SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I2P110

Volume 13 Issue 2, 132-151, February 2026

Original Article

Experimental Investigation on the Performance of Fly Ash-Based Rubberized Geopolymer Concrete under Elevated Temperature Curing

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Received: 19 November 2025 Revised: 20 December 2025 Accepted: 21 January 2026 Published: 11 February 2026

Abstract *- Geopolymer concrete has emerged as a promising sustainable alternative to conventional concrete, primarily due to its potential to mitigate the adverse environmental impacts. In addition, several industrial by-products, if not properly managed, pose serious environmental concerns. Among these, waste rubber represents a critical challenge, as its incineration releases toxic compounds detrimental to both human health and the ecosystem. Thus, utilizing such waste materials as partial replacements for natural aggregates in geopolymer concrete may seem to be beneficial in conserving natural resources as well as in facilitating effective waste management. As synthesis of geopolymer binders typically involves elevated-temperature curing, the thermal performance of rubberized geopolymer concrete necessitates comprehensive evaluation. Although numerous studies have investigated the mechanical and durability characteristics of geopolymer concrete, research addressing its behavior under high-temperature conditions remains relatively limited. In the present study, the mechanical property and durability performance of rubberized geopolymer concrete are analyzed using two alkaline activator concentrations—14M and 16M NaOH—each cured at 100 °C with varying percentages of CR. The effect of the Alkaline Ratio (*$Na_2SiO_3/NaOH$*) is also examined by increasing the ratio from 1% to 2.5% in intervals of 0.5%. The experimental findings identified an optimal mix comprising 6% Crumb Rubber (CR) content with a 16M NaOH solution and a *$Na_2SiO_3/NaOH$* ratio of 2.5. As an extension of this work, real-scale experiments on geopolymer concrete under high temperatures need to be performed in the future to substantiate its practical applicability as a replacement for conventional concrete in civil engineering construction.*

Keywords *- Geopolymer Concrete, Fly Ash, Crumb Rubber, Elevated Temperature Curing, Sustainable Construction.*

1. Introduction

Concrete is the most consumed artificial material on earth, second only to water, forming the backbone of modern global infrastructure. Its production, however, is intrinsically linked to the manufacture of Ordinary Portland Cement (OPC), an energy-intensive process that requires the calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$). This reaction, coupled with the combustion of fossil fuels to heat kilns to ~1450°C, results in the release of approximately one tonne of Carbon Dioxide (CO_2) for every tonne of cement produced [1]. The global cement industry is thereby responsible for an estimated 8% of anthropogenic CO_2 emissions, a significant driver of climate change [2]. For this reason, the construction sector is considered to be the principal contributor to global carbon emissions, primarily due to the energy-intensive production of Portland cement, which is estimated to account for approximately 8% of the world's CO_2 output. Parallel to this environmental challenge, there exists a critical issue of solid waste management, with end-of-life tires representing a significant portion of non-biodegradable waste, posing severe ecological and health hazards. In this study, fly ash is used as a base material, whereas crusher powder and rubber aggregates are incorporated as sand replacers with different Molar Sodium Hydroxide (NaOH) concentrations and activator liquid ratios at an elevated temperature of 100ºC. Thus, FA-RGPC synergistically utilizes two industrial wastes: low-calcium (Class F) fly ash as the primary Aluminosilicate Source and Crumb Rubber (CR) derived from waste tires as a partial replacement for fine aggregate.

The geopolymerization process is activated by an alkaline solution of Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3). This study systematically investigates the effects of key parameters-crumb rubber content (2-10%), NaOH molarity (14M, 16M), and elevated curing temperature 100°C-on the fresh, mechanical, and thermal properties of FA-RGPC after a thorough review of previous works as presented in the following section.

In response to the environmental crisis precipitated by OPC, the search for alternative binder systems has gained immense momentum. Initially, natural minerals that contain silica and alumina were used as base materials, such as metakaolin, clays, etc. [3]. Later, Wallah and Rangan (2006) [4] identified the suitability of the industrial by-products, viz., fly ash, GGBS, rice husk ash, and silica fume as base materials for geopolymer concrete. Cement has calcium as a binder, and in a geopolymer alkaline environment, it needs to be created artificially for bonding. Many researchers have used sodium/potassium hydroxides and silicates as alkaline liquids (Van Jaarsveld et al. 1998 [5]; Davidovits, 1999 [3]). Xu and Deventer (2000) [6] confirmed that the addition of sodium silicate and hydroxide solution has improved the chain reaction and formed a better structure with the base material. Hardjito et al (2004) [7] also affirmed that in geopolymer concrete, high compressive strength has been achieved due to the higher Sodium Hydroxide (NaOH) concentration and higher ratio of Na_2SiO_3-NaOH liquid ratio. Rajamane (2005) [8] investigated the combined usage of GGBS and fly ash as source material in geopolymer concrete under NaOH and Na_2SiO_3 as activators and reported 40MPa in 40 hours under room temperature curing. Further compressive strength was increased to 65MPa after 28 days at room temperature.

Li and Liu (2007) [9] experimented with fly ash with 4% slag and found that incorporating slag could provide a considerable increase in compressive strength. The said geopolymer concrete cured for 14 days under 30°C and 70°C resulted in 50 and 70 MPa, respectively. Li et al. (2010) [10] reviewed the properties of slag and metakaolin for the reactive mechanism and role of Ca and Al. The chemical component of GGBS consists of the $CaO–SiO_2–MgO–Al_2O_3$ system, and in the mixture of phases, the composition resembles gehlenite, akermanite, and depolymerized C-A-S glass structure. The reactions of GGBS are dominated by small particles, and it is acknowledged that Calcium Silicate Hydrate (CSH) is the major binding phase in alkali-activated GGBS. Supraja and Rao (2012) [11] studied GGBS-based geopolymer concrete under different molar concentrations of NaOH, viz. 3M, 5M, 7M, and 9M and under oven curing at 50°C and ambient curing. Their remarks say that after 3 days of oven curing, there is no increment in strength.

The strength increment is based on the rise of curing temperature and molarity concentration. Partha et al. (2014) [12] increased the percentage of GGBS up to 20% and found there was a good increase in strength properties and reduction in workability of geopolymer concrete. The GGBS addition played a vital role in setting the time of geopolymer concrete, and strength gain was slowed down after 28 days of ambient curing until 180 days. The characteristics of geopolymer concrete depend purely on the composition of the base material, and GGBS with an activator solution can produce high early compressive strength (Sarker 2014 [13]). Shahmansouri et al. (2020 & 2021) [14] proved that an increase in GGBS quantity (30% by weight) has considerably increased the compressive strength. GGBS contains a high quantity of Silica, Alumina, and Calcium compared to other industrial by-products. The steel industry has produced more than 300MT of GGBS globally in a year, and it is predicted that this will increase by around 1.6%. This hasty growth of the iron and steel industry produces a large volume of slag, and the disposal of slag is a great challenge to this industry. The utilization of GGBS in Geopolymer concrete develops a greater source of disposal opportunity and will produce a contemporary alternative binder for cement. Further, many researchers reported above that GGBS-based geopolymer concrete showed improved strength and durability properties compared to other industrial by-products because of the availability of calcium content. The essential process in geopolymer concrete is curing because it requires heat to activate the polymerization.

Ambient temperature curing is one option, but for rapid reaction, heating using an electric oven or steam has also been suggested to achieve the polymerization in a few hours/days. Davidovits (1999) [3] experimented with metakaolin-based geopolymer concrete with 90 ˚C curing temperature exposed for 1 hr. to more than 24 hours and identified that 24 hours of curing produced enhanced results in strength characteristics. Palomo et al. (1999) [15] articulated that the increase in temperature was speeding up the chemical reaction, and this became the reason behind the Change in strength properties of fly ash-based geopolymer concrete. Further, they have identified that the silicate impact was higher than the hydroxides in the alkaline solution. In 1999, Palomo et al. [15] again raised the curing temperature from 65°C to 85°C in the fly ash-based geopolymer concrete and determined the strength for the temperature exposure of 2 hours, 5 hours, and 25 hours. They have reported that a significant effect on compressive strength occurs during the increase in temperature and exposure time.

