Development of Hybrid Alkaline Activator for the Formulation of Geopolymer Concrete

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Abstract

An alternative to conventional Portland cement-based concrete, geopolymer concrete has attracted a lot of attention as a result of the rising need for eco-friendly and sustainable building materials. Fly ash and ground granulated blast furnace slag (GGBS), two industrial by-products rich in aluminosilicates, may be alkaline activated to generate geopolymers. These geopolymers show promise as a means to lessen the building industry's carbon emissions. In order to improve the performance properties of geopolymer concrete, this research aims to create and optimise a hybrid alkaline activator that employs activator solutions based on both potassium and sodium. Geopolymer concrete's fresh and hardened qualities were tested by methodically varying the hybrid activator formulation's alkali content, silicate modulus, and sodium-to-potassium ratio. Time to set, compressive strength, workability, and durability were some of the key performance indicators that were evaluated experimentally. Using scanning electron microscopy (SEM), XRD, and Fourier transform infrared spectroscopy (FTIR), the hybrid activator's effects on the reaction mechanisms and gel formation processes were further clarified. The results showed that the mechanical strength, setting properties, microstructural integrity, and long-term durability were all improved by the hybrid alkaline system. This optimised activator formulation is ideal for structural and precast applications because to its compressive strengths above 40 MPa at 28 days, enhanced resistance to chemical attack, and thermal stability. In order to achieve global sustainability goals while fine-tuning the geopolymerization process and tailoring the performance of geopolymer concrete for varied building applications, this study suggests that developing a hybrid alkaline activator is a potential method.

Keywords: Hybrid Alkaline, Geopolymer, microstructural

Introduction

Ordinary Portland Cement (OPC) is used extensively in the building sector, which is a major contributor to global carbon dioxide emissions. This is mostly owing to the fact that OPC is used extensively. Researchers and engineers are currently studying alternative construction materials that tilizat carbon footprints without compromising performance. This is in response to the growing worries over climate change and the sustainability of the environment. The conventional cement-based concrete has been replaced with geopolymer concrete, which has emerged as a viable and environmentally friendly alternative to the traditional concrete. Fly ash, slag, metakaolin, and rice husk ash are some examples of aluminosilicate-rich precursors that may be activated with alkaline activator solutions in order to produce geopolymer concrete via the synthesis process. The manufacturing of geopolymer concrete, in contrast to that of OPC, does not rely on the production of clinker based on limestone, which results in a considerable decrease in the emissions of greenhouse gases. In the process of geopolymerization, the alkaline activator plays a significant role by dissolving the reactive silica and alumina and facilitating the formation of a rigid three-dimensional polymeric gel network. This gel network is typically composed of sodium aluminosilicate hydrate (N-A-S-H) or calcium silicate hydrate (C-S-H), depending on the mix. The alkaline activator is often a mixture of sodium hydroxide or potassium hydroxide and sodium silicate or potassium silicate. This is the way that it has been done traditionally. It is possible, however, that depending entirely on sodium-based or potassium-based activators might result in limits concerning workability, setting time, heat of reaction, or the development of long-term strength. Researchers have begun investigating hybrid alkaline activators, which are a synergistic combination of sodium and potassium-based components, with the goal of overcoming these disadvantages and further tailoring the characteristics of geopolymer concrete. It has been demonstrated that hybrid activators have the potential to improve reaction kinetics, achieve greater mechanical strength, and utilizat the qualities of fresh concrete, including its workability and its behaviour after it sets. The formulation of an efficient hybrid activator, on the other hand, calls for an in-depth comprehension of the interaction between chemical species, the silicate modulus, the molar ratios of alkalis, and the characteristics of the aluminosilicate precursor. By systematically adjusting the ratio of sodium hydroxide to potassium hydroxide, the alkaline concentration, and the SiO2 to sodium hydroxide modulus, the purpose of this research is to create and evaluate a hybrid alkaline activator system for geopolymer concrete. An ideal mix design that strikes a compromise between early strength, workability, durability, and environmental performance is the goal of this endeavour. In addition to this, the study investigates the microstructural development of the concrete matrix in order to grasp the processes that are responsible for the performance enhancements that are related with the utilization of hybrid activators. With the help of this inquiry, the effort helps to the development of environmentally friendly building materials and is in line with the global aim of achieving carbon neutrality and a circular economy in the built environment.

