, the coefficient of capillary absorption 'k' relies wholly upon the porosity of the structure of pore in totality. He has examined that manufacturing of the concrete with 300 kg/m^3 has displayed a greater radius of pores since this content of the binder is insufficient to pack voids of particles of interim ingredient wholly. Nevertheless, the samples with a higher content of binder like 400 kg/m^3 have represented dense hydration products and permit them to fill spaces of the interim void. Also, Wassermann et al. (2009) have recorded analogous upshots for OPC-concrete along with relatively dense hydration product for the samples having 400 kg/m^3 content of binder. Bernal et al. (2012) have noted sorptivity through capillary for GBFS as well as MK amalgamations. Subsequent to curing for three months, they have monitored falling learning in context to values of 'k' for every sample. The values of 'k' evidenced were found low for the concrete prepared with the ratio of Silica to Aluminium ($\text{SiO}_2:\text{Al}_2\text{O}_3$) as 4.4 and 3.6 as well as the ratio of G:B [GBFS: (GBFS + MK)] as 0.9. The mixtures of zero and 20 percent Metakaolin with a boosted ratio of S:A has given rise to a declining tendency of value for 'k' of samples with three months age. On the other hand, the leaning of the samples with the lesser period of 28 days is not so distinct. Conversely, the report of Shaikh (2014) for the water sorptivity of Fly Ash-based Geopolymer concrete has displayed its inferior value in comparison with OPC-concrete. He has disclosed that the water sorptivity of Geopolymer concrete declines with the boost of Na_2SiO_3 content for a provided concentration of the solution of NaOH and the rate of dwindling value of sorptivity is found even more enhanced when the concentrations of NaOH is higher. He has stated ultimately that a noteworthy decrease in terms of sorptivity of Geopolymer concrete produced with highly-concentrated NaOH plus a high quantity of Na_2SiO_3 solutions may be liable for the formation of boosting the amount of dense Sodium-Alumino-Silicate gel in the matrix. Also, Puertas et al. (2000) have exemplified about the critical crisis of the concentration of a solution of NaOH in development of AAB where the dissolution of Alumino-silicate relies wholly upon the quantity of the content of hydroxide. Sodium silicate (Na_2SiO_3) also land a hand to make particles of Fly Ash soluble during the process of Geopolymerization, and the consequential unfilled spaces among particles of Fly Ash can be viewed because of the reduced quantity of Na_2SiO_3 in the solution. Hence, the vacant spaces of the matrix can be slimmed down with an augment in the content of Na_2SiO_3 . The inferior value of sorptivity of AAB signals towards detached fine pore structures inside the matrix and absorption of water as well as considerably declined sorptivity of concrete (He et al., 2012). Adam (2009) have accounted for superior

performance of Fly Ash based Geopolymer concrete when subjected to water sorptivity test in comparison with Slag based Geopolymer concrete, OPC-concrete incorporated with Slag and their corresponding OPC-concretes. Thokchom et al. (2009) have presented an explanation regarding Geopolymer mortar samples developed by using high quantity content of alkali that the same provided with least values for water sorptivity. Kushal and Partha (2012) have described collective absorption of water reduced with augmenting percent of alkali, i.e. Na_2O . They have documented high values of water sorptivity for Fly Ash-based Geopolymer mortar by using a low content of alkali. When Silicate ratio was augmented, they have found a gradual declining tendency in context to water absorption suggesting a more homogeneous and compacted structure. Consequently, they have winded up that the soluble Silicate optimistically impacts the values of water sorptivity. The above appraisal of the literature, divulge that the values of water sorptivity of AAB rely absolutely upon the content of alkali and ratio of Silicate of the mixture.

10. Resistance to chloride penetration

Chloride penetration is one of the most significant characteristics when coping with the durability of concrete. It first and foremost causes corrosion of reinforcing steel. The ions of Chloride can exist almost ubiquitously such as in water, fresh concrete mixture, additives, ingredients, etc. that necessitate porous structure of accessible waterway through which they could be pass and essentially transport. The salt absorptions by concrete having reinforcement result in anodic plus cathodic regions (Roa-Rodriguez et al., 2014). Hence, the development of cracks and reinforcing steel corrosion in the concrete can take place through electrolytic actions. The greater concentration of Sodium and Hydroxide ions was found present in the pore solution of Slag based Geopolymer binders. The existing Na^+ ions were found occupying the pores of the material must be present to counteract the Chloride ions which were diffused (applied electrically in the pore network) directing to an enhanced relocate of charge (Gruskovnjak et al., 2006; Puertas et al., 2004). Consequently, values of greater charge passed can provide a higher ionic strength in the pore solution of samples. Following the swift chloride permeability test by Bernal et al. (2012) who had observed charge passed for Slag and MK incorporated AAB. The values of 1000–2000 coulombs charge passed have been displayed by both pure and incorporated Geopolymer concrete which can be considered as low permeability of chlorides under testing method. Slag based Geopolymers developed by activators with very high concentrations has demonstrated values of greater charge passed subsequent to 28 days symbolizing greatly permeable chlorides. Concrete incorporated with 10 percent MK and ratio of Si:Al of 3.6 has demonstrated a declining tendency of values of charge passed which came to around 40 percent in comparison with Slag based Geopolymer concrete following 28 days. An addition of MK in the binder by 20 percent by weight with greater Si: Al ratio has displayed a drop in values of charge passed which came to about 30 percent than specimens of Slag based Geopolymer concrete (see Figure 15). They have monitored a small fall in the value of charge passed for curing of 90 days in context to every concrete mixture. They have accomplished that addition in MK in the binder may be insignificant concerning the values of charge passed for concrete samples which were subjected to 28 days curing. On the other side, Adam (2009) had examined that the Fly Ash-based Geopolymer concrete had exhibited an improved resistance when chloride penetration test was performed in comparison with Slag based Geopolymer concrete, OPC-concrete incorporated with Slag as well as pure OPC-concrete. Shaikh (2014) have investigated the durability of reinforced steel in Geopolymer concrete possessing diverse quantities of Na_2SiO_3 and dissimilar molarities of solutions of NaOH. Seven series of mixes were well-thought-out in the study experiment as represented in Figure 16. OPC-concrete has designated the first series and it was regarded as the controlled mixture. The 2nd, 3rd and 4th series comprised of three unlike Na_2SiO_3 : NaOH, i.e. activator ratios of 2.5,3 and 3.5 correspondingly where a 14M solution of NaOH was employed. The 5th, 6th, and 7th series were identical to the 2nd, 3rd and 4th series in each feature except for the concentration of NaOH solution, where 16M solution of NaOH was utilized. The solution of alkali activator to Fly Ash ratio was held identical to water: cement ratio of OPC mixture. In every series, three samples possessing a diameter of 100 mm and a length of 200 mm, each have one piece of 12 mm diameter steel bar enclosed were consider for a study of chloride-induced corrosion. The depths of chloride penetration of all seven series samples were measured, and the outcomes have displayed a low chloride penetration depth of Geopolymer concrete than OPC-concrete. A linear declining tendency of chloride penetration in Geopolymer concrete was encountered with the augmenting concentrations of a solution of NaOH and quantity of Na_2SiO_3 . In several cases,

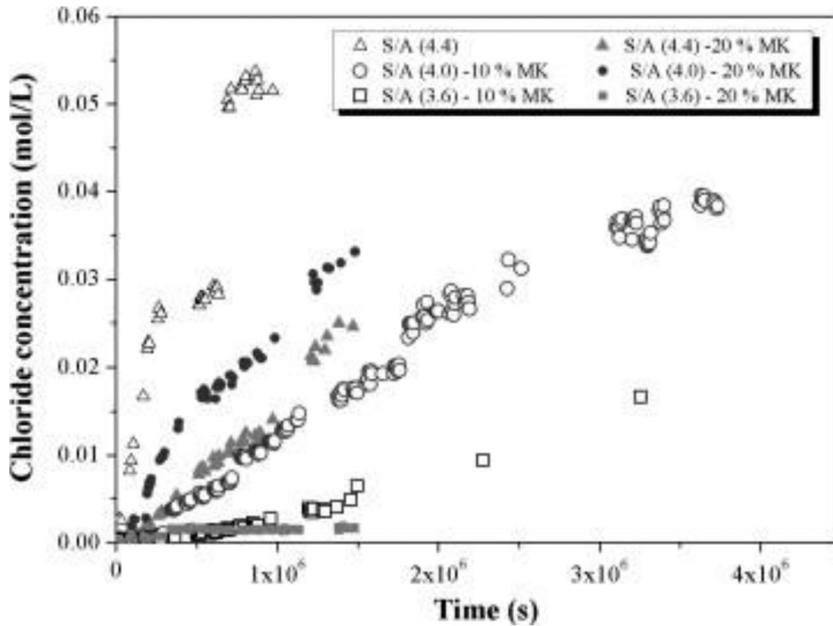


Figure 15. Chloride results in the downstream cell of GGBS and MK based geopolymer concrete (Bernal et al., 2012).