Vijaya Rangan et al. (2001) [16] examined the compressive strength of geopolymer concrete by heat curing (steam and dry curing) and ambient curing, considering age as a variable. The early (7 days) and ultimate (28 days) compressive strengths were 35MPa and 47MPa in ambient curing. The heat curing was done for the same mixture that was used for the ambient curing; it was cured at 60°C for 24 hours in both steam and dry curing. It gave the compressive strength within the range of 55 MPa for steam curing and 65 MPa for dry curing. Zhu Pan and Sanjayan (2010) [17] experimented with the geopolymer against fire and analyzed the stress-strain behaviour of geopolymer under elevated temperature. They have recognized that the strength properties of geopolymer also increase during elevated temperature. The results showed noteworthy contraction during the temperature rise between 200°C and 290°C. Kong and Sanjayan (2010) [18] conducted an experimental work using Australian fly ash to identify the impact of increased temperature on geopolymer paste, mortar, and concrete. They have inspected the size and type of aggregates, superplasticizer, and specimen. They concluded that the effect of the size of the specimen has more impact than the size of the aggregate on the thermal behavior at elevated temperature at 800°C. Patankar et al. (2012) [19] conducted an experiment using fly ash-based geopolymer mortar with the elevated temperature starting from 40°C to 120°C for a period of 24 hours. The strength gain rate was higher at 120°C. Comrie et al. (1988) [20] carried out an experiment in geopolymer mortar with an increase in temperature up to 600°C. The ultimate compressive strength of cement concrete was achieved by geopolymer specimens within the first 2 days of curing. While performing heat curing, the cement concrete specimen started rapid deterioration in compressive strength at 300°C, whereas geopolymer specimens were stable up to 600°C (Davidovits, 1988b [21]; 1994b [22]). Sarkar et al. (2014) [13] proved that fly ash-based geopolymer concrete can perform better in thermal exposure up to 1000°C. In accordance with the test results, geopolymer specimens had less damage and cracking compared to cement concrete for temperature exposure 800°C - 1000°C.

Use of geopolymer concrete as a sustainable alternative to conventional concrete has gained significant attention in the present scenario. In geopolymer concrete, industrial by-products such as fly ash, slag, and other alumino-silicate wastes are used as binders. The use of by-products reduces carbon emissions and also influences the circular economy by introducing a stream of waste materials into the construction industry. Kolade et al. [23] performed a detailed review on geopolymer concrete, highlighting the utilization of different waste materials in concrete, chemical compositions, and performance under different circumstances. Azunna et al. [24] reviewed the mechanical properties of rubberized geopolymer concrete, which indicates improved impact resistance and energy absorption capacity of concrete. Reduction in compressive strength with the increase in rubber content is reported to be significant in the review of Hassan et al. [25]. However, pretreated rubber particles are shown to be effective in minimizing the reduction in compressive strength. At the same time, Arunkumar et al. [26] conducted a characterization study on hybrid fiber-reinforced geopolymer concrete with waste wooden ash. In this work, the combined use of 0.5% polypropylene fiber and 0.5% rubber fiber-reinforced geopolymer concrete shows improvement over the mechanical properties of conventional geopolymer concrete.
Simultaneously, research into the use of waste materials as aggregates in concrete has explored the incorporation of shredded or crumb rubber from tires. Hisbani et al. [27] reviewed the performance of concrete in the presence of crumbed rubber as a partial replacement of aggregate. It indicates improvement in the durability property of concrete using crumbed rubber. A minimal reduction in compressive strength is also noted. The primary motivation for using waste materials is waste diversion, but the resulting Rubberized Concrete (RC) also exhibits uniquely beneficial properties. The replacement of conventional mineral aggregates with rubber particles significantly alters the mechanical behavior of the composite. While it typically leads to a reduction in compressive strength and modulus of elasticity—attributed to the lower stiffness of rubber, poor interfacial bonding with the cement matrix, and increased air entrainment—it dramatically enhances other characteristics [28, 29]. RC demonstrates markedly increased ductility, toughness, impact resistance, and energy absorption capacity. It also offers improved thermal and acoustic insulation properties [30, 31]. The failure mode shifts from brittle to a more gradual, plastic failure, making it highly desirable for applications like seismic-resistant structures, pavement base layers, and crash barriers.
While geopolymer concrete and rubberized concrete have been extensively studied in isolation, their combination into a single composite—Fly Ash-Based Rubberized Geopolymer Concrete (FA-RGPC)—remains a nascent and highly promising field of research. This synergy addresses the fundamental weakness of traditional RC: the weak Interfacial Transition Zone (ITZ) between hydrophobic rubber and the OPC paste. The geopolymer matrix, formed under highly alkaline conditions, may offer a different and potentially more compatible chemical environment for the rubber particles. More critically, geopolymers are inherently more stable at high temperatures than OPC paste, which suffers from the decomposition of C-S-H gel and portlandite beyond 400°C [32, 33]. This thermal resilience is crucial for compensating for the vulnerability of rubber, which softens, melts, and burns between 300°C and 600°C. Therefore, FA-RGPC is hypothesized to exhibit superior residual performance after exposure to fire or high temperatures compared to rubberized OPC concrete.

From the detailed review of the existing literature, it is evident that fly ash–based geopolymer concrete has been studied extensively. Similarly, the use of rubber as a partial replacement for aggregates in concrete has received significant attention. However, the mechanical performance of crumb rubber–based geopolymer concrete under very high curing temperatures has not been adequately investigated. In addition, its durability behavior under different accelerated environmental conditions remains largely unexplored. To address this research gap, the present study is explicitly aimed at conducting a detailed experimental investigation to evaluate the effect of alkalinity, identify the optimum percentage of crumb rubber, and assess the resistance of crumb rubber–based geopolymer concrete under adverse environmental conditions. Considering previous foundational work on the impact resistance of rubberized concrete [34] and the structural behavior of rubber-reinforced beams [35-40], this study aims to bridge a critical research gap. The novel contribution of this work is the integrated experimental and computational investigation of FA-RGPC at elevated temperature. The specific objectives of this study are to develop and systematically characterize FA-RGPC by investigating the individual and synergistic effects of crumb rubber content (0-10%), NaOH molarity (14M and 16M), and elevated curing temperature (100°C) on its workability, mechanical strength (compressive, tensile, flexural), and durability.

2. Theoretical Background

Geopolymers are inorganic materials rich in Silicon (Si) and Aluminium (Al) that react with alkaline activators to become cementitious material. The formation of gel is activated by the application of heat. This gel binds aggregates and unreacted source material, forming geopolymer concrete. Dissolution of Si and Al atoms takes place through the action of OH ions. The framework formed in this way is called polysilates. Silicate refers to a silicon-oxo-aluminate building unit. Chains and rings are formed and cross-linked through the Si-O-Al-O bridge, as shown in Figure 1.

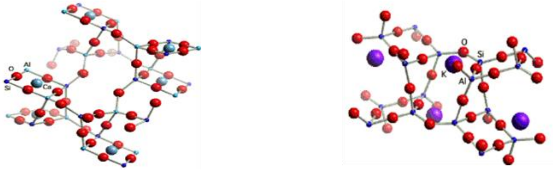


Fig. 1 Formation link and cross-link through Si-O-Al-O bridge

The development of Fly Ash-Based Rubberized Geopolymer Concrete (FA-RGPC) is situated at the intersection of three major research domains: background of geopolymerization science, development of the concept on the behavior of rubber-concrete composites, and properties of materials under thermal stress.

