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MECHANICAL AND DURABILITY PROPERTIES OF GEOPOLYMER CONCRETE – A REVIEW

Abstract

Owing to the ongoing increase in human population, there is a need for more construction projects including residential buildings and other amenities. Concrete is by far the dominant material used in construction and cement is a main ingredient. Cement manufacture is an energy intensive process and emit large amounts of carbon dioxide into the atmosphere. A reduction in the amount of cement used in construction is greatly beneficial. The use of geopolymer or alkali activated materials can serve this purpose as it attempts to totally replace cement in concrete. Geopolymers are materials that consist mainly of silica and alumina materials and activated using alkali such as sodium silicate and sodium hydroxide. This paper attempts to review recent articles on the production and properties of geopolymers and alkali activated materials. Different hardened, structural, and durability properties are studied. These include; compressive strength, flexural strength, modulus of elasticity, ultrasonic pulse velocity, shrinkage, expansion, creep, weight loss, carbonation, sulfate, and corrosion.

Keywords

Geopolymer Concrete, Alkali-Activators, CO2, Environment, sustainability, Waste.

1. INTRODUCTION

The need for buildings is becoming wider due to the massive increase in the global population. The most commonly used structures are reinforced concrete structures where concrete is considered as the dominant material used in the construction due to its relatively low cost, availability of raw materials and desired properties in construction. It possesses good mechanical and durability properties and the ability to be formed in many different shapes (Sata and Chindaprasirt, 2020).

Nowadays, one of the biggest and most dangerous challenges facing the humankind is the climate change and this was highlighted in the recent COP26 conference held in November 2021 in Glasgow (United Nations, 2021). The climate has been experiencing a steady increase in the earth temperatures which is partly due to the gas emissions emitted to the atmosphere (Shahmansouri et al., 2021; Cao et al., 2018). Cement is the main material used in concrete to bind the various constituents (Shaaban, 2021). The world consumption of concrete and cement is around 24 and 4 billion tons respectively (Gunasekera et al., 2019). The global CO_2 emission due to cement manufacturing stands at about 8% (Zannerni et al., 2020). Therefore, any reduction in the amount of cement used would be greatly beneficial to reduce the impact on the environment (Cheng et al., 2020; Zannerni et al., 2020; Sahoo et al., 2021). Many researchers investigated replacing part of the cement with waste and industrial byproducts (Bawab et al., 2021; Khatib et al., 2021; Hammat et al., 2021; Onturk et al., 2021; Merabti et al., 2021; Guettaf et al., 2020; Ghanem et al., 2020; Firat et al., 2020; Bawab et al., 2020; Ouldkhaoua et al., 2019; Baalbaki et al., 2019; Ghanem et al., 2019).

Geopolymers or alkali activated materials are relatively new materials that can be used to totally substitute the cement (Nergis et al., 2018; Daniel et al., 2017; Liu et al., 2020, Lahoti et al., 2019). They can be used in places exposed to sea water, fire, corrosion of steel bars, sulfates and other severe environmental conditions (Cheng et al., 2020; Bellum et al., 2020; Alex et al., 2016). Geopolymer concrete have a good fire resistance at elevated temperatures in contrary to traditional one (Singh et al., 2015). Despite all the massive advantages geopolymers have, there are some disadvantages including the process of production and the health and safety aspects to be employed while preparing these materials (Arunkumar et al., 2021; Nergis et al., 2018, Wulandari et al., 2021). Geopolymer concrete has numerous applications in construction including building repair, the maintenance of road transport infrastructure and precast structural elements (Abdul Aleem and Arumairaj, 2012). Moreover, it is very essential when used in; marine environments and concrete pipes exposed to a large volume of water, sandwich panels where a low weight and a high rigidity are needed and in structural elements such as beams, columns, slabs and footings in all its types isolated, combined, strip, raft and piles (Amran et al., 2020; Mahmood et al., 2020; Hassan et al., 2019; Tchakouté et al., 2017).

This paper reviews recent articles on the basic properties of geopolymer concrete. The fresh properties and absorption characteristics were reported in another paper (ElKhatib et al., 2021). This paper reports the mechanical properties and some durability parameters of geopolymer concrete.

2. MATERIALS USED IN GEOPOLYMERS

The main materials used in the production of geopolymers are silica or alumino silicate materials and the activating materials. Silica and alumino silicate materials include; metakaolin, natural zeolite, ground granulated blast slag, silica fume, natural pozzolans, calcined shale, red mud, nano-particles, rice husk ash, wheat straw ash, rice straw ash, fly ash, palm ash, wood ash, sugarcane bagasse ash, reed canary ash, bamboo leaf ash, banana leaf ash, elephant grass ash, corn ash, sunflower ash, palm oil ash (Chopra et al., 2015; Qudoos et al., 2018). Activating materials include; sodium hydroxide (SH), potassium hydroxide and sodium silicate (SS) (Jeevanandan and Sreevidya, 2020). Other materials include water, chemical admixtures and in some cases small amounts of cement.