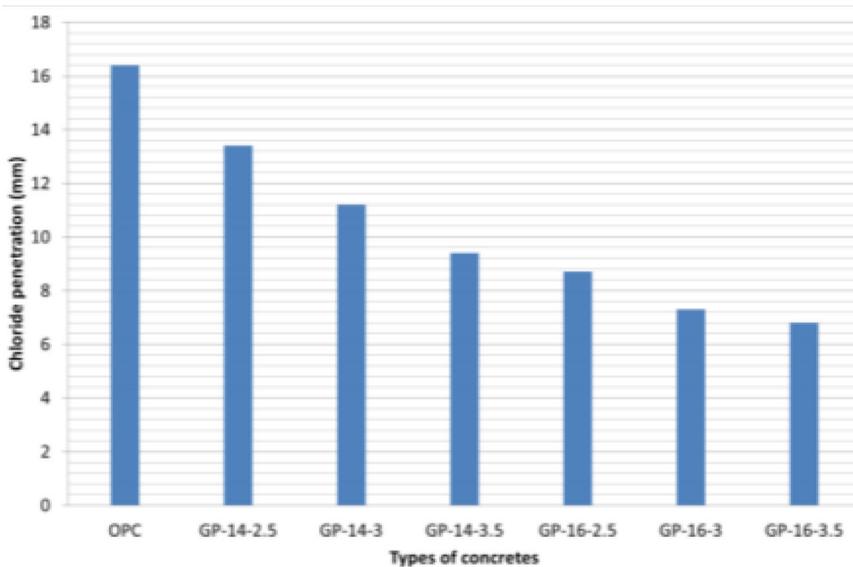


Figure 16. Chloride penetration results for geopolymer concrete (Shaikh, 2014).

the chloride resistance of Geopolymeric materials is equal or superior to OPC-materials by keeping an identical grade of strength. Chaparro et al. (2011) have found that the likelihood of corrosion of steel of Slag based Geopolymer concrete was equivalent to OPC-concrete in 3.5 percent solution of NaCl, and the chloride penetration touched at the interface of steel and Slag based Geopolymer concrete could trim down the resistance to corrosion. Also, Babae and Castel (2016) have revealed that the reinforced low calcium fly ash and slag based Geopolymer concrete display analogous values of polarization resistance to OPC-concrete when employed in environments which got contaminated by Chlorides. Monticelli et al. (2016a, 2016b) were of the view that improved protection of steel in fly ash based Geopolymer mortars may be associated to the low quantity of chloride ion and particular corrosion inhibition which

was provided by soluble Silicate ions. While the Fly Ash mortars suffer rapid carbonation, instead of only a restricted quantity of Chloride inside, the depassivation of rebars takes place concomitantly, as the plunged pH in pore electrolyte creates a decline in the dangerous chloride concentration, so that low Chloride concentrations are required to activate the corrosion of reinforcement. Tennakoon et al. (2017) have reported that the time consuming to start the chloride persuaded rebar corrosion in fly ash and slag based Geopolymer concrete was considerably more lengthy than in OPC-concrete. The content of chloride in Geopolymer at the rebar is recorded ten times inferior to in OPC-concrete. Furthermore, Ma et al. (2016) disclosed that the rate of corrosion of steel of Slag based Geopolymer concrete was also linked to sulphide concentration in pore solution. With a boost in sulphide concentration, the rate of corrosion, in general, declines because of the plummeting environment furnished by sulphides. When maintaining of the dosage of alkali as 6 percent and M_s value as 1.5, the rate of corrosion found is minimum in the chloride-environment, since the value of M_s about 1.5 is optimum for the hydration of Slag based Geopolymer concrete. The resistance to corrosion by Slag based Geopolymers also depends upon kind of activator. $\text{Ca}(\text{OH})_2$ activated slag demonstrates the most excellent resistance to Chloride in comparison with NaOH or KOH activated slag. This is assigned to the probability of $\text{Ca}(\text{OH})_2$ precipitations in the matrix which might have reacted with Chlorides to develop Calcium Hypochlorite ($\text{Ca}(\text{ClO})_2$) to diminish the free chlorides concentration in the pore solution (Park et al., 2015). The Slag based Geopolymer exhibited very low deepness of infiltration by Chloride in 30 percent solution of CaCl_2 in comparison to OPC and enhanced compressive strength in a 5 percent solution of MgCl_2 by Tennakoon et al. (2017). Also, the resistance to Chloride by fly ash based Geopolymer concrete was represented well than OPC-concrete. Effectual passivation of steels takes place in fly ash based Geopolymer mortars when subjected to exterior Chlorides. There monitored no deterioration in the case of samples of fly ash based Geopolymer on immersion into the solution of NaCl for a prolonged time of 1 to 2 year (Škvára & Kopecký, 2005). Nevertheless, in-house mixed CaCl_2 could speed up the rate of corrosion (Miranda et al., 2005). Class-F fly ash based Geopolymer concrete have greater resistance to Chloride in comparison with Class-C fly ash based Geopolymer and OPC, which is supposed to the lower Calcium products and dense matrix by Patil & Allouche (2013). Also, Shaikh (2014) has made known that the depth of infiltration of Chloride ion in Class-F fly ash based Geopolymer concrete is lesser than OPC-concrete and declined linearly with the enhancement in the compressive strength. Additionally, they have displayed the greater quantity of activator, the improved resistance to corrosion as pointed to low values of negative potential. In the case of Slag and fly ash based Geopolymer, Ismail et al. (2013) have disclosed that the gel chemistry, particularly chemical composition, had a significant influence on the transport of mass and ions in Chloridic environments. Meticulously, the resistance to chloride by Slag based Geopolymer controlled by C–A–S–H was superior to fly ash based Geopolymers, which were found dominated by N–A–S–H, i.e. the later is, of course, not as much compact as former.

10.1. Chloride binding

The capability of Chloride binding can be characterized by one or more parameters as an activity of the whole concentration of Chlorides. Generally, it is explained as a concentration of leapt Chloride Ion (Cl) as an act of free concentration of Cl. This ability of Cl binding is associated with the development of 'Friedel's salt' mostly in case of blended cement and afterwards the presence of oxide of Aluminium, i.e. Al_2O_3 . The formation of the said salt in the course of Chloride binding in OPC can restrain the relocation of Chloride and diminish the Chloride and Hydroxide ions in pore solutions (Balonis et al., 2010). This system is employed for estimating the jeopardy of corrosion to reinforcing steel. In cases of Slag based Geopolymer mortars, the possible impact of NaCl could influence the time for setting and improvement of strength. Nevertheless, novel produce of crystallization, especially, 'Salt of Friedel' was unobserved (Brough et al., 2000). In context to Geopolymer materials, Ismail et al. (2013) have stated that the occurrence of Friedel's salt was not found involved in the binding of Chloride. The binding of Chloride relies chiefly upon the absorption of products of reaction physically in place of a chemical reaction (Lee & Lee, 2016). As illustrated in Figure 16, the specimens of OPC have demonstrated the greater bound content of Chloride than fly ash and slag based Geopolymeric materials where the amount of bound chloride is diminishing as the slag quantity augmented. Still, the Chloride binding mechanism of Geopolymer materials requires certain clarifications and hence, more future investigations are desirable. Kayali et al. (2012) have revealed that formation of the 'Hydrotalcite' – Talc like alteration mineral with a high content of

water, in Slag based Geopolymer could soak up ions of Chloride through its exclusive feature of exchange of anion. They have utilized 16 g. 'Calcined Hydrotalcite' in a solution of NaCl and stirred it for one day period and found that the said mineral eliminated 72 percent ions of Chloride. Moreover, Park et al. (2015) have recorded the development of 'Calcium Hypochlorite $\{Ca(ClO)_2\}$ ' – an inorganic compound and key dynamic element of 'bleaching or chlorine powder or chlorinated lime', useful for the treatment of water and also as a bleaching agent – in Slag activated by Calcium hydroxide $[Ca(OH)_2]$ with 0.5 to 3.0 percent content of NaCl. This was attributed to the adsorption of $Ca(OH)_2$ physically to neighbouring Chloride.