The most effective application of fly ash is in the building or preparation of geopolymer during geopolymerization. This involves dissolving silicon and aluminium without the need of an alkaline activator through polycondensation in order to produce a cemented solid using geopolymer concrete. The results of previous studies indicate that geopolymers based on Class F fly ash perform better thermophysically and physically at temperatures lower than 500 degrees Celsius. In addition, the researchers demonstrated that cementitious materials based on Class C fly ash function well thermally and maintain their stiffness even when heated to temperatures higher than 800 degrees Celsius. The incorporation of glass waste particles into fly ash-based cementitious materials, on the other hand, resulted in an improvement in the compaction performance of the Geopolymer, a reduction in the curing process, and a strengthening of the gel’s integrity, all of which contributed to an increase in the Geopolymer’s resistance to fire.

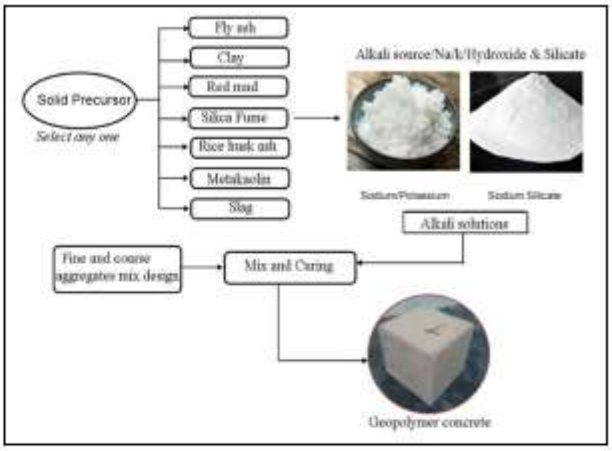

Fig. 1: Various Procedures Involved in the Synthesis of Geopolymers

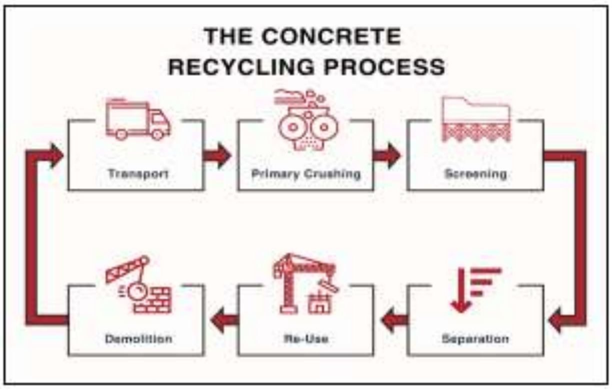

Fig. 2: The facility that recycles aggregate

Copper slag (Youssf et al. 2022), blast furnace slag (Zawrah et al. 2016), and waste aggregates (Gupta et al. 2017) are the items that are utilised the most often. According to Siddika et al. (2018), the most effective substitutes for cement and coarse aggregates are comprised of coconut shells, fibres (Alyousef et al., 2020), and waste tobacco products. The flammability of substantial aggregates makes concrete blocks one of the most significant non-static artificial structures. Concrete blocks are widely used in construction. The present manufacturing capacity for Portland cement is thirty million metric tonnes per year. This capacity is currently being utilised. As a result of this rise in total consumer spending, it is anticipated that the demand for new items would expand over the course of the next ten to fifteen years. According to Behera et al. (2014), the manufacturing of cement is extremely resource-intensive, which results in substantial environmental, electricity, and financial exploitation. This is due to the fact that cement production generates around fifty percent waste aggregates, forty percent total energy, and fifty percent primary material. As a substantial source of recyclable materials, recycling and demolition waste (also known as C&D trash) is becoming a main issue for both governments and construction businesses (Ferronato et al. 2019). C&D waste is predominantly created by the construction sector. An considerable amount of research has been conducted over the years on recycled aggregates (R.A.) from the building and waste disposal industries in order to gain a better understanding of the distinctive properties that they possess. The process that was followed in order to create the R.A. process is depicted in Figure 2.