Table 1: Chemical and Physical Properties of Sodium Silicate (Jeevanandan and Sreevidya, 2020)

Chemical Properties	
N_2O or Na_2O (Mass %)	14.7
SiO_2 (Mass %)	29.4
H_2O (Mass %)	55.7
Boiling point	102°C
Molecular Weight	183.03
Physical Properties	
Chemical formula	Na_2SiO_3
Appearance	White to greenish opaque crystals
Density	2.61 g/cm³
Melt point	1.088°C (1.990°F)
Solubility in water	22.2 g/100 ml (25°C)
	160.6 g/100 ml (80°C)
Solubility	Insoluble in alcohol

Table 2: Chemical and Physical Properties of Sodium Hydroxide (Jeevanandan and Sreevidya, 2020)

Chemical Properties	
Carbonate (Mass %)	2%
Chloride (Mass %)	0.01%
Sulphate (Mass %)	0.05%
Potassium (Mass %)	0.10%
Silicate (Mass %)	0.05%
Zinc (Mass %)	0.02%
Heavy Metals (Mass %)	0.00%
Iron (Mass %)	0.00%
Minimum assay (Mass %)	97%
Molarity	30
Physical Properties	
Chemical formula	NaOH
Molar mass	40.0 $g.mol^{-1}$
Appearance	White, waxy, opaque crystals
Density	2.13 g/cm³
Melting point	318°C (604°F; 591 K)
Boiling point	1,390°C (2,530°F; 1,661 K)

3. MECHANICAL PROPERTIES

3.1. Compressive Strength

The compressive strength of geopolymer concrete is highly affected depending on various factors including; water to binder ratio, amount of alkali activators such as sodium silicate, sodium hydroxide and nano-Al_2O_3, curing time and temperature and in some cases the amount of cement (Loganayagan et al., 2021; Carmichael et al., 2021; Li et al., 2019; Ramesh and Srikanth, 2020; Paul et al., 2020). Figure 1 displays the compressive strength values of geopolymer mixes containing rice husk ash as partial cement replacement and activated with sodium hydroxide and sodium silicate with a ratio SH/SS equals to 2.5 and a water to binder ratio of 0.45. The strength increased from 45 MPa at 50% cement replacement to 53 MPa at 100% replacement for mixes containing 0.3 polypropylene (PP) fiber. Similar trend is observed at 0.5% PP (Zabihi et al., 2018).

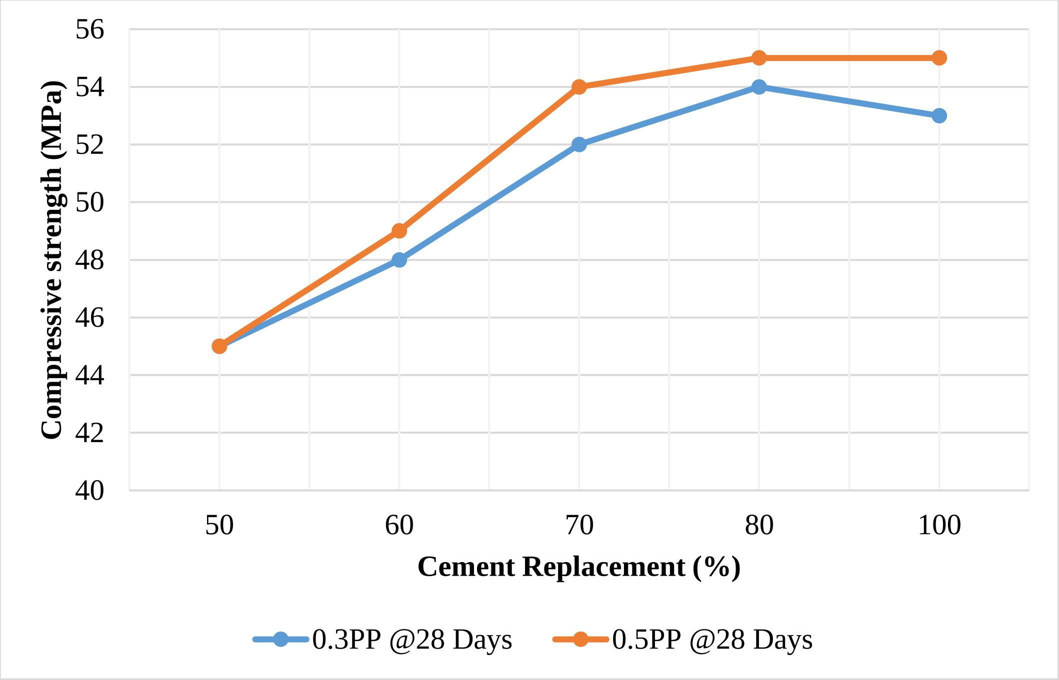

Fig. 1: Compressive Strength versus Cement Replacement (Zabihi et al., 2018)

Figure 2 shows that the compressive strength is highly affected by the molarity of sodium hydroxide. The optimum and highest value recorded to be 25.5 MPa and 27 MPa at 16 molars at both 7 and 28 days (Chowdhury et al., 2021).