10.2. Tests of resistance to chloride penetration

The migration of Chloride ions in concrete can be determined to employ diverse direct and indirect techniques. However, the familiar techniques are Chloride diffusion test, rapid chloride penetration test (RCPT) and non-steady-state chloride migration test (NSSM). The said three kinds of test methods provide dissimilar migration parameters.

10.3. Chloride diffusion resistance

The ingress of Chloride can be reviewed by Chloride diffusion or migration test, together with ASTM C1543. Here, the solution of NaCl was pooled on a slab or cylinder top of concrete structure for an extended period and specimens collected subsequently from definite depths to verify Chloride ingress silhouette. The inferior coefficient of Chloride diffusion encountered by analyzing Geopolymer materials than OPC (Mithun & Narasimhan, 2016). Della et al. (2000) have made known that the coefficient of Chloride diffusion of OPC and Slag mixes activated by NaOH has represented a gradual decline in boosting of Slag amount. Even though the Slag based Geopolymer materials have a greater capacity to absorb water, the coefficient of Chloride diffusion was notably subordinate than OPC, as disclosed by Ismail et al. (2013). The amalgamation of fly ash would boost the porosity and Chloride infiltration of Slag based Geopolymer concrete, and it gives the impression that the more, i.e. greater than 50 percent, the addition of fly ash, the mightier competence for Chloride binding. Both, the bound and free Chlorides in the mortar amalgamated with 75 percent fly ash are found with a declined coefficient. Incrementally, the upshots also gesticulate towards the impact on the infiltration of Chloride by a high concentration of activators (12 percent Na_2O). Following Ma et al. (2016), the Slag based Geopolymer concrete possesses greater content of superficial entire Chloride ions with an inferior unstable coefficient of Chloride diffusion in comparison with its corresponding OPC-concrete. While the coefficient of Chloride diffusion of Slag based Geopolymer concrete has declined with the quantity of alkali (4 to 8 percent). On the one hand, the diffusion of Chloride of saturated natural pozzolan incorporated Geopolymer concrete has boosted with the enhancement of water to binder ratio. Whereas, on the other hand, in context to the unsaturated fly ash based Geopolymer mortar and paste, Zhu et al. (2014) have accounted that the rates of infiltration of Chloride ion were greater than the majority of samples of OPC by keeping the equivalent degree of compressive strength on immersion into the saturated solution of NaCl for a week. Furthermore, they have regarded the rate of diffusion of Chloride ion of Geopolymer materials as having a relation with pore tortuosity and porosity. This had mitigated the ratio of liquid to solid and boosted the replacement of Slag, which could decrease the rate of infiltration of the chloride ion of unsaturated fly ash based Geopolymers efficiently. Tennakoon et al. (2017) have unveiled that the coefficient of diffusion of Chloride of fly ash and Slag based Geopolymer concrete is inferior to matching OPC-concrete, and the coefficient of diffusion have trimmed down with the boosting the content of slag in the binders.

10.4. Rapid chloride permeability test (RCPT) and non-steady state migration (NSSM)

RCPT and NSSM are frequently used to examine the infiltration of Chloride of OPC in a petite time phase. In the experimental study of RCPT include an application of a 60 V potential among the electrodes positioned on both faces of the sample. The value of RCPT is the passed on total charge in the testing for 6 h. Rodríguez et al. (2008) have established that the value of RCPT of Slag based Geopolymer concrete had the negligible influence of the content of Slag. Based on the outcomes of RCPT, the application of

silica fume with Slag based Geopolymer concrete has declined the rate of passing on current and enhanced the resistance to diffusion of Chloride (Steffens, 2002). Mehta and Siddique (2017a) have monitored that the adding up of OPC from 10 to 30 percent could considerably diminish the total charge passed of low calcium fly ash-based Geopolymers. Augment in quantity of Calcium with OPC has boosted more the C–A–S–H gels, which resulted in shaping the dense matrix. Bernal et al. (2012) have divulged that the integration of MK had only a slight influence on the charge passed of Slag and MK based Geopolymer concrete. Having been passed the supplied charge of 28 days or samples cured for three months were all found in the range of 1000–2000 °C whereas the capillary absorption and porosity have slimmed down drastically with age. They have put up the shutters starting that the formative factor in RCPT examination was the chemistry, i.e. chemical composition, of pore solution, instead of microstructures. The alkalinity and modulus of activators could also sway the value of RCPT of Slag based Geopolymer concrete. The broad-spectrum outcomes which were recorded reveal that the greater the Ms, the inferior the charge passed (Law et al., 2012). Chi et al. (2012) had evaluated the value of RCPT of Slag based Geopolymer concrete and met with a drop off when the alkalinity declined from 6 to 4 percent. Balcikanli and Ozbay (2016) have brought to a close that the value of RCPT could not stand for the authentic Chloride permeability, on account of the impact of high concentration of an ion in pore solution. Undeniably, the relationship among RCPT consequence and a direct measure of the coefficient of Chloride diffusion are pitiable in slag and Mk incorporations Puertas et al. (2000). Nevertheless, the earliest current of Slag based Geopolymer concrete was identical to OPC-concrete while that of fly ash based Geopolymer concrete was greater than OPC-concrete and developed exponentially (Adam, 2009). The charge passed of natural pozzolans incorporating Geopolymer concrete was greater than OPC-concrete when the compressive strength has recorded as 33 MPa, but a greater strength was found in this case (Adam, 2009). The RCPT technique cannot be considered as reliable one to verify the authentic resistance to permeability of Chloride for Geopolymer materials on account of the presence of other free ions along with Chloride ions in pore solution that having an impact on the value of examined RCPT. Looking at the NSSM test, the coefficients of Chloride diffusion of Slag based Geopolymer concretes and mortars were slighter than OPC counterpart (Ismail et al., 2013). The depth of infiltration of chloride ion boosted as the quantity of fly ash augmented, analogous to the upshots of ‘Chloride ponding examination’. By maintaining the same degree of compressive strength, the coefficient of diffusion of Chloride for 28 or 90 days curing of Slag based Geopolymer concrete where Na_2SiO_3 was an activator found lower than OPC counterpart, though, the earlier had towering VPV. A few investigators have made a comparison of RCPT with NSSM. Ravikumar and Neithalath (2013b) have revealed that the compressive strength of Slag activated by water glass was greater than solid activator-like Na_2SiO_3 . Nevertheless, the earlier had a greater value of RCPT, perhaps linked to the excellent conductivity of a solution of the pore. The coefficient through NSSM is more dependable, owing to scarcer reliance on the conductivity of a solution of the pore in comparison with RCPT. Vance et al. (2014) have made known that the value of RCPT for 28 days curing of Slag based Geopolymer concrete where Na_2SiO_3 was an activator has been found identical to 56 days curing pure Portland cement concrete and OPC-concrete having 20 percent fly ash, and the coefficient of diffusion of chloride of Slag based Geopolymer concrete has been found similar to 90 days curing OPC-concrete having 6 percent silica fume. Ravikumar and Neithalath (2013a) accounted that the value of RCPT of solid powder of sodium silicate as an activator in preparing the Slag based Geopolymer concrete was inferior to pure Portland cement concrete, but it was alike to OPC-concrete possessing silica fume and fly ash.