Materials And Methods

Table 1 contains the results of the X-ray fluorescence (XRF) chemical analysis performed on the metakaolin that was utilised in this investigation. The preparation of the alkaline activator solution involved the utilisation of NaOH with a purity level of 98%, KOH with a purity level of 90%, and liquid Na2SiO3 with a molar ratio of SiO2/Na2O equal to 2. This table displays the results of the chemical analysis performed on the compounds Na2SiO3, NaOH, and KOH. An aggregate with granular sizes ranging from 7 to 10 millimetres was utilised as coarse aggregate (sand), whereas aggregates with a size of less than 4 millimetres were utilised as fine aggregate. The ASTM C33 standard was followed in order to sift both fine and coarse particles. Using the protocols outlined in ASTM C127 and ASTM C128 respectively, SSD specific gravity and water absorption tests were carried out on the coarse and fine aggregates. The results of these tests are presented in Table 3. Both the fineness modulus (as determined by ASTM C136) and the sand equivalent (as determined by ASTM D2419) values of the fine aggregates were found to be equal to 3.01 and 73, respectively. The use of polycarboxylate-based Super Plasticiser (SP) was done with the intention of lowering the amount of water present in concrete and enhancing its workability.

Table 1. Metakaolin's physical and chemical features are utilised in this study.

Content	Result	Unit
SiO2	54	%
Al2O3	31.7	%
TiO2	1.41	%
Fe2O3	4.89	%
ZrO2	0.1	%
K2O	4.05	%
Na2O	2.32	%
MnO	0.11	%
L.O.I	1.41	%
SiO2/Al2O3	1.71	-
Specific Gravity	2.67	g/cm3
Fineness	21400	cm2/g

Table 2. NaOH, KOH, and Na2SiO3 solutions were subjected to a chemical analysis.

NaOH			KOH			Na2SiO3		
Chemical substance	Result	Unit	Chemical substance	Result	Unit	Chemical substance	Result	Unit
NaOH	98	%	KOH	90.7	%	SiO2	30	%
Na2CO3	1	%	K2CO3	0.3	%	Na2O	14.5	%
NaCl	200	ppm	KCl	0.006	%	Water	55.5	%
Fe	6	ppm	Fe	2	ppm			
SiO2	15.7	ppm	NaOH	1.2	%			

Table 3. The specific gravity of aggregates as well as their water absorption

Material	SSD Specific gravity(gr/cm3)	Water absorption (%)
Coarse aggregates	2.62	1.3
Fine aggregates	2.59	3.2

EXPERIMENTAL PROGRAM

Mix Designs

The first portion of the investigation, which focused on studying the impact of various alkaline solutions on the compressive, tensile, and flexural strengths of GPC, was carried out by preparing five different alkaline solutions, which are listed in Table 4. It was determined that the concentration of all of the NaOH and KOH solutions was 12 M, and the weight ratios of Na2SiO3/NaOH, Na2SiO3/KOH, and Na2SiO3/KOH+NaOH were all adjusted to 1.5. In addition, the weight ratio of the alkaline solution to the metakaolin and the ratio of the fine aggregate to the coarse aggregate that was used in the preparation of the first series of specimens were respectively 0.9 and 1. As a representation of the mixed design of specimens for the initial portion of the investigation, Table 5 is presented below.