3. Materials and Experimental Setup

An extensive experimental investigation is performed to evaluate the optimal molarity of Fly Ash-Based Rubberized Geopolymer Concrete (FA-RGPC) at a temperature as high as 100°C at varying alkalinity ratios. The mechanical properties, such as compressive strength, split tensile strength, and flexural strength, are then evaluated. To examine the durability of the geopolymer concrete with rubber at higher curing temperatures, concrete cubes are tested separately with H_2SO_4, HCL, $MgSO_4$, and NaCl solutions. The effectiveness of the concrete to perform under adverse conditions is reported in terms of Change in weight as well as reduction in compressive strength. Preparation of materials and concrete cubes for the experiments, along with the design mix, is provided in detail in the following sections.

3.1. Mix Proportions and Experimental Variables

The design mix is worked out assuming the density of geopolymer concrete is 2400 kg/m^3. The total number of concrete cubes is calculated in such a way as to isolate and study the effect of the key variables. It is presented in Table 1 of Annexure 1. A constant Alkaline Liquid-To-Fly Ash (AL/FA) ratio of 0.40 and curing temperature of 100°C is maintained for all design mixes based on optimizations from previous studies [19, 20]. Na_2SiO_3/NaOH ratio is varied as 1, 1.5, 2, and 2.5. Other independent variables are as follows,

- Crumb Rubber (CR) Content: 0%, 2%, 4%, 6%, 8%, and 10% by volume of fine aggregate.
- NaOH Molarity (M): 14M and 16M.
- Na_2SiO_3/NaOH: 1,1.5,2, and 2.5

A Control Geopolymer Mix (0% CR) and a Conventional OPC Concrete Mix of Equivalent Grade (M30) were also cast for benchmark comparisons. The mix ID nomenclature is defined as GPX-MY-CRZ (e.g., GP14M1.0CR1.0 denotes a mix with 1% CR, 14M NaOH, and 1.0 alkaline ratio). The design mix for the current study is fixed as 1:1.40:3.28:0.40 (Fly Ash: Crusher Powder: Coarse Aggregate: Alkaline Liquid). A detailed calculation of materials taken for a trial mixture is given in Table 2 of Annexure 1. A slump value of 70 to 80mm is noted for all the mixes, which is achieved after adding an additional 3% water and 1% CONPLAST SP430 super plasticizer (Figure 2).

Fig. 2 Workability test of FA-RGPC specimen

3.2. Mixing, Casting, and Curing Regimes

The mixing sequence is carefully standardized to ensure the homogeneity of the rubberized geopolymer concrete:

- The fly ash, natural sand, rubber aggregates (if any), and coarse aggregates are dry-mixed in a pan mixer for 3 minutes.
- The alkaline activator solution (NaOH + Na_2SiO_3, pre-mixed) and superplasticizer are added to the dry mix. The wet mixing continued for 5 minutes until a uniform, cohesive mixture was achieved.
- The fresh concrete is cast into pre-oiled steel moulds for:
    - Cubes: 150 mm × 150 mm × 150 mm (for compressive strength and density).
    - Cylinders: 150 mm diameter × 300 mm height (for split tensile strength).
    - Prisms: 100 mm × 100 mm × 500 mm (for flexural strength).
- The specimens are compacted on a vibrating table to remove the entrapped air.

- The cast specimens are covered with a plastic sheet and left at ambient temperature (27 ± 2°C) for a 1-hour rest period to allow the geopolymerization process to initiate.
- After the rest period, the specimens were transferred to a forced-air oven and subjected to heat curing at the specified temperatures, 100°C for 24 hours.
- Post heat curing, the specimens were demoulded and stored at ambient laboratory conditions until the day of testing (7, 14, or 28 days). This step evaluates the stability of the geopolymer matrix after the initial heat-induced polymerization.

The arrangement of the test setup for these three different types of tests conducted for material property investigation is shown in Figure 3.


(a) Compressive Strength Test **(b) Split Tensile Strength Test** **(c) Flexural Strength Test**

Fig. 3 Arrangements of the test setup

3.3. Elevated Temperature Exposure

Selected specimens from optimal mixes are subjected to elevated temperatures in a computer-controlled muffle furnace (Figure 4). A heating rate of 4.4°C/min was maintained to reach the target temperature of 100°C. The specimens were held at the target temperature for 2 hours to ensure thermal equilibrium, then allowed to cool down naturally inside the furnace. The residual compressive strength and visual appearance (cracking, spalling, colour change) were evaluated after cooling.

Thus, an extensive experiment has been planned to study the mechanical properties and durability characteristics of Fly Ash-based rubberized geopolymer concrete under 100 °C curing temperature. The whole experimental process is summarized in the following flowchart in Figure 5.


(a)Before heating **(b)After heating**

Fig. 4 Different states of the test apparatus for elevated temperature curing

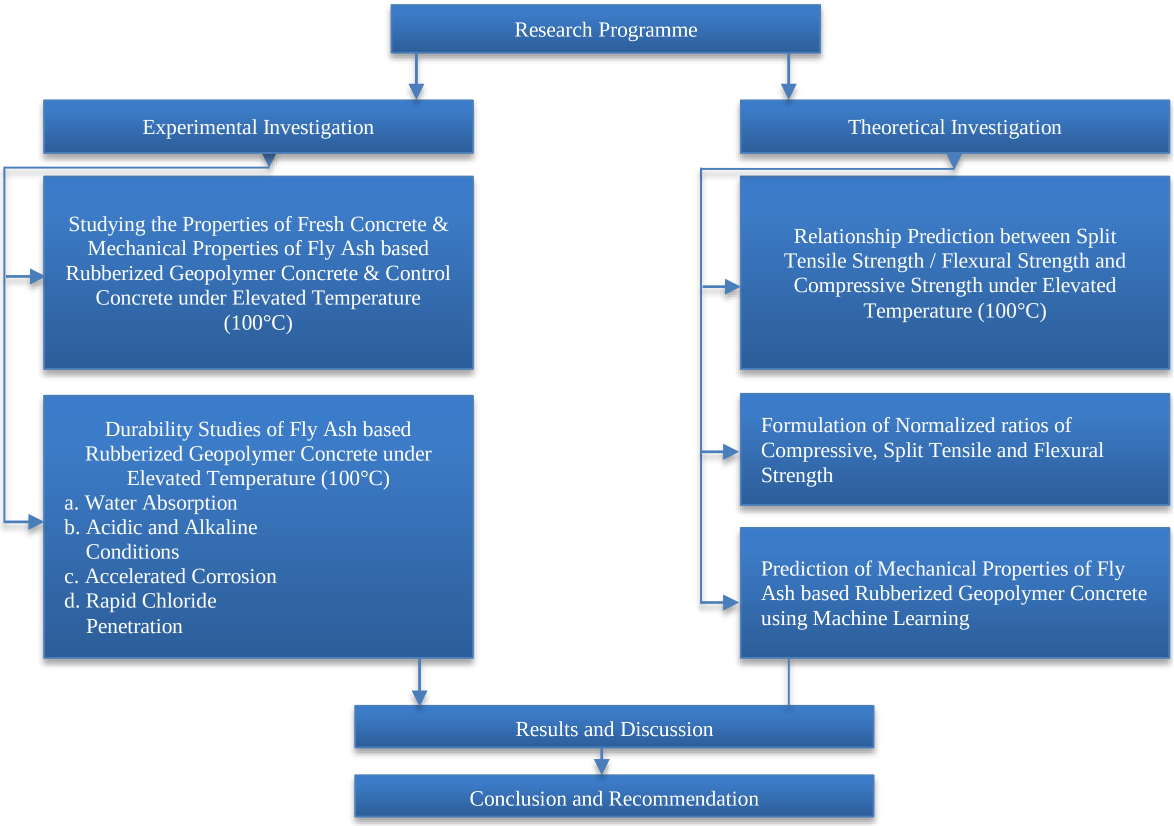


Fig. 5 Flowchart of the experimental investigation and description of work

(a) HCL solution **(b) H_2SO_4 solution**

(c) $MgSO_4$ solution **(d) NaCl solution**

Fig. 6 Concrete cubes specimen immersed in different solutions for durability test

For the durability test, concrete cubes are separately immersed in four different solutions. The Change in weight is then measured before and after immersion of cubes in H_2SO_4 solution, HCL solution, NaCl solution, and $MgSO_4$ solution. All cubes are then experimented with for their compressive strength. The Change in compressive strength with respect to conventional concrete highlights the effectiveness of FA-RGPC in adverse environmental conditions. The preparation of cubes in these four solutions is shown in Figure 6.