11. Carbonation

Carbonation or depassivation of concrete is a significant issue related to its durability, which occurs when CO_2 of the atmosphere along with moisture, reacts with a hydrated product of cement forming Carbonates. It penetrates extremely slowly beneath the superficial exterior area of concrete. That means it is the attack on the existing phases that bear Calcium by CO_2 from the air converting it to CaCO_3 affecting the durability of the concrete. Puertas et al. (2006) have manufactured mortars of Slag based Geopolymer and OPC with aggregate to binder ratio maintained as 2:1 and activated by solutions of Na_2SiO_3 (ratio of $\text{Na}_2\text{O}:\text{SiO}_2$ was 0.85) and NaOH. There was no addition of any additives in the first sample, but in the rest, two shrinkage mitigating admixtures like Vinyl copolymer was added. Admixture utilized in the mortar was manufactured by employing one percent of Slag with the activator solution. The

outcomes of experiments have made known that 26 percent increase was found in the mechanical strength of samples of OPC subsequent to 120 days period of Carbonation as compared to the value of it for 28 days. No, augment in strength was monitored for 120 to 240 days for the duration of Carbonation. Puertas et al. (2006) have found out that disparity in terms of strength owing to Carbonation was reliant wholly on the kinds of activator employed. A decrease of mechanical strength by 14% was recorded for Na_2SiO_3 activated samples of Slag following 120 days period of Carbonation sans the admixtures. But, no more decrease of mechanical strength was found subsequent to 240 days time period of Carbonation. No momentous impact on the performance of mechanical attribute was encountered owing to carbonation for the adding on of Vinyl co-polymer plus admixtures mitigating shrinkage. The Slag based Geopolymer mortars where NaOH was an activator has displayed an analogous performance in context to mechanical strength akin to OPC-mortars where 93 percent augment in mechanical strength was noted for Slag based Geopolymer mortar having NaOH activator subsequent to 120 days period of Carbonation. Nevertheless, it has not demonstrated any modification concerning mechanical strength following 120–240 days age for Carbonation. A rate of Carbonation in concrete can be made certain through physical attributes of the solid binder, chemistry of the binder phase plus the porosity and permeability of the binder (Steffens, 2002). Also, Puertas et al. (2006) have quantified depth of Carbonation for Slag based Geopolymer mortars along with its OPC counterpart for an episode of Carbonation of 120 days using phenolphthalein indicator. Although a little Carbonation was monitored for OPC-mortar, a highly cavernous and concentrated Carbonation was evidenced for Slag based Geopolymer mortars. The Carbonation front recorded by them as maximum to 10 mm deep for Slag based Geopolymer mortar were utilized the only activator was Na_2SiO_3 (Puertas et al., 2006). While the application of only NaOH as an activator made, the deep Carbonated front noticed was mere of 3 mm depth. Aperador et al. (2011) have as well accounted greater values for Carbonation of Slag based Geopolymer-concrete where the samples of concrete possessed bars of steel entrenched with it. They have described the cause behind it that there were regions that may keep touch with decalcified precipitates of C–S–H gel within bars of steel of Slag based Geopolymer-concrete. What's more, they added on exposing the samples of concrete to CO_2 , Na^+ ion ruined bit by bit the matrix of Slag based Geopolymer-concrete through developing a more soluble compound. Consequently, in the pore solution, a Ca^{2+} of the C–S–H gel is merely answerable to hold back pH. However, a ratio of Ca:Si in C–S–H of OPC-concrete samples met with was 1.7 to 2.0, but the samples of Slag based Geopolymer concrete has represented the ratio as 1. For that reason, it can be wrapped up that the OPC-concrete possesses the greater aptitude to influence the pH of the pore solution in comparison with Slag based Geopolymer concrete. The C–S–H of the sample of Slag based Geopolymer concrete has been altered to $\text{Ca}(\text{OH})_2$ that, in turn, develops CaCO_3 when exposed to CO_2 of the atmosphere (Adam, 2009). The porosity may enhance in a matrix of the concrete because of the reaction of the Carbonates supporting the deposition of carbonate ions with simultaneous emission of CO_2 gas inside the concrete. That's why the reaction front infiltrates effortlessly inside the concrete (Adam, 2009). The carbonation of Slag based Geopolymer concrete takes place unswervingly at the C–S–H gel creating a low silica-containing gel and content of Calcium plus alumina phase. Consequently, greater rates of Carbonation by Slag based Geopolymer concrete was also encountered to Palacios and Puertas (2006). Also, analogous obiter dictum was crafted by Song et al. (2014) in context to Slag based Geopolymer binder. On top of that, they have chronicled that the key products of hydration of Slag based Geopolymer were C–S–H, having nearly no content of Portlandite, in contrast to OPC products. Subsequent to Carbonation, the C–S–H of Slag based Geopolymers had transformed into a non-crystallized Silica gel that was mainly expected to be answerable for declining of the compressive strength of them. Also, they have disclosed that a boosted dosage of the activator has reflected in the swifter reaction by Slag based Geopolymers and more formation of C–S–H, that might have favoured the compaction, resistance to Carbonation of the microstructure and compressive strength. Bernal et al. (2012) have investigated Carbonation attributes of Slag based Geopolymer and MK amalgamations. They have represented the monitored findings (see Figure 17), where they have met with a diminishing tendency regarding compressive strength (Figure 17(A)) directly as Carbonation progresses. Hence, it is more or less unclouded that the compressive strength relies upon the territory of binder which has not suffered Carbonation. Even though the area of the binder undergone Carbonation achieved a slight strength, but it was insignificant in sample s with 20% MK in comparison with other trials. Alike leaning was encountered for zero and 10% MK samples in context to a depth of Carbonation. On the other side, the correlation among the degree of Carbonation and volume of the pore (Figure 17(B)) have attained almost

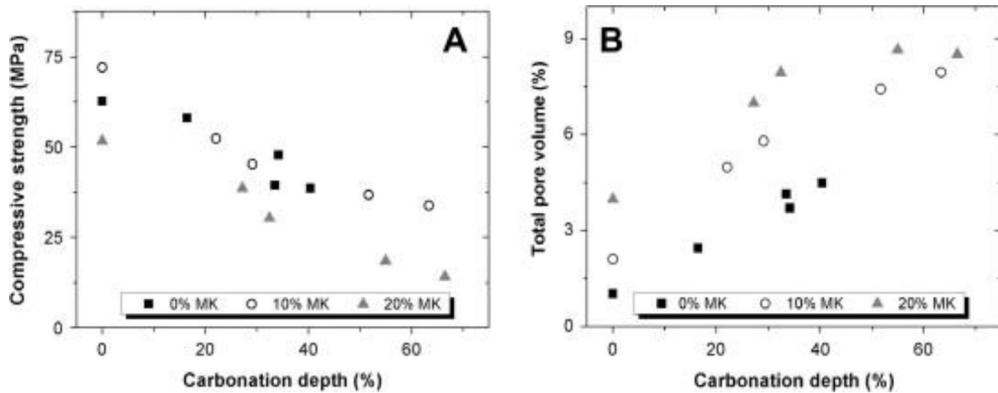


Figure 17. Carbonation depth and total pore volume of MK based geopolymer concrete (Bernal et al., 2012).

identical with 10% and 20% MK samples in comparison with GBFS samples. This signifies that the porosity is not the solitary factor controlling the diminution of the compressive strength in samples which have undergone the Carbonation. Bernal et al. (2012) have made known that the chemistry of binder gel must influence subsequent to speeded up carbonation, the leftover echelons of strength. Also, Bernal et al. (2010) have pointed up the impact of silicate modulus for the declined strength of Slag based Geopolymer and MK amalgamation because of Carbonation. They further described that on escalating content of MK with the binder rapid carbonation process has displayed a fall concerning compressive strength. They also monitored a greater likelihood of Carbonation for samples without MK that was activated by a low solution modulus ($\text{SiO}_2\text{:Na}_2\text{O}$ ratio). This feature facilitates the entry of aggressive agencies responsible for developing micro-cracks in structures and enhances the likelihood of degradation by the mechanism of transportation as well as also belittles mechanical presentations (Collins & Sanjayan, 2001). Bernal et al. (2013) have expressed the marvellous attributes of binders developed by Slag and Fly Ash-based Geopolymers for low discharge concrete manufacturing. They have exemplified that an extremely polymerized and steady Alumino-silicate gel stays in Slag based Geopolymers past Carbonation with acceleration. On the other side, alkali salts precipitation from the pore solution with a slight disparity in binder gel was accounted for Fly Ash based AAB. Nevertheless, two distinctive gels (C–A–S–H and N–A–S–H) were reported for activated Fly Ash and Slag incorporations owing to speeded up Carbonation Bernal et al. (2013). Besides, they have also disclosed that N–A–S–H gel behaved chiefly in Fly Ash-based systems whereas C–A–S–H gel operated mostly for Slag based system. On comparing AAS and OPC based binders, it has been found that Fly Ash based AAB have displayed an unlike structural and chemical characteristic, which was largely owing to the dissimilarities of Calcium of the binder as revealed by Li et al. (2010). Criado et al. (2005) have monitored crystallized Na-products in the Carbonated pore solution for Fly Ash-based Geopolymer binders throughout open curing. The samples which were in carbonated solutions have also exhibited a low rate of reaction plus inferior compressive strengths as compared to samples which had not undergone carbonation. Moreover, they have put forward the *raison d'être* that the burning up of alkali more probable for Fly Ash based Geopolymer binders throughout reaction of Carbonation piloting to an inferior rate of reaction along with a dwindle in pH value in the pore solution.