Table 4. Alkaline solutions' chemical make-up and composition

Alkaline solution ID	NaOH12M(%)	KOH12M(%)	Addition Time delay(min)
N	100	0	-
K	0	100	-
T-K50N50	50	50	0
3-K50N50	50	50	3
6-K50N50	50	50	6

Table 5. Samples are arranged in a mix design (kg/m3)

Mix design ID	met kaolin	NaOH12M	KOH12M	Na2SiO3	Coarse aggregate	Fine aggregate	Extra water	SP
N	400	144	0	216	850	850	10	8
K	400	0	144	216	850	850	10	8
T-K50N50	400	72	72	216	850	850	10	8
3-K50N50	400	72	72	216	850	850	10	8
6-K50N50	400	72	72	216	850	850	10	8

At first, solutions of sodium hydroxide and potassium hydroxide with a concentration of 12 M were produced. Subsequently, in order to set up the mix designs N, K, and T-K50N50, these solutions were included into the Na2SiO3 solution twenty-four hours prior to the day when the tests were carried out. This is indicated by the "T" prefix, which implies that KOH and NaOH solutions are being added to the mixing process simultaneously. While the GPC specimens were being prepared, dry components such as metakaolin, coarse and fine aggregates were mixed together for a period of three minutes. After that, the alkaline activator solution, which consisted of NaOH (mix design N) or KOH (mix design K) or NaOH+KOH (mix design T-K50N50), Na2SiO3, and SP, was added to the dry mix and stirred for an additional ten minutes. It was necessary to combine the KOH and Na2SiO3 solutions with the SP and dry components in order to create the 3-K50N50 and 6-K50N50 mixes. After that, a solution of sodium hydroxide was added to the mixes after three and six minutes of mixing. This was done in order to determine the impact that the delay in adding the sodium hydroxide solution had on the compressive strength of the GPC. Both the "3" and "6" prefixes in the mix design IDs indicate that there will be a delay of three and six minutes, respectively, in the addition of the NaOH to the mixing process. Ten minutes was the entire amount of time that was spent mixing the 3-K50N50 and 6-K50N50 combinations, just like it was 10 minutes for other mixtures.

RESULTS AND DISCUSSION

In Table 6, the compressive, tensile, and flexural strengths of specimens after seven and twenty-eight days are shown, together with the coefficients of variation that correlate to those strengths. These strengths are also displayed in Figures 1 through 3, respectively. As can be observed, the mix 3-K50N50, in which the NaOH solution was added to the mixture after three minutes after adding KOH and Na2SiO3 to the dry components, had the greatest initial (7-day) and lateral (28-day) compressive strengths, which were equivalent to 84.3 and 93.7 MPa, respectively. This was the case for both the initial and lateral compressive strengths measurements. It was the mix T-K50N50 that exhibited the lowest compressive strengths during a period of seven and twenty-eight days, with values of 40.4 and 49.7 Mpa, respectively. The findings that were obtained suggest that the strength gaining of the mix N after seven days of curing was superior to that of the other mixes, consisting of 92% of the increase. After seven days of curing, the mix K was able to achieve 74% of the compressive strength that was measured after 28 days. On the other hand, the rate of strength gain for the mix K from seven days to twenty-eight days was the most significant of all the rates included, which was around thirty-one percent rise.