4. Result and Discussion

4.1. Hardened Properties

4.1.1. Compressive Strength

The compressive strength of the concrete cubes at 14M NaOH and 16M NaOH is presented in Figures 7 and 8 at different Alkaline-Liquid ratios. These molar concentrations are chosen based on the work of Hardjito et al. (41), which indicated an increasing trend of compressive strength with the increase in molarity. In addition, compressive strength seems to be significantly influenced by all three variables- i) molarity of NaOH, ii) Alkaline-Liquid Ratio, and percentage of Crumb Rubber. A non-linear trend in the reduction in strength is observed with increasing CR content. However, the rate of reduction is strongly controlled by NaOH molarity and alkaline ratio.

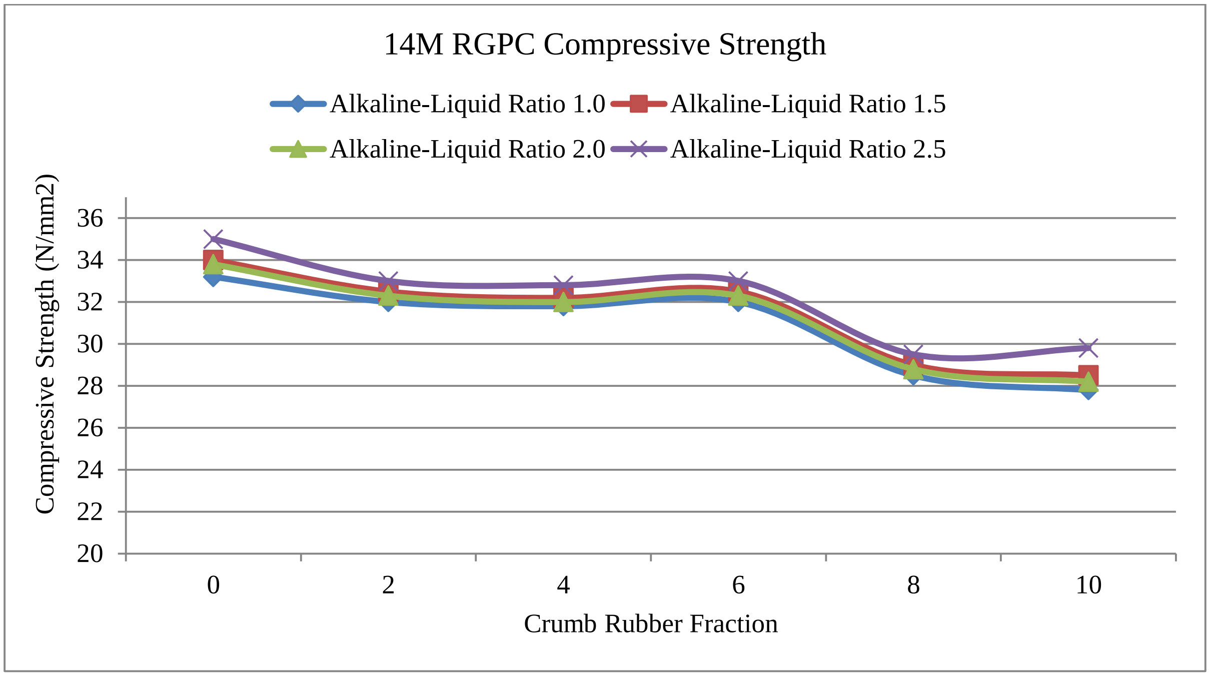


Fig. 7 Compressive strength of FA-RGPC at different alkaline-liquid ratios for 14M NaOH

For a mix with 14M NaOH cured at 100°C, the 28-day compressive strength decreased from 35 MPa at 0% CR to 29.8 MPa at 10% CR for an alkaline-liquid ratio of 2.5. Similarly, the lowest compressive strength is obtained for an Alkaline-Liquid Ratio of 1 at both 0% CR and 10% CR which are 33.2 MPa and 28 MPa, respectively**.** This represents a 14.86% reduction at an Alkaline-Liquid Ratio of 2.5 and 15.66% at a ratio of 2.5 for the Change in CR fraction from 0% to 10%.

In 16M NaOH-based FA-RGPC, a similar observation is obtained with the lowest compressive strength attained at 10% CR for an Alkaline-Liquid Ratio of 1.0. The reduction in compressive strength in this case is 16.93% and 18.15% for Alkaline-Liquid Ratios of 2.5 and 1.0, respectively. It is to be noted that in both cases, 6% CR replacement can be considered as the optimum replacement percentage. Beyond this fraction, compressive strength quickly reduces to the lowest value.