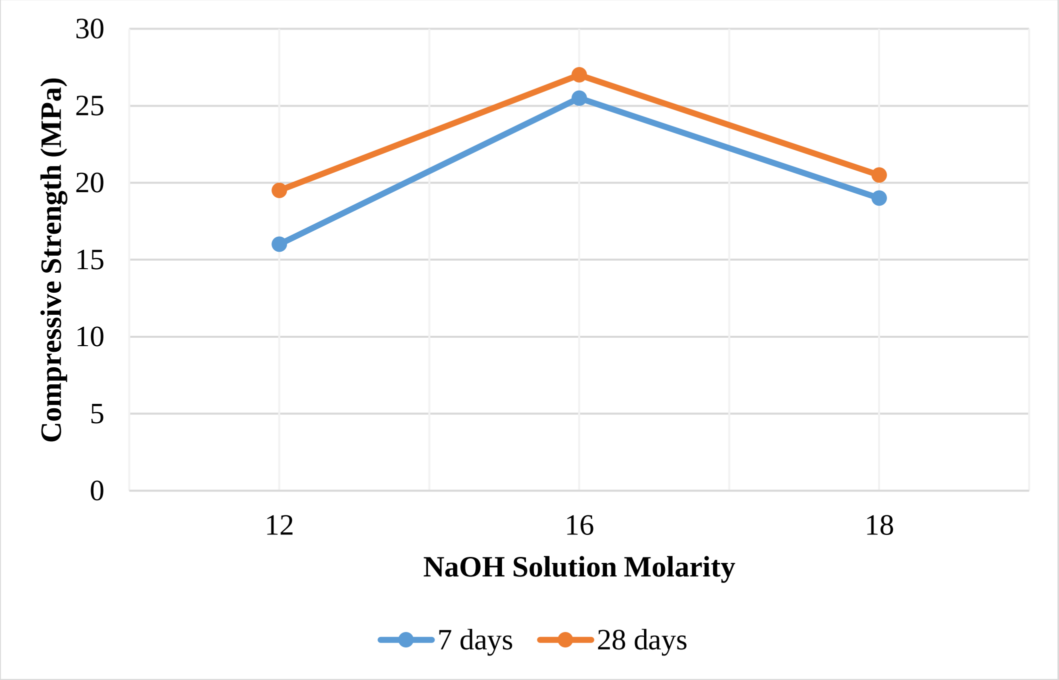

Fig. 2: Compressive Strength as Function of NaOH Molarity (Chowdhury et al., 2021)

When SH/SS ratio is expanded from 0.3 to 0.5, the compressive strength is reduced at both 7 and 28 days from 32 MPa to 23 MPa and from 35.5 MPa to 25 MPa respectively as shown in Figure 3 (Chowdhury et al., 2021).

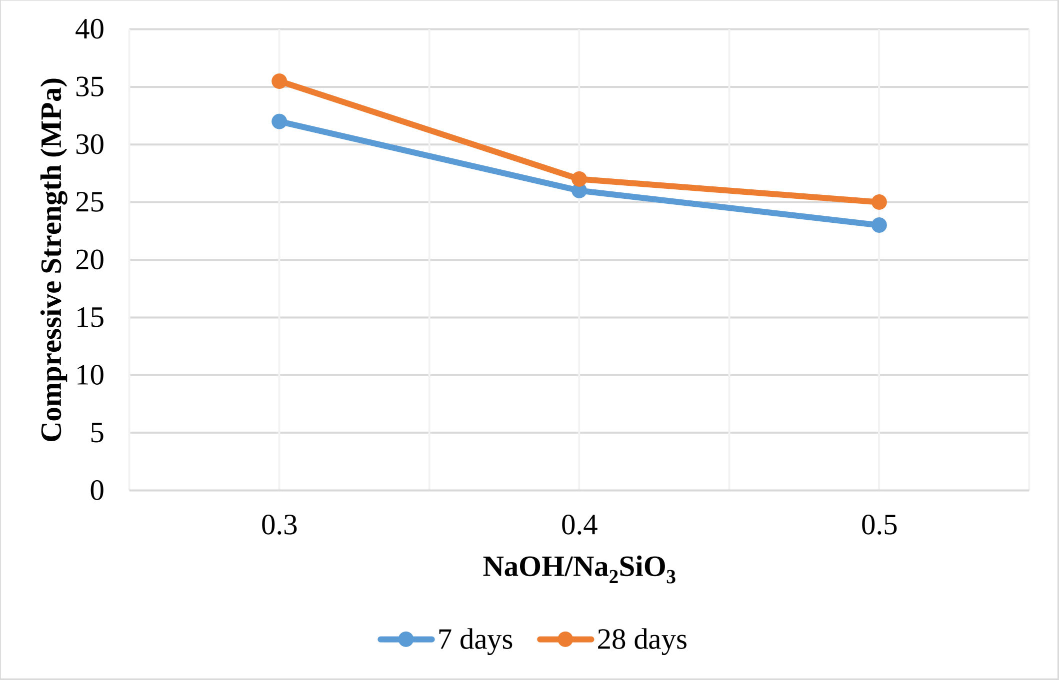

Fig. 3: Compressive Strength as Function of NaOH/Na2SiO3 (Chowdhury et al., 2021)

3.2. Flexural Strength

A study was done on geopolymer concrete mixtures containing different percentages of 2 different ashes: fly ash (FA) and low calcium waste wood ash (WA) in order to check the flexural strength behavior (Arunkumar et al., 2021). A value of 0.45 was used for activator to binder ratio and 2.5 for SS/SH solutions. Figure 4 demonstrates that as the percentage of WA increases in the mixture from 0% to 100% in contrast to that of FA, the flexural strength decreases at all studied days by around 2 MPa. Also, it was shown that as the time passes from 3 days to 90 days, the flexural strength is enhanced in all mixes despite the percentage of FA: WA used (Arunkumar et al., 2021).