Table 6. The values of the coefficients of variation for compressive, tensile, and flexural strengths, as well as their respective values

Mix ID	Compressive strength(MPa)		Tensile strength(MPa)		Flexural strength(MPa)	
	7-days	28-days	7-days	28-days	7-days	28-days
N	24.2±0.5	26.4±0.8	1.5±0.1	1.7±0.2	2.8±0.3	3.1±0.4
T-K50N50	16.9±0.2	18.9±0.4	1.06±0.1	1.2±0.1	1.9±0.2	2.2±0.2
3-K50N50	29.8±0.6	33.5±1	1.9±0.3	2.2±0.2	3.4±0.4	3.8±0.3
6-K50N50	26.4±0.7	31.7±0.4	1.7±0.2	2.1±0.1	3.1±0.3	3.6±0.2
K	22.3±0.4	29.1±0.8	1.4±0.3	1.9±0.2	2.4±0.2	3.3±0.2

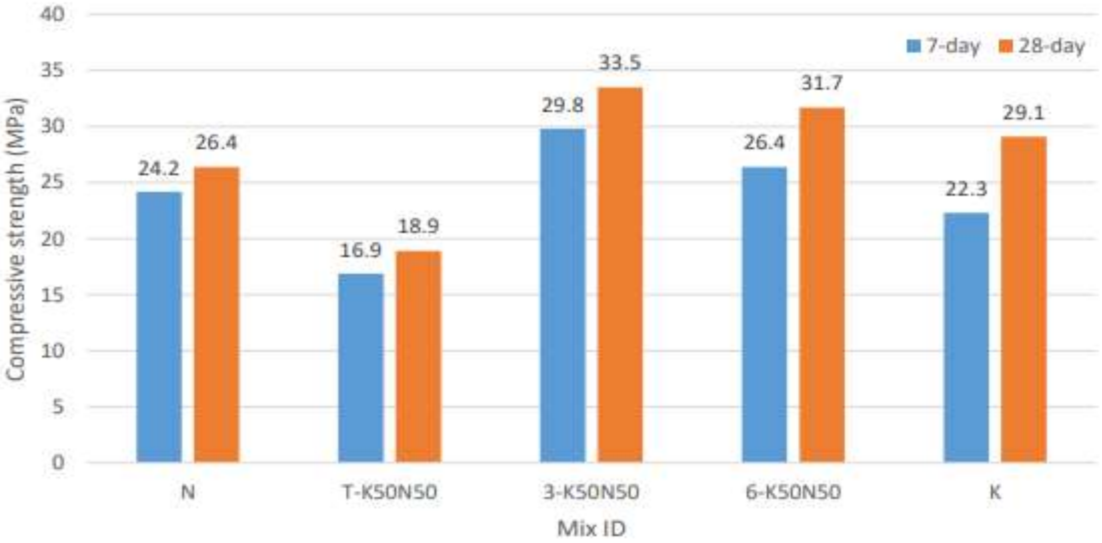

Figure 1. GPC specimens with compressive strengths as measured after 7 and 28 days

The findings of the tensile and flexural tests exhibit a pattern that is comparable to that of the compressive strengths. The simultaneous and equal inclusion of KOH and NaOH solutions (mix TK50N50) revealed the lowest values of tensile strength, which is roughly 29 and 37% lower than the N and K single solution mix designs, respectively. This was the case because the tensile strength of the mixture was equal to both solutions. Mix 3-K50N50, on the other hand, had the highest tensile strength (about 28, 16, and 84% greater than the N, K, and T-K50N50 mix designs), which is indicative of the considerable favourable effect of delaying the addition of KOH to the mix for three minutes. Furthermore, the flexural strengths are also subject to the same general patterns as were described earlier.