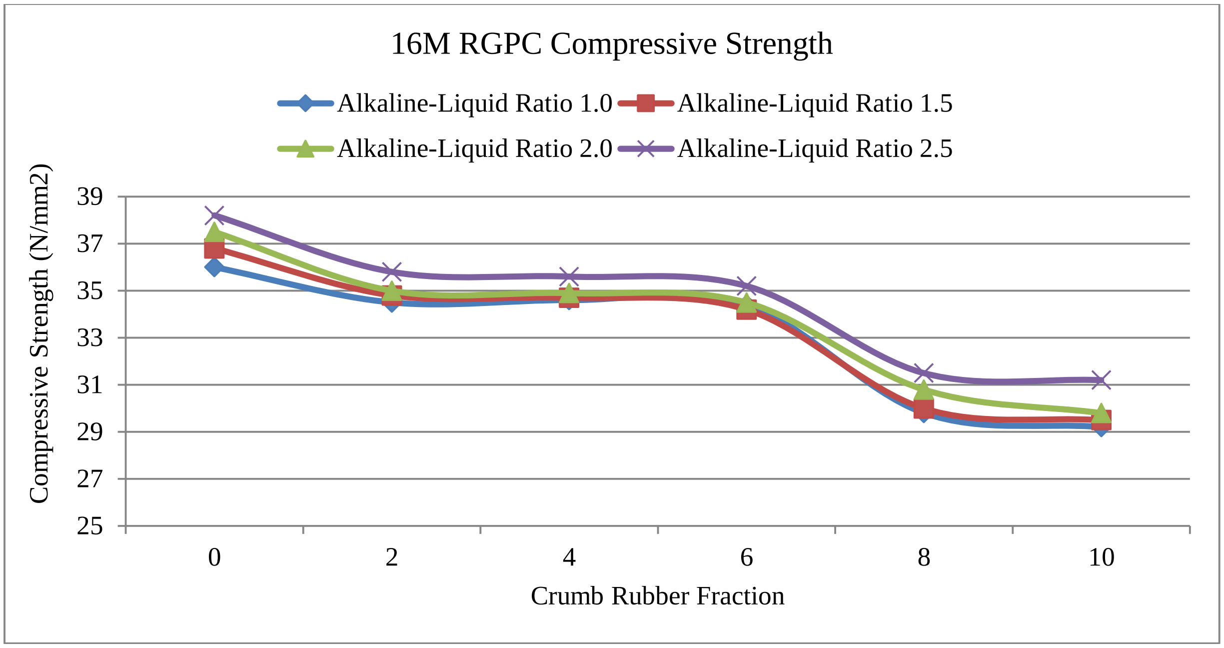
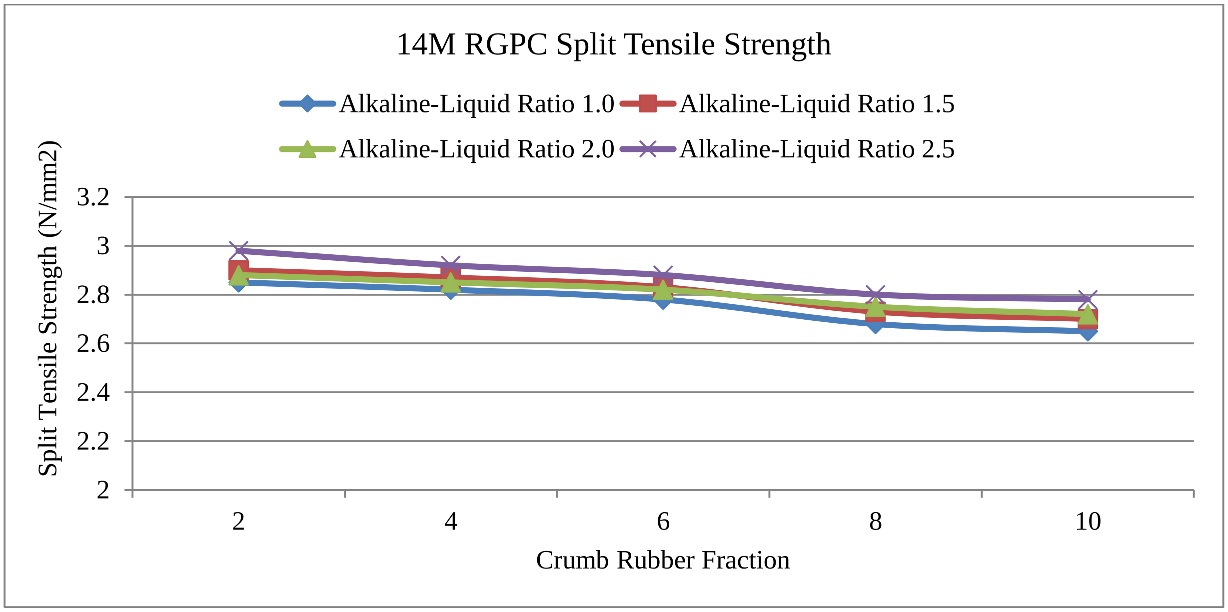


Fig. 8 Compressive strength of FA-RGPC at different alkaline-liquid ratio for 16M NaOH

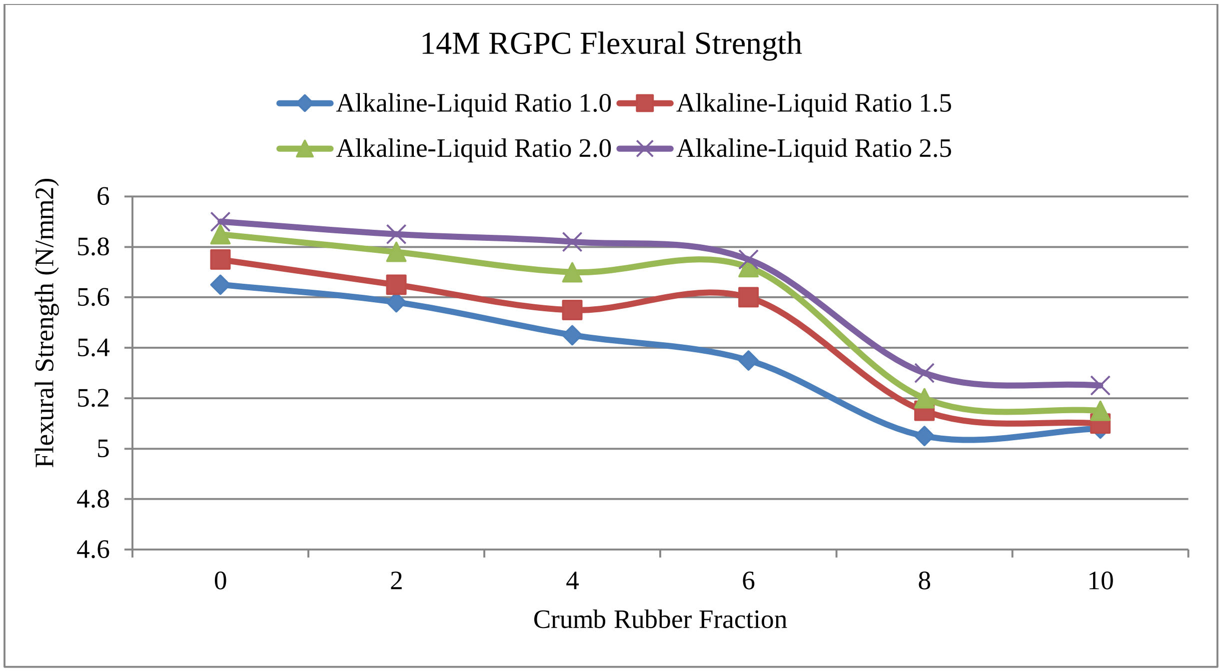
The strength reduction with CR addition is expected due to the lower stiffness and strength of rubber particles compared to mineral aggregates, which creates stress concentration points and a weaker ITZ. The 16M NaOH concentration likely provides the optimal alkalinity for complete dissolution of fly ash, leading to a denser and more Homogeneous Geopolymeric (N-A-S-H) gel matrix. This robust matrix better accommodates the compliant rubber particles upto a certain fraction of CR, resulting in a greater strength at 6% CR than 14M NaOH. This percentage has also been reported to provide better compressive strength in conventional concrete with waste tyre rubber as a partial replacement for aggregates, as reported in [35]. The decline in performance at both 14M and 16M suggests potential premature precipitation of reaction products, leading to a more porous and brittle microstructure after a certain fraction of CR, as hypothesized in the theoretical background.

4.1.2. Split Tensile and Flexural Strength

Results of split tensile strength and flexural strength are provided in Figure 9 (a) and (b) for 14M NaOH solution and in Figure 10 (a) and (b) for 16M NaOH solution. The reduction in split tensile and flexural strengths with CR addition is observed to be less pronounced than in compressive strength.



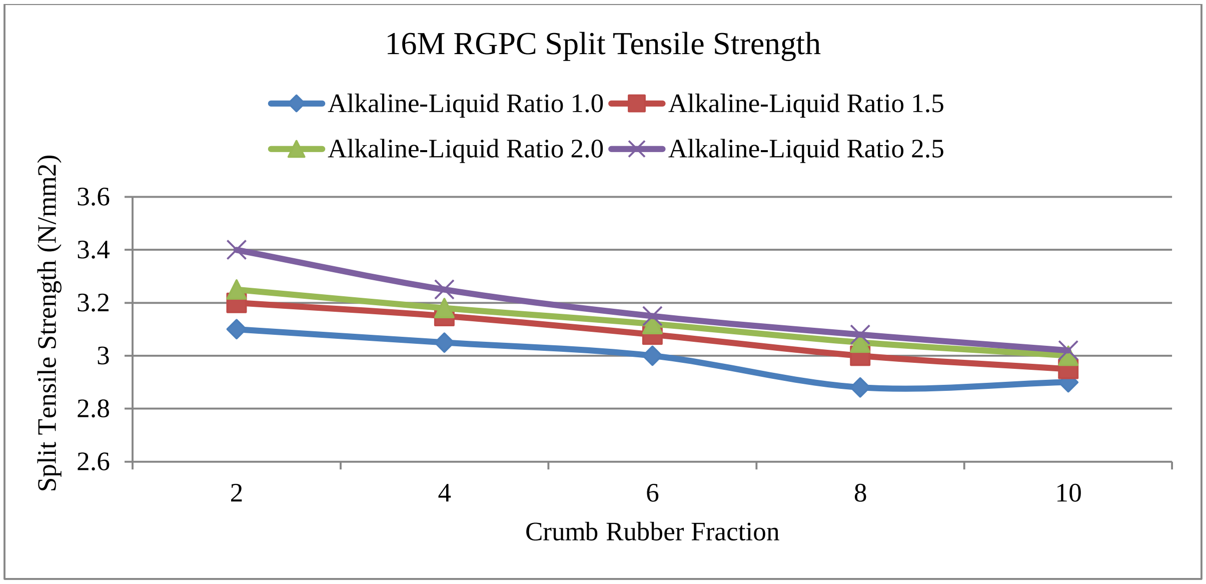
(a)