11.1. The impact of precursors on carbonation

The content and kind of precursors of Geopolymer composites impact the process of their Carbonation significantly. Augment of the quantity of Slag in Slag based Geopolymer concrete can not merely trim down the rate of penetration of CO_2 (Rodríguez et al., 2008) but also the depth of Carbonation (Bernal et al., 2013) on account of the formation of the denser matrix. Nevertheless, while the quantity of Slag was boosted from 400 to 500 kg/m^3 , the factor of water binder ratio had influenced the rate of Carbonation to a great extent. This was assigned to the formation of micro-cracks and also an impact of self-desiccation (Bernal et al., 2013), and hence, the optimum quantity of Slag should be employed in developing Slag based Geopolymer concrete to slim down the rate of Carbonation and associated jeopardy. Bernal et al. (2015) have studied under lower conditions of concentration, i.e. 0.2, 0.4 and 1.0

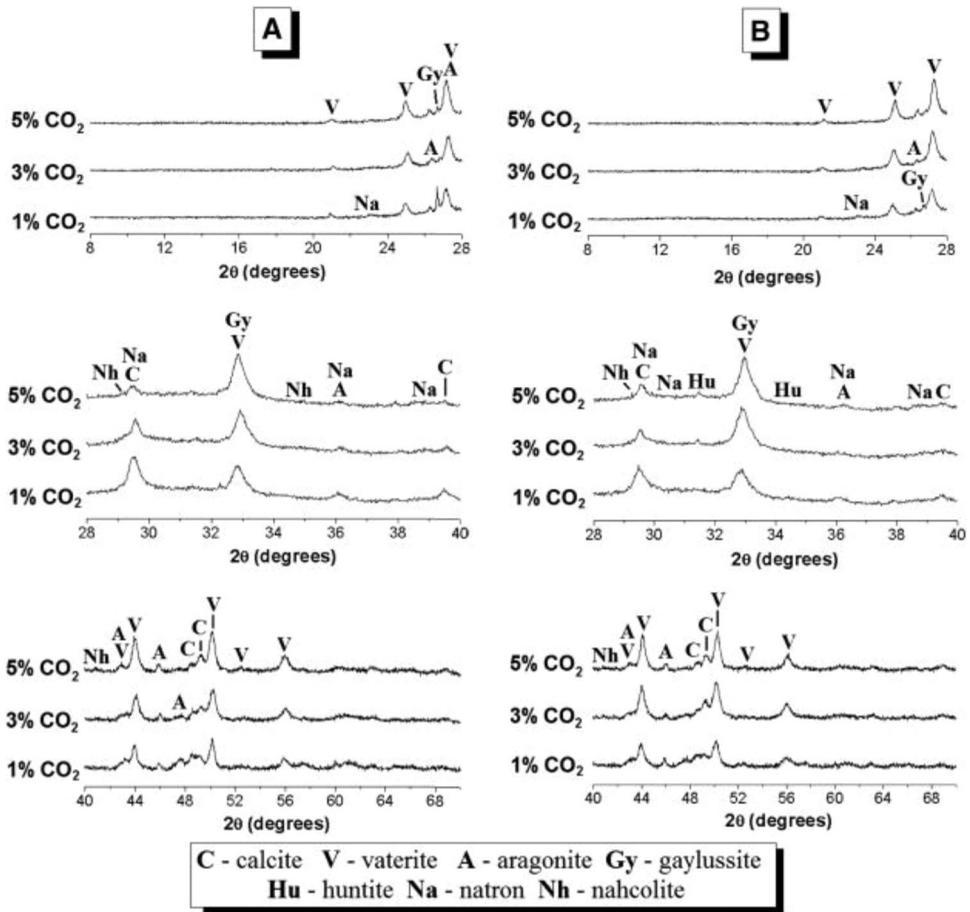


Figure 18. XRD image of slag based on alkali-activated concrete after (A) 1 day and (B) 7 days (Bernal, 2015).

percent of CO_2 that in what way the content of 1.2, 5.2 and 7.4 percent MgO with Slag has impacted the phase evolution and modification in the structure of Slag activated by Na_2SiO_3 . They established that the more is the quantity of MgO with Slag, the less is the depth of Carbonation. The development of mineral 'Hydrocalcite [$\text{Mg}_6\text{Al}_2(\text{CO}_3)(\text{OH})_{16} \cdot 4\text{H}_2\text{O}$]' in higher MgO conditions have played the role as an in-house adsorbent of CO_2 , that accordingly mitigated the concentration of CO_2 in pore solution. XRD image of slag based on alkali-activated concrete shown Figure 18. Normally, this type of impact is more palpable in natural surroundings. Sufian Badar et al. (2014) have revealed that the application of low Calcium content fly ash can enhance the resistance to Carbonation because of their low porosity in comparison with high Calcium content fly ash, i.e. Class F, $\text{CaO} = 12.93$ percent. The high Calcium fly, ash-based geopolymer concrete, demonstrates high values of permeability subsequent to Carbonation under 5 percent CO_2 conditions, and high threat of corrosion because of considerable diminution in the pH. In Slag and fly ash mixes of Geopolymer enclosing both C-A-S-H as well as N-A-S-H gels, Carbonation mechanism of particular gel is analogous to manufacturing with the single meticulous component. Bernal et al. (2013) have established that the decalcification of C-A-S-H in Slag based Geopolymers can create great scale modifications in the structure of the gel. The N-A-S-H gel of fly ash based Geopolymers is more permeable and highly alkaline pore solutions are all set to face Carbonization. Yet, the molecular structure of gel appears obligatorily unaffected following Carbonation. Slag and Metakaolin amalgamation based Geopolymers, the presence of Metakaolin can enhance the permeability of water subsequent to Carbonation. The sorptivity, through capillary action by Slag based Geopolymer concrete in the condition of 1 percent CO_2 for 250 h, was found threefold the samples sans Carbonation (Bernal, 2015). While, the addition of Metakaolin was 20 percent in Slag and Metakaolin Geopolymer mixtures, the entire

porosity of mortars declined following 340 h of Carbonation and the coefficient of sorptivity through capillarity plunges so much as 40 percent in comparison with samples which did not undergo Carbonation, as well as the coefficient of resistance of permeability of water, have also boosted consequently. When the conditions set were highly alkaline (9.1–14.5 percent), the addition of Metakaolin would pick up the pace for the structural advancement of Slag based Geopolymer at early juncture decreasing as a consequence the compassion of Carbonation since the Al plus Si of Metakaolin will be dissolved and precipitated, as well as the number of products of reaction augments. This viewpoint establishes the impact of precursors and essentiality of selecting their quantity and type for the Carbonation course of Geopolymer composites to get better durability.