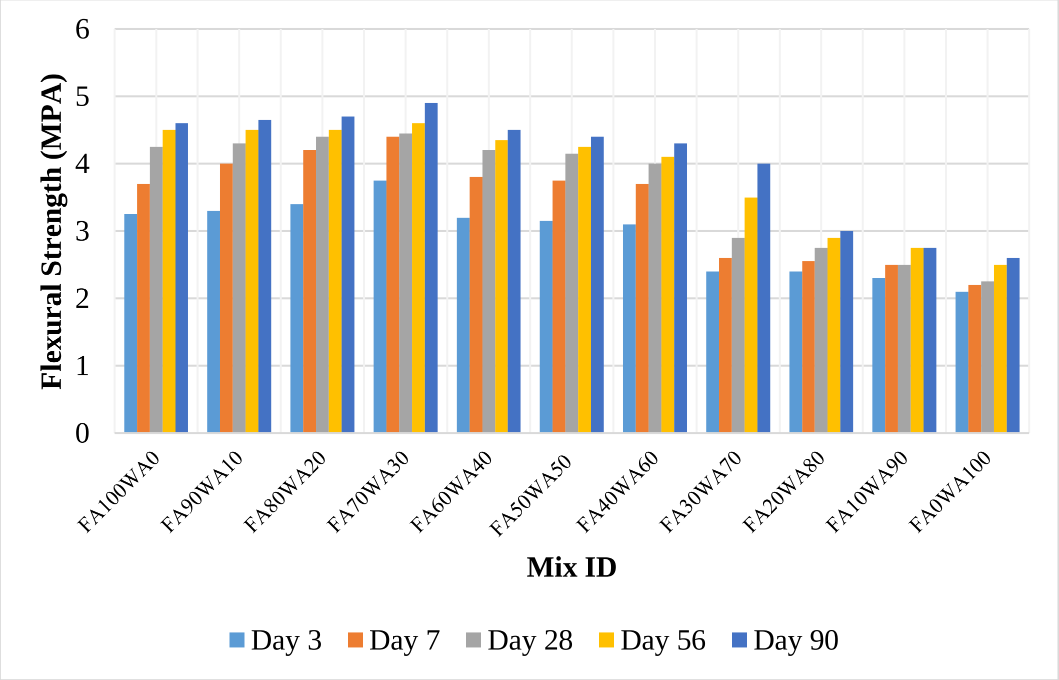

Fig. 4: Flexural Strength in Geopolymer Concrete Mixes with Different FA: WA Percentages (Arunkumar et al., 2021)

3.3 Modulus of Elasticity

The modulus of elasticity was tested where different percentages of fly ash (FA) and low calcium waste wood ash (WA) were used with an alkaline activator to binder ratio of 0.45 and SS/SH ratio of 2.5. Figure 5 portrays that as the percentage of FA decreases in the mixture from 100% to 0%, the modulus of elasticity is reduced slightly. Also, the modulus of elasticity is enhanced as time passes from 3 days to 90 days (Arunkumar et al., 2021).