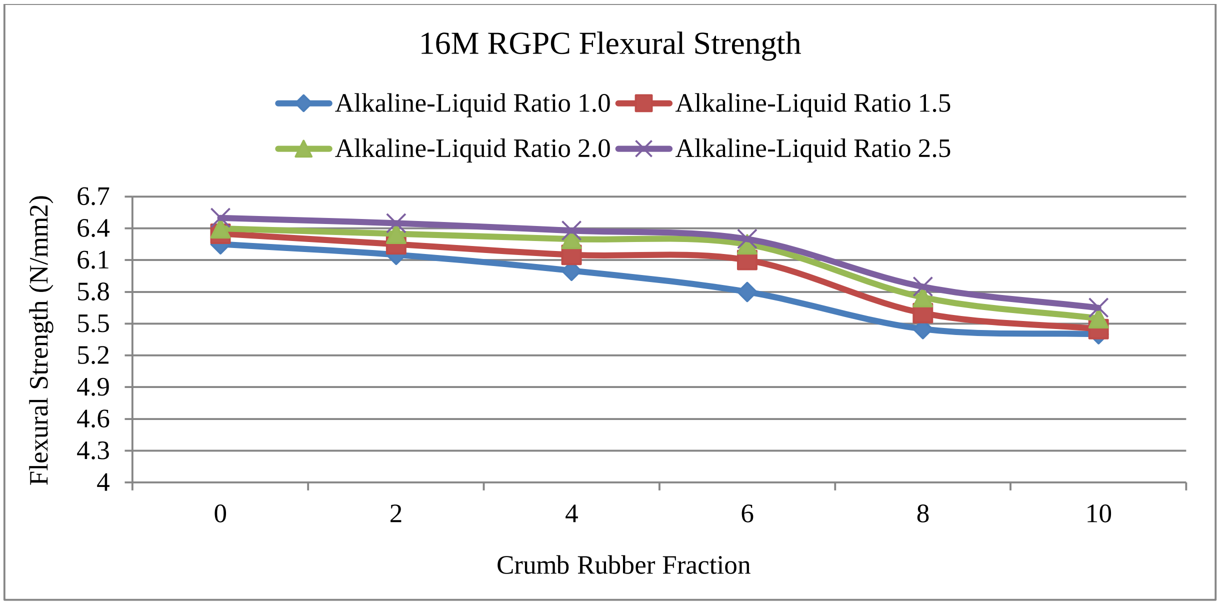
(b)

Fig. 9 (a) Split tensile strength, and (b) Flexural strength of FA-RGPC at different Alkaline-Liquid ratios for 14M NaOH

This behavior underscores the positive role of rubber in modifying the failure mode. In tension and flexure, crack initiation and propagation are the governing failure mechanisms. The soft rubber particles act as internal crack arresters. As a microcrack approaches a rubber particle, the particle's property to deform elastically absorbs energy. Consequently, the crack tip gets wider instead of propagating further and thus deflects the crack path, changing the failure pattern. This necessitates more energy to cause failure, leading to a higher retained percentage of tensile and flexural strength relative to compressive strength. This phenomenon of improved relative performance in tension is an important characteristic of fiber-reinforced and rubberized composites. Split tensile strength and flexural strength are higher than those of control concrete up to 6% rubber fractions in 14M. On the other hand, in the case of 16M NaOH solution, split tensile and flexure strength outperforms control concrete in all the fractions up to 10%. The higher molar concentration promotes early hydration, and pore water reduction results in higher strength properties.



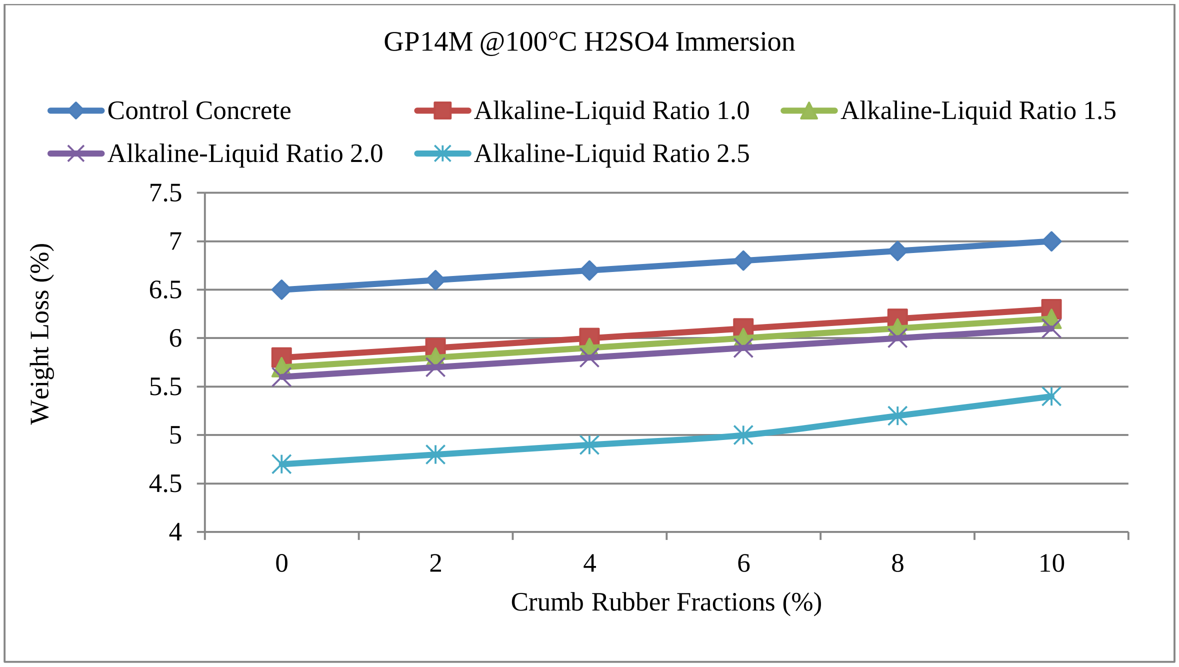
(a)