11.2. The impact of activators on carbonation

Analogous to the impact of precursors, the activators concentration and its kind have an immense impact on the carbonation of Geopolymer composites too. Deja, (2002) have accounted that the rate of carbonation of Slag activated by Na_2SiO_3 was inferior to Na_2CO_3 -activated. Puertas et al. (2006) have studied the course of carbonation of Slag based Geopolymer mortars keeping conditions of saturated CO_2 plus the 'Relative Humidity (RH)' as 43.2 percent. In their outcomes, they found that when water-glass was employed as an activator, the decalcification of C–S–H has resulted in the mitigation of consistency of matrix of mortars and concrete strength on one side of the coin but a boost in the porosity after suffering Carbonation on another side of the coin. Nevertheless, when activator NaOH was utilized, the matrix coherence of mortars and strength of concrete found enhanced on the one hand, but entire porosity and the average dimension of pore declined subsequent to Carbonation on the other hand (Palacios & Puertas, 2006) Also, Pasupathy et al. (2016) have disclosed that the rate of Carbonation of fly ash and slag based Geopolymer concrete relies exceedingly upon the chemistry of activator. In natural conditions of Carbonation following a prolonged period of eight years, the Geopolymer concrete developed with activators like Hydroxides of Sodium plus Potassium ($\text{NaOH} + \text{KOH}$) along with Na_2SiO_3 , had displayed a pitiable resistance to Carbonation in comparison with OPC-concrete. Conversely, the presentation of the Geopolymer concrete manufactured with the activators NaOH and KOH only, though, with an identical mixture design and compressive strength has exhibited resistance to Carbonation equal to OPC-concrete. Two contradictory opinions on Carbonation performances of Slag based Geopolymers and Geopolymer concrete are floating. One has been argued by Law et al. (2009) that the Ms of activators of Na_2SiO_3 had an insignificant impact on them, whereas, Bernal et al. (2010) have declared in favour of the noteworthy impact. The quantity of Calcite and sorptivity through capillarity by Slag based Geopolymers with Na_2SiO_3 having Ms of 2.0 was higher than of Ms value of 2.4 following Carbonation by CO_2 under 3 percent conditions, and have revealed that the earlier had a better depth of carbonation, more amount of Calcite and larger sorptivity via capillarity. The influence of pore blockage resulted owing to the precipitation of CaCO_3 was found feeble than the humiliation of micro-structures subsequent to Carbonation. The key products of carbonation of Slag based Geopolymers are found in form of Calcite, Vaterite and Aragonite containing CaCO_3 (Puertas et al., 2006). Highly alkaline solutions of the pore may escort to the development of Natron having a chemical formula of $(\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O})$ in Carbonation while the lower alkaline solutions support the growth of Trona, i.e. $[\text{Na}_3\text{H}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}]$. That means the concentration of solutions of alkalis has an impact not only on the course of Carbonation but also on the formation of its products to a great extent. What's more, waste boosting of the concentration of activator, Na_2SiO_3 , from 3 to 7 percent (i.e. the percentage of Na_2O by mass of binders) can shrink the rate of carbonation Geopolymer composites (Song et al., 2014). Bernal (2015) has made known that a higher concentration of Na_2SiO_3 activator such as 9.1–14.5 percent, support the dissolution of the ultimate products of reaction and Metakaolin too. Subsequent to Carbonation of specimens, the compressive strength recorded was sans any evident loss but the rate of Carbonation and permeability were found mitigated in opposition to, preceding research work by Bernal et al. (2012) which had signalled that the compressive strength of Slag and Metakaolin based Geopolymer concrete was met with a decreasing trend-following Carbonation but the permeability was found boosted with the identical activator concentration. The said deviation may have a relation with dissimilar CO_2 -concentrations of 1 and 3 percent in that order of these two tests of Carbonation.

11.3. The impact of CO₂ - concentration on carbonation

The conditions for Carbonation together with a concentration of CO₂ must be considered for Carbonation examinations and in framing the specifications. Visser (2014) have investigated OPC concrete in context to the impact of a high CO₂-concentration that it will not alter the Carbonation course and the lone influence of the high CO₂-concentration is swifter transportation of the CO₂ to the interface of pore air and pore solution. Nevertheless, Cui et al. (2015) have accounted that the speeded-up Carbonation test with higher CO₂-concentration of more than 20 percent is inappropriate to forecast the natural Carbonation of OPC, owing to the dissimilar dispersal mechanisms among higher (50–100 percent) and lower (2–20 percent) CO₂-concentrations. About accelerated Carbonation tests, Castellote et al. (2009) have reported that the micro-structures under 3 percent of CO₂ (65 percent RH) is more identical to respective natural Carbonation (0.03 percent CO₂) than those at 10 and 100 percent CO₂. Also, Leemann and Moro, (2016) have revealed that the enhancement of CO₂-concentration from 0.045 to 1% and 4 percent (57 percent RH) has an insignificant effect on the level of resistance to Carbonation. Fascinatingly, the significance of CO₂-concentration concerning the course of Carbonation of Geopolymer composites has been investigated by many researchers. Häkkinen (1993) has made known that the rate of carbonation of Slag based Geopolymer concrete at 3 percent CO₂-concentration was swifter than the Slag incorporated Portland cement and concrete manufactured with Portland cement. The upshots of Carbonation was characterized by the development of micro-cracks. Rodríguez et al. (2008) have studied the carbonation rate of Slag based Geopolymer concrete at 7 percent CO₂-concentration and have monitored it around threefold of OPC-concrete along with a bigger loss in context to compressive strength supporting the outcomes obtained by Law et al. (2012) through tests at 20 percent CO₂-concentration. Pouhet and Cyr (2016) have investigated the Metakaolin-based Geopolymer concrete of Carbonation of the pore solution. The accelerated Carbonation at 50 percent CO₂-concentration has supported the development of huge quantities of Sodium Bicarbonate, which is accountable for an inferior pH of the pore solution. Nevertheless, in natural CO₂-concentration conditions, the development of Sodium Carbonate has not demonstrated any decline of pH beneath 10.5 for 1 year, which was found greater than the steel depassivation perimeter of 9. Bernal et al. (2013) have divulged that the crystal stages and the quantities of products of Carbonation in Slag based Geopolymer were dissimilar in the cases with higher CO₂-concentration conditions and with natural atmosphere. There was an absence of Bicarbonate in Slag based Geopolymer following Carbonation for three years under the atmospheric conditions, but while CO₂-concentration was boosted, the appearance of Sodium bicarbonate in association with a little monohydrate Sodium carbonate as well as more amount of Vaterite and Aragonite was also observed (Bernal et al., 2015). Subsequent to a long-standing Carbonation, meta-stable Vaterite and Aragonite has altered to Calcite, as the only stage of Calcium carbonate. Also, Calcite is the key product of carbonation of Slag based Geopolymer in natural environmental conditions Bernal et al. (2013). The impact of CO₂-concentration is strongly interrelated to the phase equilibrium of Na₂CO₃-NaHCO₃-CO₂-H₂O (Huseien et al., 2018). Bernal et al. (2013) have instituted that the ratio of Carbonate or Bicarbonate in Slag based Geopolymers was constantly bigger than 1 throughout natural conditions of Carbonation but lesser than 0.1 concerning higher CO₂-concentration (4 percent CO₂). When the CO₂-concentration was 4 percent, the key product of the Carbonation encountered was 'Nahcolite', but when there was a natural condition, it was 'Natron'. A boost to some extent of CO₂-concentration from 0.03 to 0.2 percent had encouraged the development of Nahcolite (NaHCO₃) and Trona. Nevertheless, the molar volume of Nahcolite is lesser than Natron; consequently, the pore blockage impact is not noticeable, and could not put a stop efficiently to the penetration of CO₂ (Bernal et al., 2013). On testing of Carbonation at 1 percent CO₂, the porosity of Slag and Metakaolin has enhanced monotonously, and the sorptivity through capillarity reduced (Bernal et al., 2015). Moreover, when CO₂-concentrations greater than 1 percent, the decalcification of C-A-S-H gel could be resultant uncharacteristic smash up of structures of the pore, modify the pH of pore solution and structures of gel (Bernal et al., 2013). Instead of the porosity of gel, inside comparative dampness and the grouping of Na⁺ ions and gels could also affect the CO₂ dispersal and precipitation of sodium salt (Bernal et al., 2013). It may be settled on the quick tests for carbonation of Geopolymer composites where, CO₂ > 1 percent and it would be tricky to demonstrate the performance of carbonation in natural environmental conditions, because of the altered equilibrium of carbonate of alkali stages with the escalating CO₂-concentration. A concise synopsis on the products of Carbonation of Geopolymer composites under diverse CO₂-concentrations.