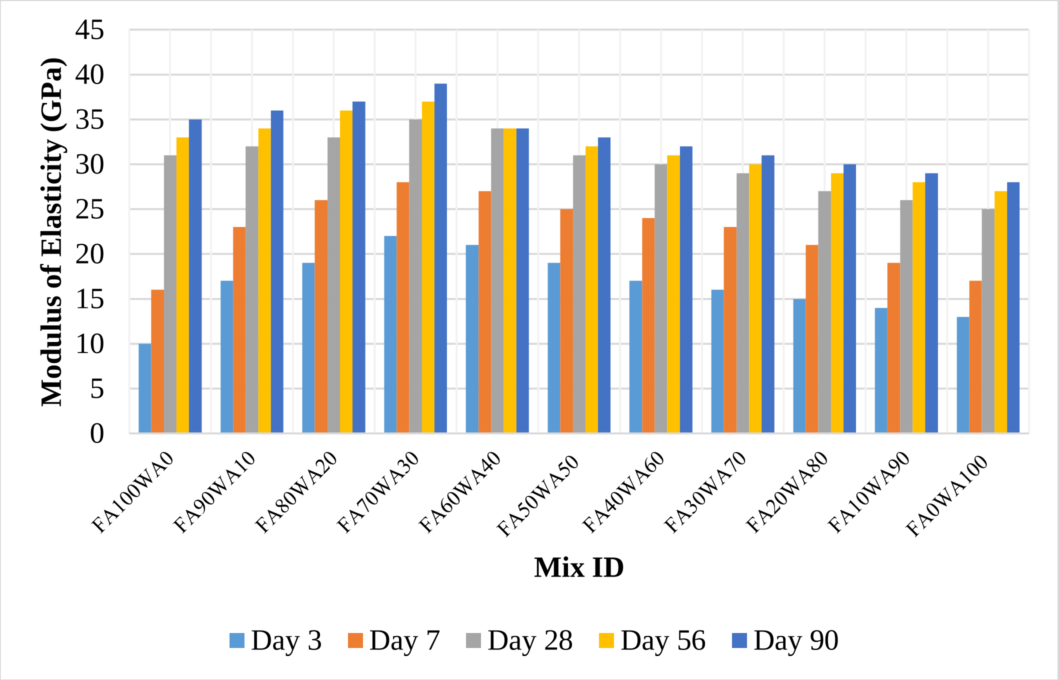

Fig. 5: Modulus of Elasticity in Geopolymer Concrete Mixes with Different FA: WA Percentages (Arunkumar et al., 2021)

3.4. Ultrasonic Pulse Velocity

High pulse velocity (UPV) reading is an indication of the quality of concrete. Table 3 presents the UPV data for fly ash (FA) and rice husk ash (RHA) activated concrete mixtures (Bayuaji et al., 2019). The ratio of sodium silicate to sodium hydroxide (SS/SH) was 1.5. FA activated mixtures showed the highest UPV values at 3, 28 and 56 days. However, concrete mixtures containing rice husk ash (RHA) recorded the lowest values.

Table 3: Ulrasonic Pulse Velocity Results for Geopolymer Concrete Mixtures (Bayuaji et al., 2019)

Binder (%)		**Time (Days)**	**UPV (m/s)**
FA	**RHA**		
0	100	3	531.7
		28	810.0
		56	1653.0
100	0	3	1711.7
		28	2187.5
		56	2777.5
50	50	3	679.2
		28	1047.2
		56	1140.0

3.5. Shrinkage

Ruengsillapanun et al. (2021) reported the results on total shrinkage for 3 geopolymer concrete mixes containing fly ash activated with sodium silicate (SS) and sodium hydroxide (SH). The SH had 3 concentrations; 2 molars (M2), 4 molars (M4) and 6 molars (M6). The SS/SH ratio was 0.3 for all mixes. Figure 6 demonstrates that the mix with the lowest SH solution concentration recorded the highest shrinkage at all age. As the molarity increased from 2 molars to 6 molars, the total shrinkage is reduced at all ages (Ruengsillapanun et al., 2021).

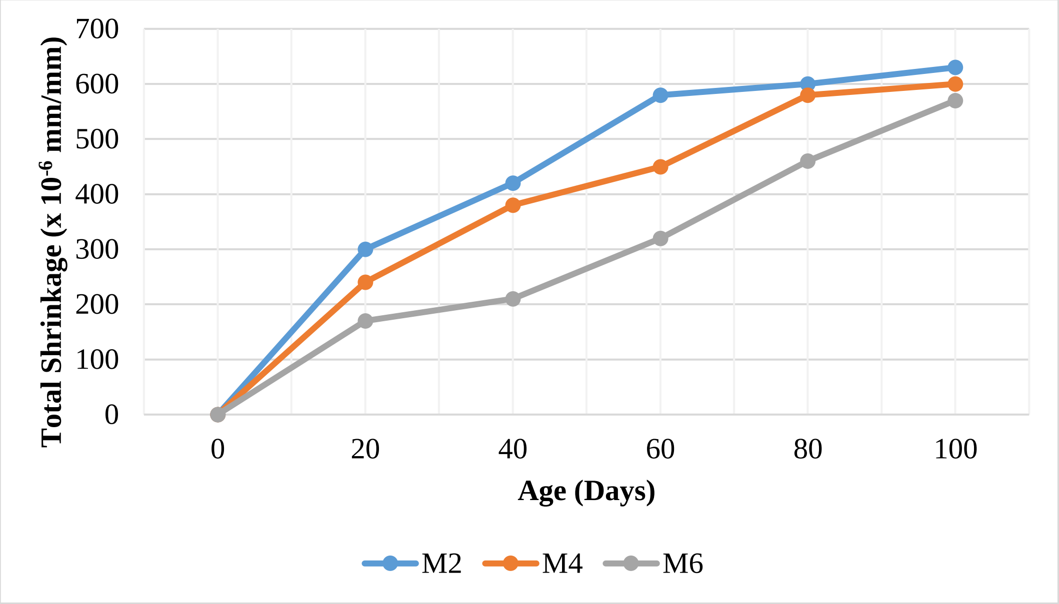

Fig. 6: Total Shrinkage as Function of Age of Concrete with Different Sodium Hydroxide Concentrations (Ruengsillapanun et al., 2021)

The results of shrinkage in the presence of different types of alkali-activators (i.e. KS, SH, SS) are presented in Figure 7 (Panchmatia et al., (2020). Concrete mixtures containing ordinary Portland cement (OPC) with no alkali-activators have the highest values of shrinkage, while geopolymer concrete mixtures containing fly ash (FA) with potassium silicate (KS), sodium hydroxide (SH) and sodium silicate (SS) showed reduced shrinkage values.