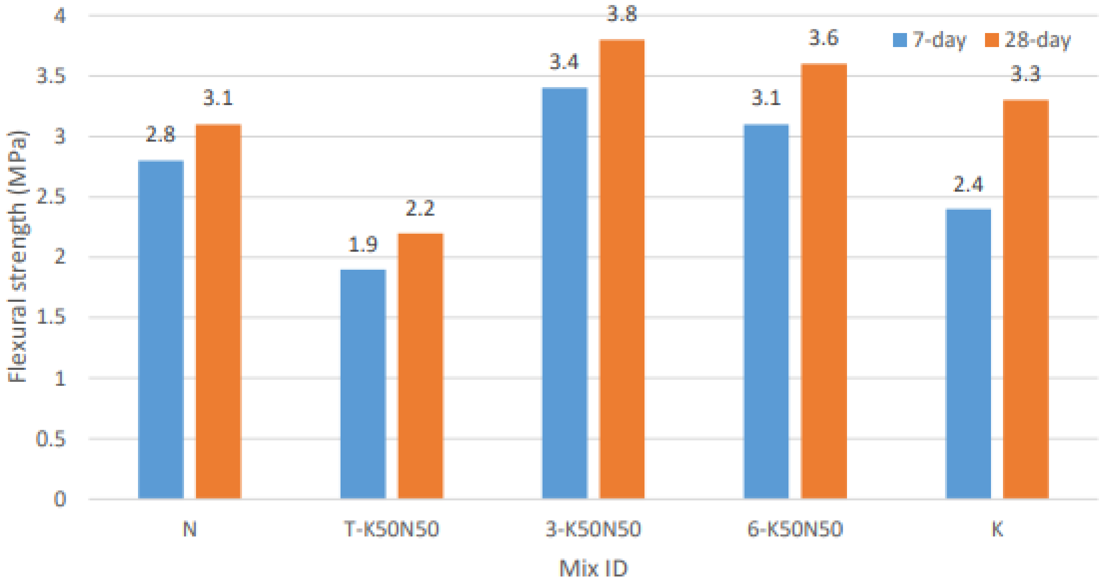

Figure 2. specimens of GPC with flexural strengths measured after 7 and 28 days

The impact of time delay in the addition of NaOH to the fresh mixes, namely T-K50N50, 3-K50N50, and 6-K50N50, on the compressive, tensile, and flexural strengths of the corresponding GPCs is depicted in

Figures 3 and 4, respectively. It is clear that the addition of NaOH to the dry components of the mix designs at intervals of three and six minutes resulted in greater compressive, tensile, and flexural strengths after seven and twenty-eight days. This was in comparison to the simultaneous addition of NaOH, KOH, and Na2SiO3 to the dry components of the mix designs. The addition of NaOH to the mixture resulted in the highest initial and lateral compressive, tensile, and flexural strengths. This was accomplished three minutes after the addition of KOH and Na2SiO3, which resulted in increases of 77% and 6% for compressive strength, 84% and 5% for tensile strength, and 73% and 6% for flexural strength, respectively. The compressive, tensile, and flexural strengths of the material after seven and twenty-eight days exhibited a declining tendency when the delay time was increased to six minutes; nevertheless, the values for these strengths were still greater than the findings for the simultaneous addition of sodium hydroxide and potassium hydroxide. For this reason, it is possible to draw the conclusion that when using a combination of NaOH and KOH alkaline solutions, the optimal interval for adding NaOH to the mix is the delay time of three minutes, which is equal to one-third of the total mixing time. This results in the highest initial and lateral compressive strengths for the metakaolin-based GPC.