11.4. The impact of RH on carbonation

The RH factor concerning Carbonation is also important. In a study by De Ceukelaire and Van Nieuwenburg (1993), the utmost rate of Carbonation was monitored at 50 percent RH (may vary among 40 to 90 percent) in Slag-concrete under 0.03 and 10 percent CO₂ concentration. Russell et al. (2001) have explained that the rates of Carbonation of OPC found mitigated with boosting of RH from 55, 65 and 75 percent under 5 percent CO₂ concentration. While, at 4 percent concentration of CO₂, there found an augmenting RH trend from 57 to 70 percentage, whereas, 80 percent dwindle in the value of the coefficient of carbonation encountered because of the arising quantity of pores filling up with water as investigated by Leemann and Moro (2016). Galan et al. (2013) have revealed that the enhancement of RH from 53 to 75 percent has trimmed down the rate of combination with CO₂ noticeably, but the highest CO₂ binding has enhanced a little. The both RH-inner and external, have also affect on the Carbonation of geopolymer composites. The chief product of the reaction was free Lime (CaO) exposed for 24 h at higher RH (of 80 percent) condition was Calcite (0.03–0.04 percent of CO₂ concentration), whilst three kinds of Calcium Carbonate stages have coexistence at the moderate value of RH (of 20 to 60 percent) (Dubina et al., 2013). Gas permeability of Slag based Geopolymer concrete is susceptible to the spatial allocation of damp and content, meticulously while is greater than 65 percent (Yang et al., 2016). The possible swiftest rate of Carbonation of Geopolymer composites generally forms at 65 percent (maybe plus or minus 5 percent) of RH or sometimes with the wide range of 50–80 percent RH (Bernal et al., 2015). This was attributed to the sluggish dispersal of the CO₂ at high conditions of RH, whereas the dissolution of CO₂ and the development of Carbonic acid have mitigated in lower RH (Deja, 2002). Nevertheless, the slow stabilization of structures of the gel may be answerable to the absence of an obvious effect of RH following a long-lasting Carbonation. An improvement in context to the resistance to Carbonation of Geopolymer composites can be brought about by upholding higher inner RH (Adam, 2009). The curing is controlling rules at higher RH can eradicate the early Carbonation of fly ash based Geopolymers. Consequently, the decline in the rate of activation and strength of fly ash occurred through primary Carbonation can be managed efficiently (Criado et al., 2005). Also, Ismail et al. (2013) have made it known that the pre-drying course of action ahead of tests of permeability would impact on the attributes of the microstructure of Geopolymer composites by the likely micro-cracks. Nevertheless, the rate of Carbonation of gels of saturated nature will be sluggish, particularly for samples having inferior permeability provided the procedure of pre-drying is absent. Hence, a correctly designed pre-drying technique of Carbonation is still very essential.

12. Drying shrinkage

Prior to loading, on account of the loss of capillary water, the contracting of a toughened concrete mix takes place and this shrinkage is causing a boost concerning tensile stress that ultimately may escort to exterior deflection, inner warping, and significantly cracking. Owing to the chemical reaction of water with the reagent, the cutback cropped up in the entire volume which is known as chemical shrinkage. The boost in chemical shrinkage of AAB occurs chiefly by Hydrotalcite and C–S–H gel (Chi et al., 2015). The chemical shrinkage is a momentous characteristic of materials that impact on the long-standing durability and structural attributes of the designed concrete structures. Rashad (2013) have researched on Fly Ash-based Geopolymer mortar samples which demonstrated a very negligible shrinkage when subjected to drying and the drying shrinkage has enhanced as the content of Slag augmented in the matrices of mortar (see Figure 19). Also, they have examined a higher steadiness of Fly Ash-based Geopolymer mortar in comparison with Fly Ash plus Slag incorporated Geopolymer mortars. According to them, this is assigned to the sphere-shaped particles of Fly Ash which performed as a micro-ingredient and thereby amplified the volume steadiness. Shen et al. (2011) have investigated on activated tidy Slag plus Slag incorporated with Fly Ash for drying shrinkage test for the period up to two months and compared with shrinkage of OPC-binder. They further met with the bottommost value of drying shrinkage for OPC-paste and for neat Slag based Geopolymers was the topmost while Fly Ash was responsible for subordinating the drying shrinkage of pure Slag based Geopolymer paste. Chi et al. (2015) have explained the rate of drying shrinkage concerning OPC-mortars and fly ash plus Slag based Geopolymer mortars subsequent to curing of 7, 14 and 28 days. The rate of modification in length of all samples enhanced with the boost in maturity and liquid to the binder. Likewise, AAFly ash plus Slag based Geopolymer mortars represent

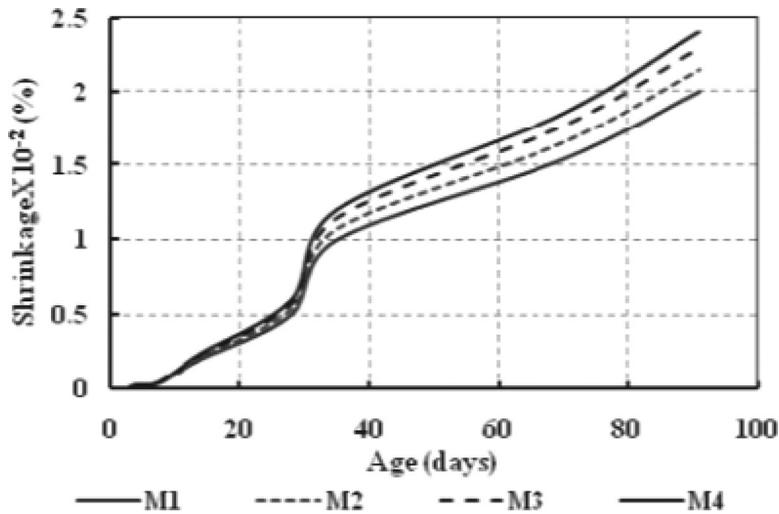


Figure 19. Dry shrinkage results for different mortar mixture (Rashad, 2013).

better rate concerning a change of length as compared with OPC-mortars for curing of all ages. Maintaining a constant ratio of liquid to the binder, a greater rate of change of length has been encountered in slag based Geopolymer mortars than Fly ash plus Slag based Geopolymer mortars. An inferior rate of change in length was evidenced for a greater quantity of Fly Ash addition to Fly ash plus Slag based Geopolymer mortars which have signified that the ratio of Fly Ash as to Slag has considerably impacted drying shrinkage attribute of Fly ash plus Slag based Geopolymer mortars and an adding up of Fly Ash directed to a dwindling rate of length change. It has been noted that Fly ash plus Slag based Geopolymer binder possessing ratios of Fly Ash:Slag as 100:0 illustrate an approximately equal rate of length change as OPC-mortars have. Looking to the one side of a coin, a few researchers (Rangan et al., 2006; Shen et al., 2011; Wallah & Rangan, 2006) have recorded an inferior drying shrinkage of Fly Ash-based Geopolymer binders as compared to OPC-binders, while the on the other side of the coin, there found an account by some other investigators favouring a greater drying shrinkage of Slag based Geopolymer binder than their counterpart OPC-binder (Cartwright et al., 2013a, 2013b; Chi et al., 2012). Though, the scientific way of thinking behind the higher drying shrinkage performance of Slag based Geopolymer materials is still mysterious and hence, necessitates to study in detail. Also, a hypothesis in context to the same by some of the researchers has put forward that on subjecting to drying, a higher capillary force might arise in the materials possessing fine pore structures analogous to Slag based Geopolymer materials (Collins & Sanjayan, 2000; Neto et al., 2008).