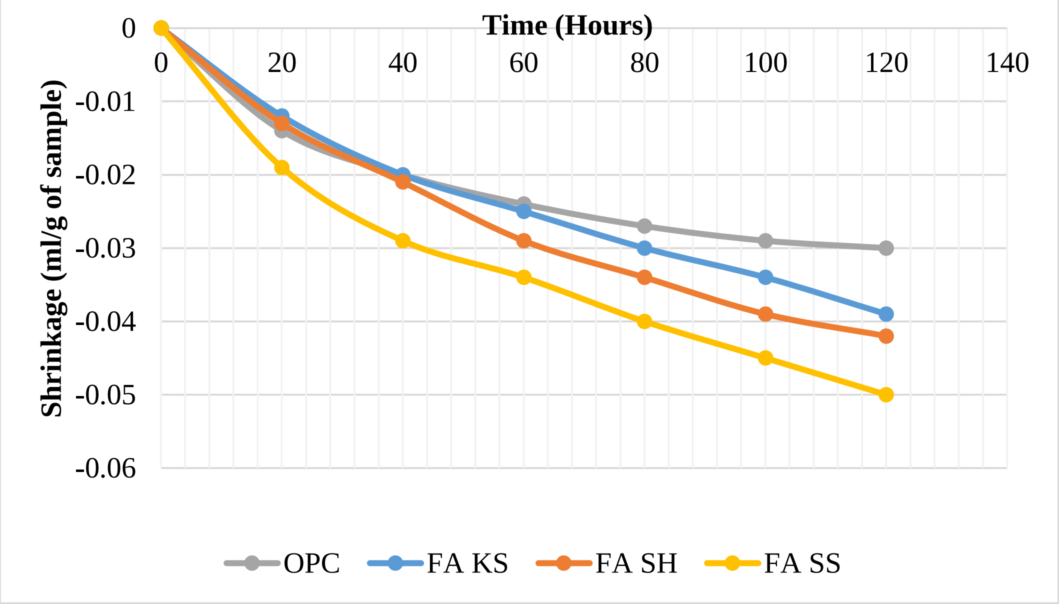

Fig. 7: Shrinkage Values in Presence of Different Alkali-Activators (Panchmatia et al., 2020)

3.6. Expansion

Dayarathne et al. (2013) reported the expansion values for ordinary Portland cement (OPC) concrete and geopolymer concrete containing fly ash (FA) and activators only as the binding materials. The water to binder ratio was fixed at 0.47. The geopolymer concrete showed less expansion compared with the traditional concrete.

Table 4: Difference in Expansion Between OPC and FA Concrete Mixes (Dayarathne et al., 2013)

Age (Days)	**Expansion (%)**	
	OPC	**FA**
0	0	0
10	0.005	-0.005
20	0.004	-0.002
30	0.006	-0.001
40	0.009	0
50	0.01	0
60	0.01	0.005
70	0.016	0.008
80	0.02	0.008
90	0.025	0.015
100	0.02	-0.005
110	0.01	-0.008
120	0.01	-0.007
130	0.018	0.002

3.7. Creep

Figure 8, shows that the creep coefficient in traditional mixes containing cement (OPC) is much more than that for geopolymer concrete mixes containing fly ash (FA) at all ages. Also, the creep coefficient was found to increase after 28 days in traditional concrete whereas there is hardly any change in FA activated concrete beyond this age (Neupane and Hadigheh, 2021).

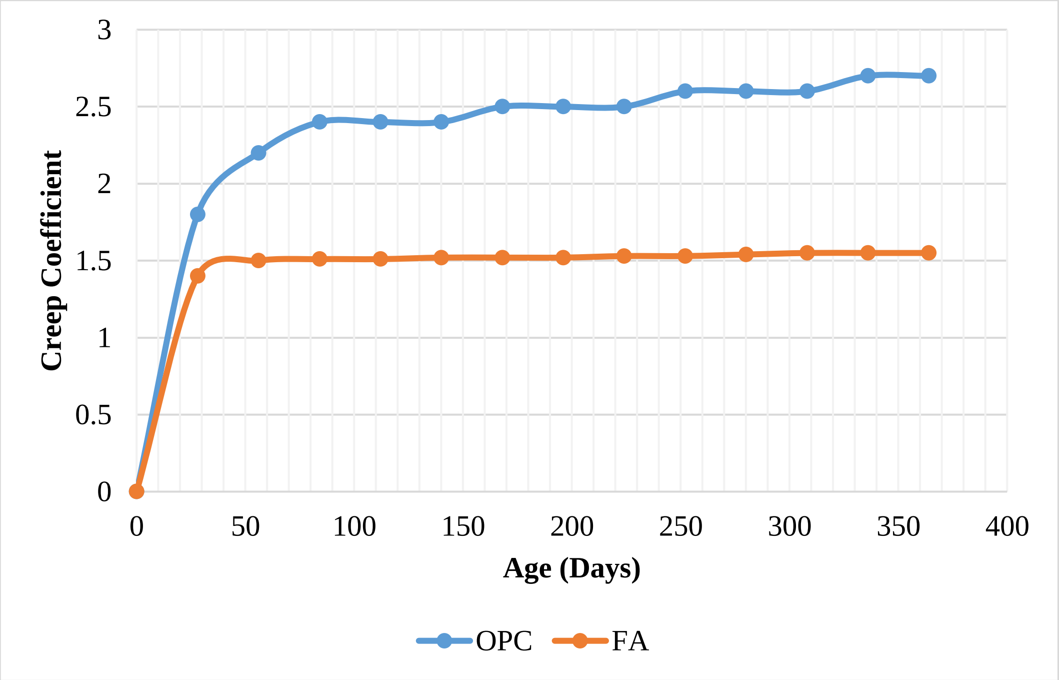

Fig. 8: Creep Coefficient as Function of Concrete Age (Neupane and Hadigheh, 2021)