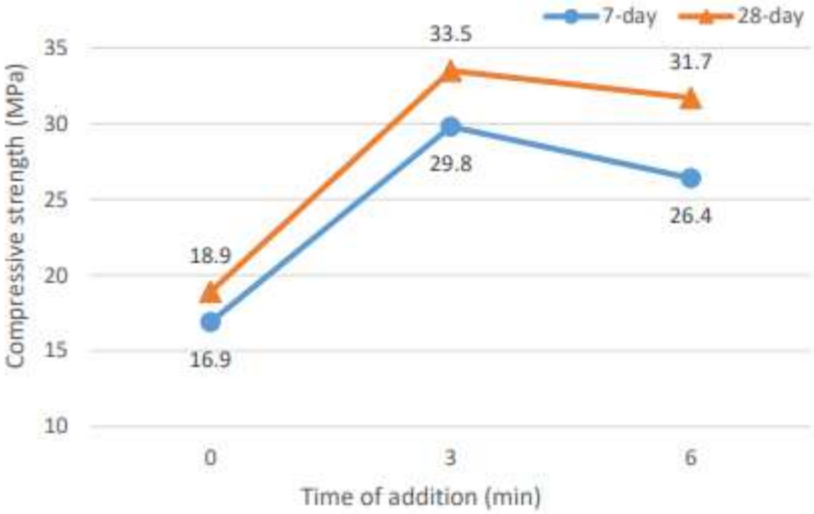

Figure 3. T-K50N50, 3-K50N50, and 6-K50N50 compressive strengths as a function of time of NaOH solution addition

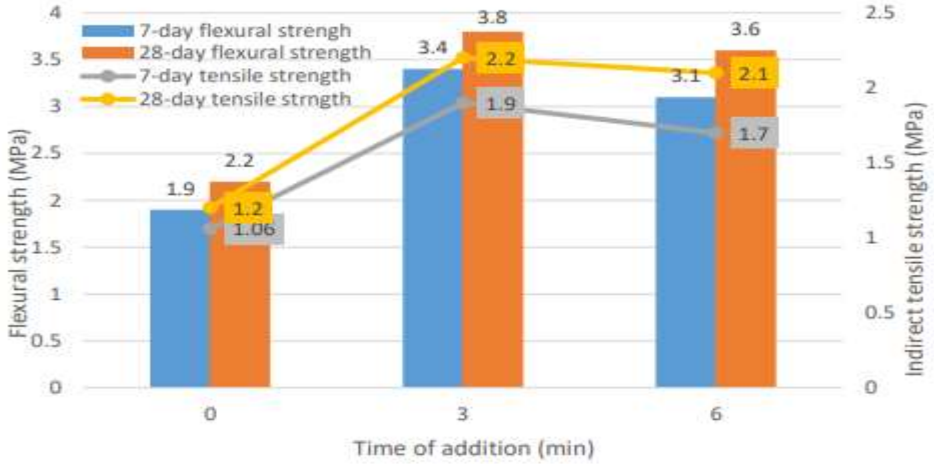

Figure 4. The effect of adding NaOH solution at different times on the flexural and tensile strengths of T-K50N50, 3-K50N50, and 6-K50N50 mixtures

It is necessary to take into consideration the performance mechanism of the alkaline solutions in order to provide an explanation for the trends that have been noticed. In comparison to NaOH, the use of potassium hydroxide (KOH) results in the production of a greater quantity of geopolymers, which in turn leads to a microstructure that is both more compact and more robust. This, in turn, leads to a lack of compressive, tensile, and flexural strengths after seven days, as well as sluggish hardening and high compressive tensile and flexural strengths after 28 days. NaOH, on the other hand, is capable of dissolving a greater number of inorganic components than KOH does at the same concentration. This results in a quicker reaction rate for Na+ than it does for K+. Because of the faster reaction rate of Na+, the use of NaOH would result in a higher initial compressive strength as well as a more quick hardening when compared to other methods. On the other hand, the compressive, tensile, and flexural strengths of GPC would be significantly diminished if NaOH and KOH were to be included with each other simultaneously. It is possible that this is due to the fact that NaOH and KOH operate differently during the geopolymerization process. It was not possible to strike a compromise between the strong reactivity of Na+ and the inclination of K+ to undergo some kind of condensation reaction. However, as can be shown for the mixes 3-K50N50 and 6-K50N50, the addition of NaOH at intervals of three and six minutes would allow both K+ and Na+ to have sufficient time to establish bonds in the required directions. This would result in the development of higher quantities of geopolymer gel and a denser geopolymer cement matrix. A visual representation of the outcomes of water absorption and weight loss experiments conducted on GPC specimens in acidic conditions is presented in Figure 5. It was determined that the water absorption capacity of the N, T-K50N50, 3-K50N50, and K mix designs was around 6,2 percent, 6.6 percent, 5.3 percent, and 5.8 percent, respectively. Additionally, the weight loss in acidic conditions was measured to be around 3.8, 4.3, 3.5, and 3.6% for the N, T-K50N50, 3-K50N50, and K mix designs, respectively. Based on the findings presented in figure 5, it can be observed that the water absorption capacity and weight loss in an acidic environment of the 3-K50N50 mix design were lower in comparison to other specimens. This is mostly attributable to the increased density of the geopolymeric matrix structure that was utilised in this sample.