13. Efflorescence

'Efflorescence' – a French word meaning 'to flower out' or a Latin word 'flourish' meaning 'flower', i.e. literal or metaphorical act of blossoming much analogous to flower – is a brilliant or off-white colored powdery deposit of crystallized salts in form of coating left behind through evaporation of water and commonly encountered on the exterior surfaces of brick, concrete, stucco, natural rocks, soils, other masonry structures like plasters, etc. in mostly warm regions of the earth. That means when the water suffers evaporation; the minerals leftover is commonly known as 'efflorescence'. It happens to occur when there is a presence of water on or inside the surface of concrete or other masonry structures. In the case of mineral-rich water, sometimes containing other dispersible materials, in the inner side of a structure, water came out on the exterior surface of concrete, mortar, other masonry products like brick, etc., through the action of capillarity and subjected to subsequent evaporation under dry, warm conditions. Usually, the mineral content was found representing Gypsum, Calcite, salts, etc. Hence, it is a migration of inner dissolved salts to the surface of a structure which is mostly porous. In short, it is all about structural smash up to constructional materials via forces of capillary challenging the durability of

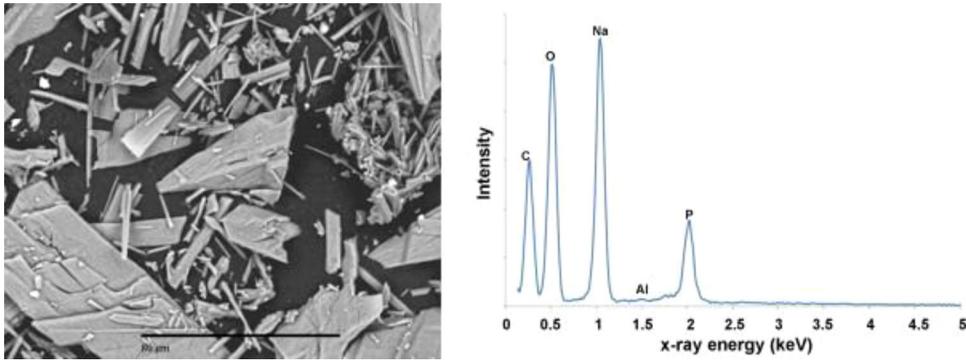


Figure 20. SEM and XRD image of efflorescence crystals present in the concrete (Temuujin et al., 2009).

edifice materials. Although the topic of efflorescence in Geopolymer materials, especially binders, is comparatively new-fangled, a few researchers have endeavoured to address the said crisis. By with Skvara et al. (2008), the bonding among the Sodium ions (Na^{+1}) and the structure of Alumino-Silicate are feeble, which favours leaking attitude. They further have expressed in context to the crystallized Zeolites the leaking of Sodium is found very slight in contrast to the Alumino-Silicate possessing polymers. The presence of water is answerable for the weakening of the bonding between Sodium ions and the Alumino-Silicate polymers. This type of phenomenon is verified with the structure model of Geopolymer binder too. Also, Pacheco-Torgal and Jalali (2010) have revealed that Na-efflorescence is greater in Geopolymer binders based on Alumino-Silicate as predominant source materials Calcined at arrange of temperature less than the temperature level for dihydroxylation with the adding up of Na_2CO_3 as a source of Na^+ . Temuujin et al. (2009) have reported that even though ambient cured fly ash based Geopolymer binders have displayed efflorescence, but the above said phenomenon had not been monitored when the same Geopolymer binders have subjected to curing at higher temperatures. This means that the leakage of sodium could be a signal for inadequate Geopolymerization. SEM and XRD image of efflorescence crystals present in the concrete shown in Figure 20. Quite recently, Van Deventer et al. (2010) have disclosed that existing two-part Geopolymers experience severe efflorescences which are derived from the fact that additional 'alkaline and soluble Silicates during the process could not devour completely all through Geopolymerisation'. Another recent study by Kani et al. (2012) has represented that efflorescence can be diminished either by the adding up of admixtures rich in Alumina content or by applying to cure of hydro-thermal nature at temperatures of 65°C or more. Supplementary to this, they made it evident that the application of 8 percent of Calcium Aluminate cement declines largely the of alkali mobility escorting to least amount of efflorescences depicted. The cement employed by them was containing 28 percent of CaO content.

14. Conclusion

Ultimately, in conformity with the published literature, a state-of-the-art review, which studied the modern steps in the developments of the set of environmentally benevolent green geopolymer concrete (GGPC) technology in the light of its advancement history of research and durability bewilderment, the following conclusion, emerges out:

- Sufficient research investigations have previously been carried out to apply the pozzolanic Slag and Fly Ash in this field using diverse activators of a range of concentrations to study water absorption, porosity, sorptivity, chloride penetration, sulphate resistance, carbonation, corrosion resistance, acid resistance, drying shrinkage, etc. of green geopolymer concrete.
- An enhanced durability of GP-concrete is revealed by researchers when incorporated with Slag, Fly Ash, Meta Kaolin, POFA and RHA both alone or in their blending.
- Even though, the opinion of all researchers concerning durability is not unanimous as it leaves behind some divergences on their results, they all are agreed upon establishing a preset standard for the said property of green GP-concrete.

- A few researchers have encountered better-quality durability of green GP-concrete with a variety of activators of dissimilar concentrations to that of OPC- concrete.
- An effectual supplement of the pozzolanic materials into GGPC could put forward benefits viz., diminution of OPC consumption, Costing of construction projects and mitigated emission of CO₂ along with with with a systematic solution to its disposal predicaments.
- GGPC appears to be competent enough to resist to freeze-thaw cycles highly, but still elaborating investigations are desirable to establish ultimately.
- Nevertheless, GGPC are susceptible to the creation of efflorescence, this drawback can be mitigated to a great extent by employing treatments of hydro-thermal curing or by applying admixtures of Calcium Aluminate.

15. Viewpoints

- A. The characteristics of permeability and absorption of water of GGPC depend mainly on the structures of pores and chemistry of gel, for instance, a boost in slag percentages and concentration of activator up to fixed boundary can diminish the both of them. But, at this point, the influence of paste ingredient interface, the age of specimen and other related factors affecting both these factors should also be remembered. Specifically, the induced cracks at some stage in before drying course have a gargantuan impact on the test outcomes following the OPC specifications and standards. Therefore, the inapposite design process for pre-drying e.g. drying to constant weight at 40 °C, or even far better technique to confirm both – permeability and the absorption of water – in the days to come.
- B. The activators and precursors are affecting principally, the process of carbonation of GGPC, i.e. a boost in a concentration of activator along with MgO present in the Slag, or decreasing Calcium from low calcium fly ash can improve the resistance to carbonation. In laboratory tests (pre-drying temperature below 60 °C), when CO₂ concentration is beyond 1%, it is challenging to symbolize the process of natural carbonation course of GGPC. More studies on the staged reaction among CO₂ and pore solutions gel phases are desirable, and the impact of drying setting and maturity of the specimen on the carbonation behaviour is essential to look for suitable circumstances for experiments. The acceleration of carbonation of GGPC at CO₂ concentration less than 1% and RH 65 ± 5% can be helpful to achieve more authentic results.
- C. However, the resistance to the chloride of GGPC is normally found higher than OPC for low permeability, but the mechanism of bonding of chloride ions is still not fully comprehensible. The pore structures and chemistry of pore solution are the key factors controlling the Rapid Chloride Penetration Test (RCPT) results in OPC. On account of the complex chemical composition of pore solution in GGPC, the link among passed charge and chloride diffusion coefficient are found inadequate.
- D. Looking at the sulphate resistance of GGPC, it is mostly found better than OPC-concrete. The resistance to Na₂SO₄ by GGPC with high-calcium, e.g. Na₂SiO₃-activated slag, demonstrates better results than resistance to MgSO₄, while, the resistance to MgSO₄ by GGPC with low-calcium exhibits better outcomes than resistance to Na₂SO₄, specifically when NaOH is used as an activator. Additionally, the impact of alkali leaking on the sulphate resistance by GGPC is also a topic to investigate in days to come.
- E. The research on the durability of GGPC structures for belligerent environments should take into account the chemical and physical attributes of source materials, and proven track records of their prolonged durability demonstrations, rather than augmented experimental test outcomes under the great concentration of salt solutions or CO₂.

16. Suggestions for potential investigations

No doubt, the previous researches are quite enough to establish GGPC as an efficient construction material, but still, more supporting researches should fill some of the hiatus as well as its promotion for acceptance to employ, and for that, the following suggestions are proposed for potential investigations:

- A study of comparison of durability outcomes of a range of GGPC can be carried out utilizing diverse pozzolans and activators by modifying the concentrations of reagents to determine which the better one is.

- The durability characteristics of GGPC incorporating pozzolans may be further studied with exposure to different degree environmental conditions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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