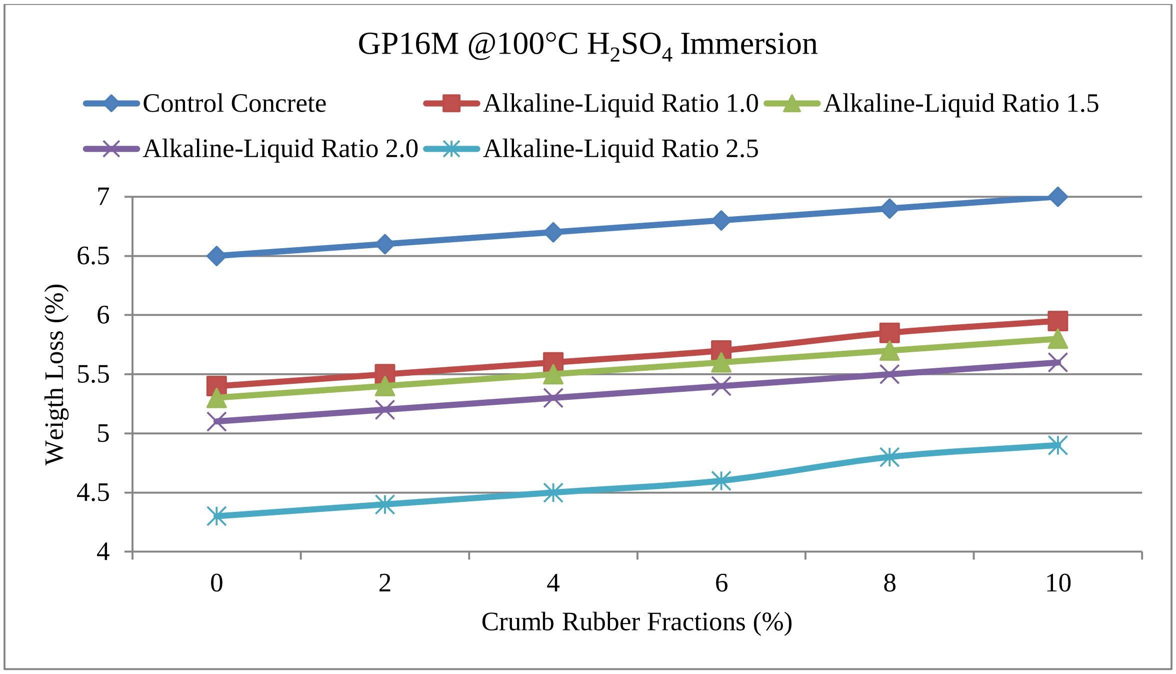
(b)

Fig. 10 (a) Split tensile strength and (b) Flexural strength of FA-RGPC at different alkaline-liquid ratios for 16M NaOH

The above results at elevated temperature curing are the most significant finding of this study, highlighting the core difference in properties between the two materials. After high-temperature curing, in control concrete, two detrimental processes occur simultaneously: (1) the decomposition of the Portlandite and C-S-H gel in the cement paste, leading to its disintegration, and (2) the combustion of rubber particles, leaving behind voids. These processes act simultaneously, leading to failure. In contrast, in FA-RGPC: (1) the Geopolymer (N-A-S-H) gel is inherently more thermally stable and can maintain its structural integrity up to ~800°C [10, 21]; while the rubber particles still combust, leaving pores. These pores are effectively contained within the intact, refractory geopolymer skeleton. The geopolymer matrix acts as a robust scaffold, preventing widespread cracking and spalling, thereby maintaining a significantly higher load-bearing capacity post-fire. This makes FA-RGPC a far more promising material for applications where fire resistance is a concern.



(a) Weight loss of cubes with 14M NaOH solution after immersion in H_2SO_4



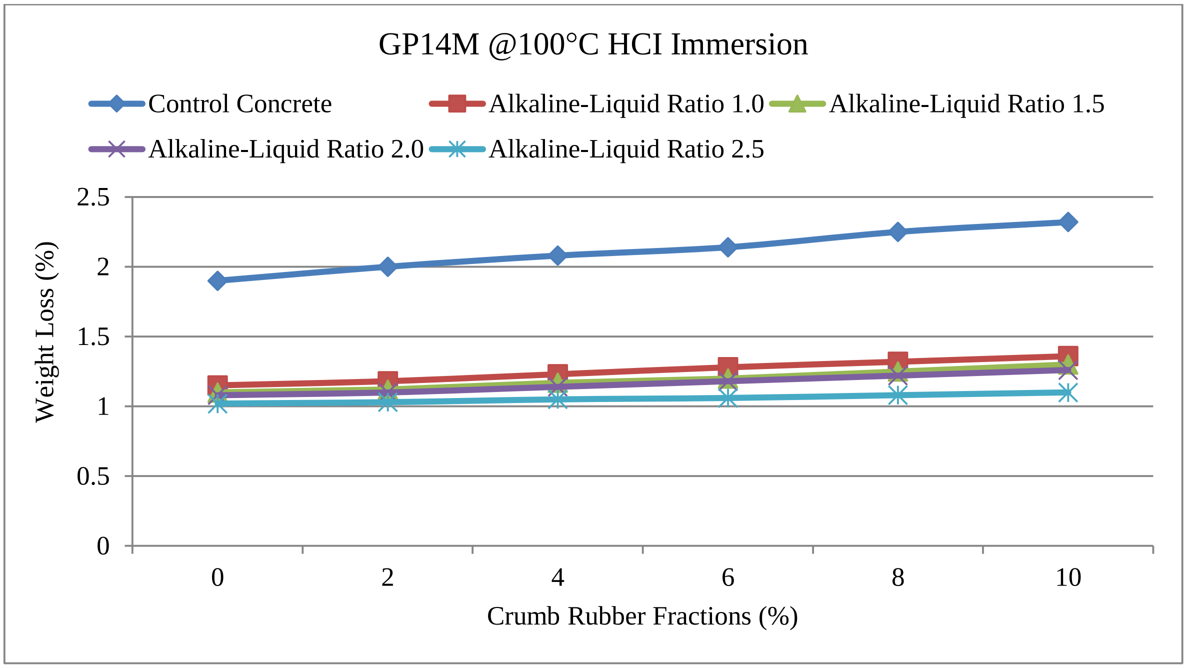
(b) Weight loss of cubes with 16M NaOH solution after immersion in H_2SO_4

Fig. 11 Change in weight after high-temperature curing and immersion in H_2So_4 solution