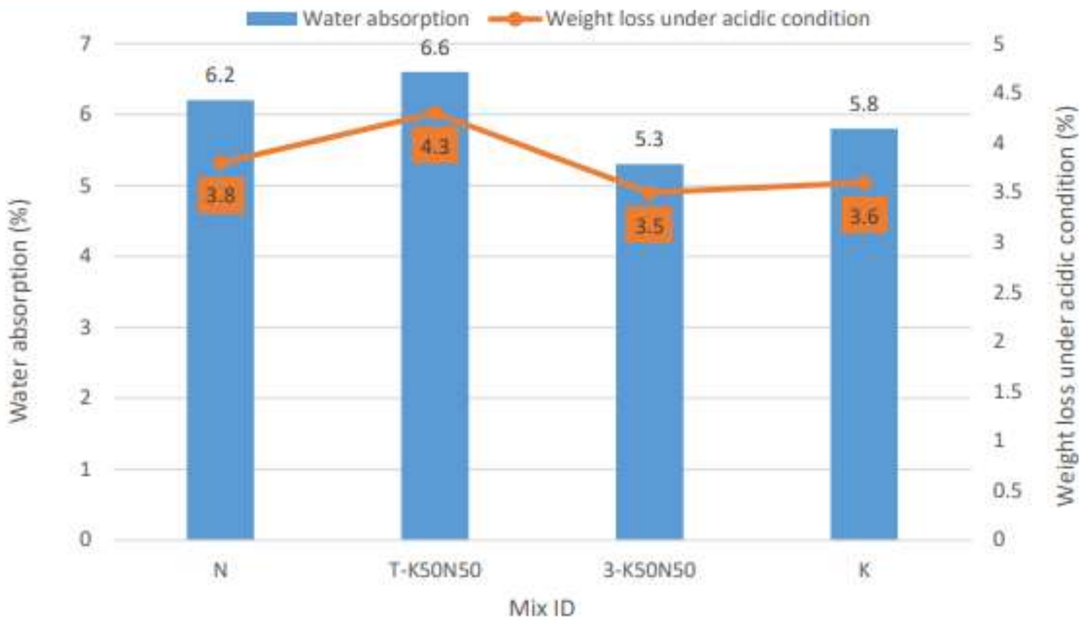

Figure 5. In an acidic environment, N, T-K50N50, 3-K50N50, and K mixtures absorb water and lose weight.

Conclusion

The results of this study reveal that it is possible to improve the performance characteristics of geopolymer concrete by employing a hybrid alkaline activator that is composed of components based on both sodium and potassium. The hybrid activator was shown to have greatly better workability, setting time, compressive strength, and durability in comparison to typical single-component activator systems. This was discovered through rigorous experimentation. The most effective combination of alkali concentration, silicate modulus, and the ratio of sodium to potassium led to a more refined microstructure, which was validated by scanning electron microscopy and X-ray diffraction analysis. This resulted in improved resistance to chemical and thermal degradation, as well as superior mechanical performance. Additionally, the hybrid method enabled improved control over the geopolymerization process, which in turn made it possible to customise the characteristics of concrete to specific structural applications. Within the context of geopolymer concrete, the development of hybrid alkaline activators is a promising technique that has the potential to improve both the quality and the sustainability of the material. As a low-carbon, high-performance alternative to conventional cement-based materials, it lays the way for a wider acceptance of this material in the building sector.

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