3.8. Load-Deflection behavior

Nath and Sarker (2017) reported on the load-deflection behavior of traditional concrete and FA activated concrete at 28 and 90 days of curing. The shape of the curve is similar for both concretes, however, the maximum load is higher for traditional concrete. The SS/SH ratio was 2.5 in geopolymer concrete mixes and the water to binder ratio was fixed to 0.4, while in traditional concrete mixes it was fixed at 0.55.

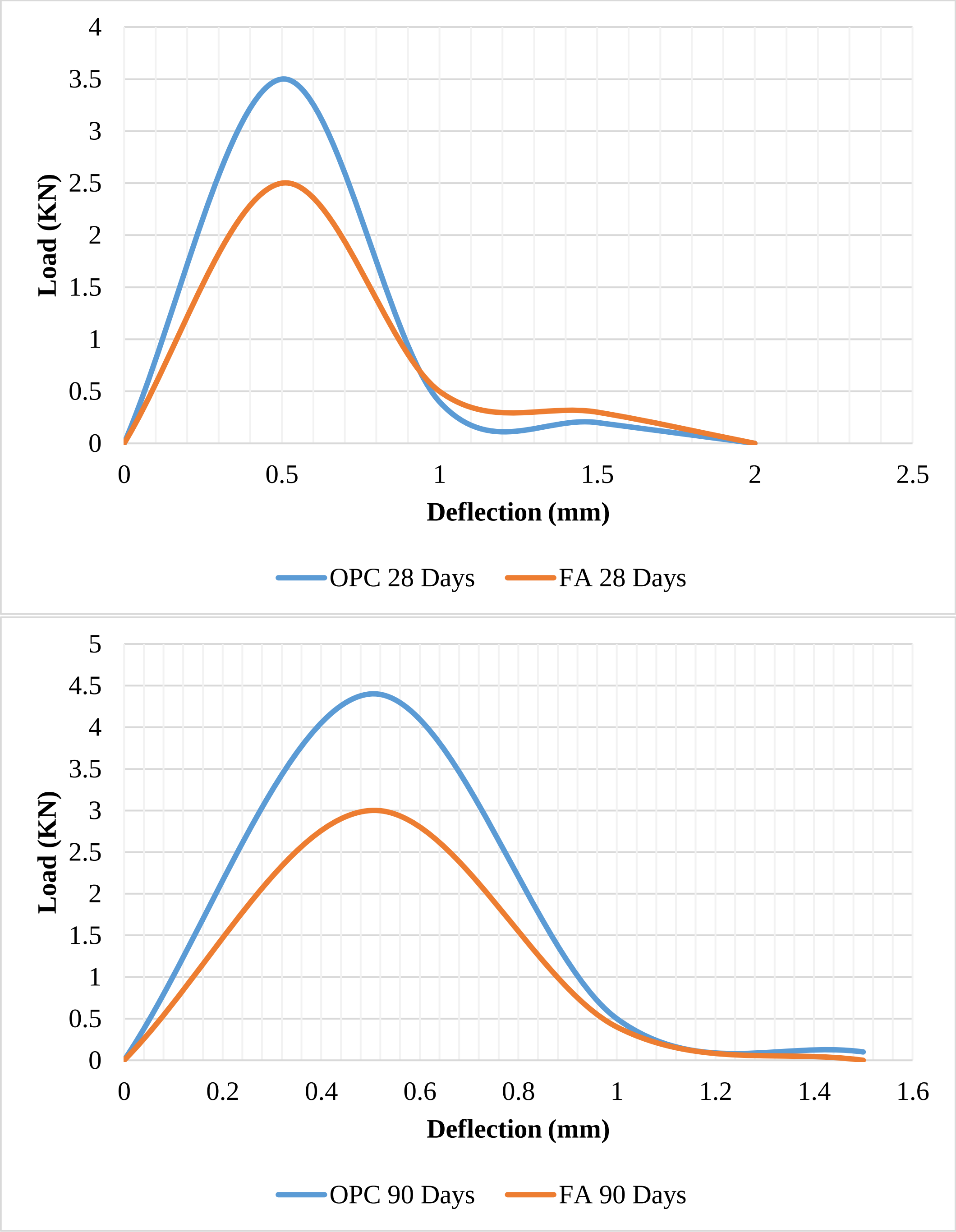

Fig. 9: Load-Deflection for traditional and FA activated concretes (Nath and Sarker, 2017)

4. DURABILITY PROPERTIES

4.1. Sulfate Resistance

Nnaemeka and Singh (2020) reported that the sulfate resistance is more in fly ash activated concrete compared with the control mixtures during the first 100 days of exposure to sulfate solution. The data were based on the weight loss for both concrete mixture. At 100 days of exposure, the weight loss was 5.5% and 4% for the control and fly ash activated mixtures respectively.

Pasupathy et al. (2017) examined the sulfate ions concentrations at different depth of two concrete mixtures; one is a normal concrete and the other if fly ash activated concrete with sodium silicate and sodium hydroxide. As shown in Figure 10, the concentration of sulfate ions at different depths are higher in the fly ash activated mixture compared with the control. For example, at 2.5 mm depth, the concentrations of sulfate ions were, 0.45% and 0.7% for the control and fly ash activated mixtures respectively.

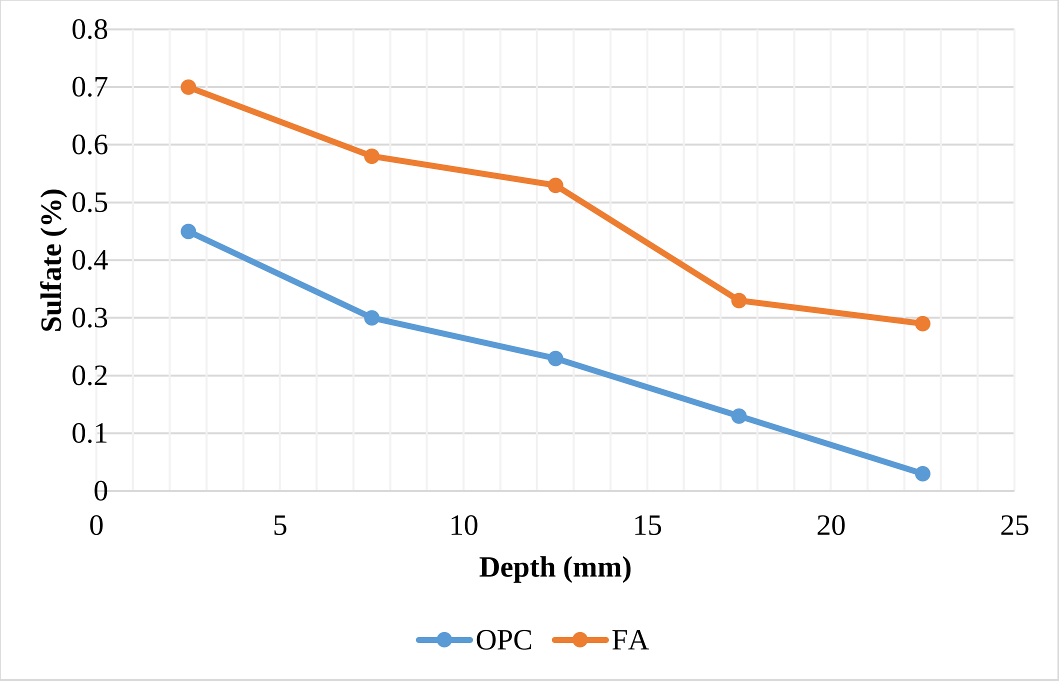

Fig. 10: Sulfate Percentage as Function of Depth (Pasupathy et al., 2017)

4.2. Carbonation

Table 5 presents the carbonation depth at different ages for the control concrete and the fly ash activated concrete. (Luhar et al., 2021). The FA activated concrete showed a lower carbonation depth at all curing ages compared with the control.

Table 5: Carbonation in Concrete as Function of Different Days (Luhar et al., 2021)

OPC Concrete		**FA Concrete**	
Ages (days)	**Carbonation depth (mm)**	**Ages (days)**	**Carbonation depth (mm)**
14	1.8	14	1
21	3.6	21	1.5
28	3.7	28	2
35	3.8	35	2.5
42	3.9	42	3.3
56	4.8	56	4
90	7.9	90	5

4.3. Reinforcement Corrosion

Morla et al. (2021) examined the corrosion resistance of reinforced using traditional concrete and FA activated concretes. It was concluded that the FA activated mixtures showed better resistance to corrosion compared with the control. Table 6 presents the corrosion current and corrosion rate for the two mixtures. Specimens containing fly ash (FA) showed moderate and high corrosion conditions. However, reinforced concrete mixtures containing ordinary Portland cement (OPC) shows a very high corrosion condition.

Table 6: Corrosion Conditions (Morla et al., 2021)

Mix ID	**Corrosion Current I_{CORR} (µA/cm²)**	**Corrosion Rate (µm/Year)**	**Corrosion Condition**
OPC 1	4.9214	57.233	Very high
OPC 2	4.101	47.696	Very high
OPC 3	5.0471	58.698	Very high
FA 1	0.9113	10.598	Moderate
FA 2	1.2303	14.308	High
FA 3	1.7429	20.27	High

5. CONCLUSION

To sum up, substituting cement in traditional concrete with alkali activated ashes to produce geopolymer concrete will become more popular in the future, as this will reduce the environmental pollution due to the extensive use of cement. Also, another advantage is that alkali activated concrete can have improved properties compared with traditional concrete. However, more research and field studies should be conducted to establish the practical use of geopolymer concrete. This will include cost and performance. In addition, other pozzolanic materials from bio-sources should be investigated for the production of alkali activated or geopolymer materials.

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