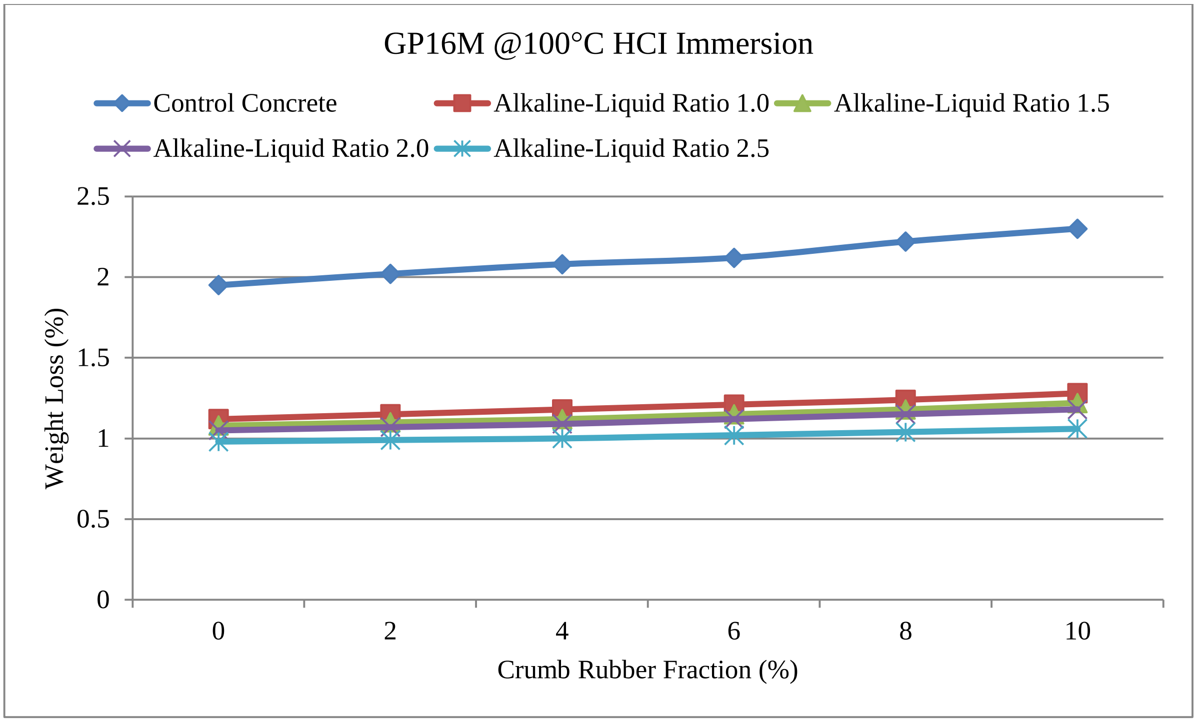
4.2. Durability Performance

4.2.1. Weight Loss/Gain

Following the previous results of the present work, where the optimized rubber fraction is estimated to be 6%, durability tests are also performed with the CR fraction varying from 0% to 10%. In Figures 11-14, FA-RGPC exhibits significant residual strength retention after exposure to high temperatures, in comparison to a conventional control concrete of equivalent mix design. After exposure to H_2SO_4 solution, the FA-RGPC mix with 6% CR at an Alkaline-Liquid Ratio of 2.5 results in only 4.8% weight loss, whereas the control concrete cube loses its weight by 6.75% at a similar CR fraction. It is also observed from Figures 11(a) and (b) that the effect of the 14M NaOH solution in reducing weight is slightly higher than that of the 16M solution.



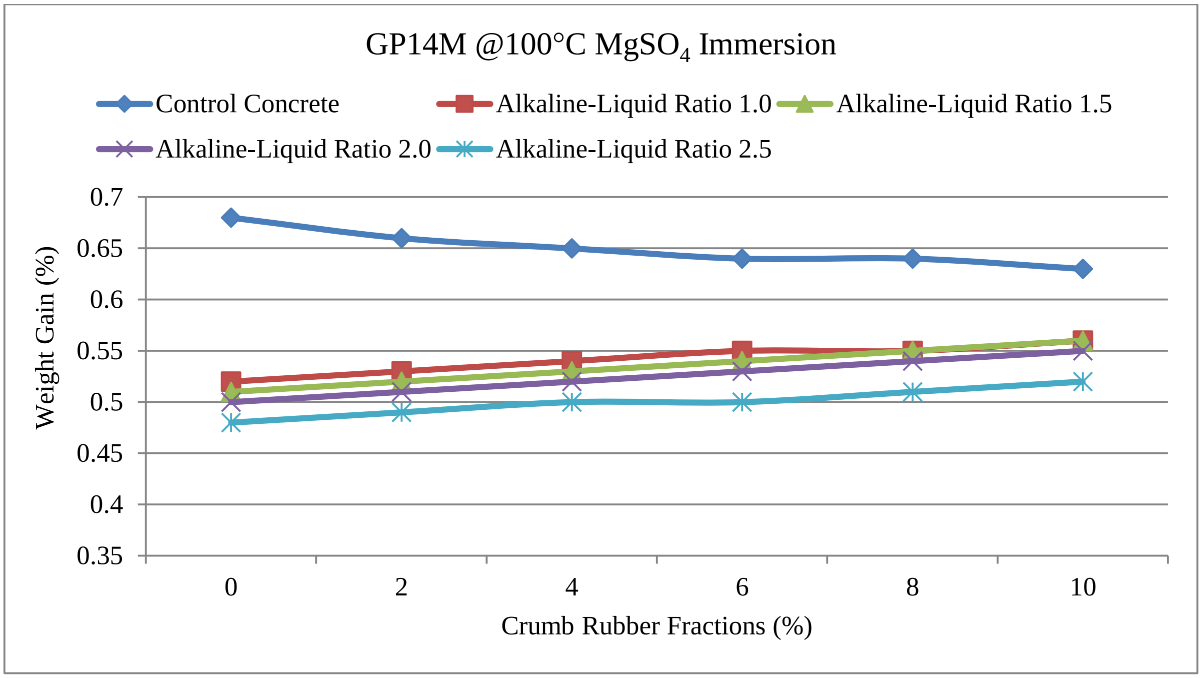
(a) Weight loss of cubes with 14m NaOH solution after immersion in HCl



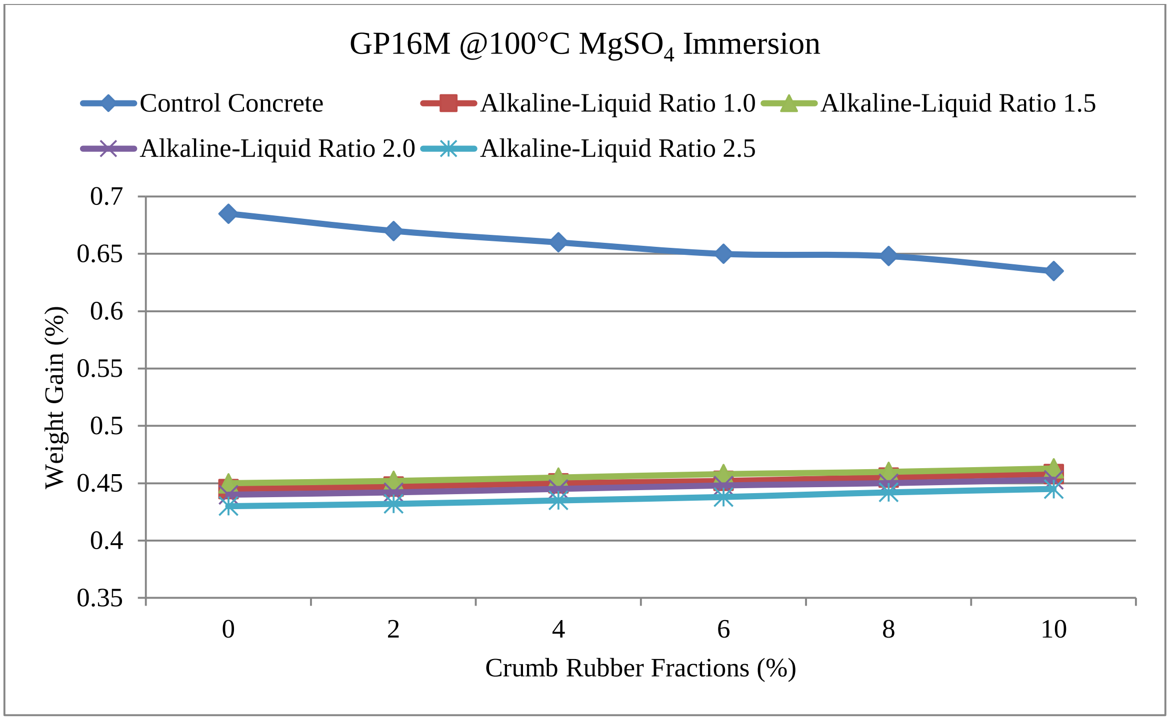
(b) Weight loss of cubes with 16M NaOH solution after immersion in HCl

Fig. 12 Change in weight after high-temperature curing and immersion in HCl solution

The loss of weight in HCl-exposed Rubberized Geopolymer (RGP) specimens with different alkaline ratios and molar concentrations is all within 0.97% to 1.42% whereas in control concrete, the losses are 1.92% to 2.32%. The weight loss in the H_2SO_4 exposure is higher than that in the HCl in the entire rubberized geopolymer specimen, which varies between 4.32 to 6.32% and it is found to be comprehensively less than control concrete specimens (6.48% to 6.94%). Higher molar concentration and higher alkaline ratios support the hydration and polymerization process and make the geopolymer densified. So that when it is exposed to any environment, the losses are minimal.



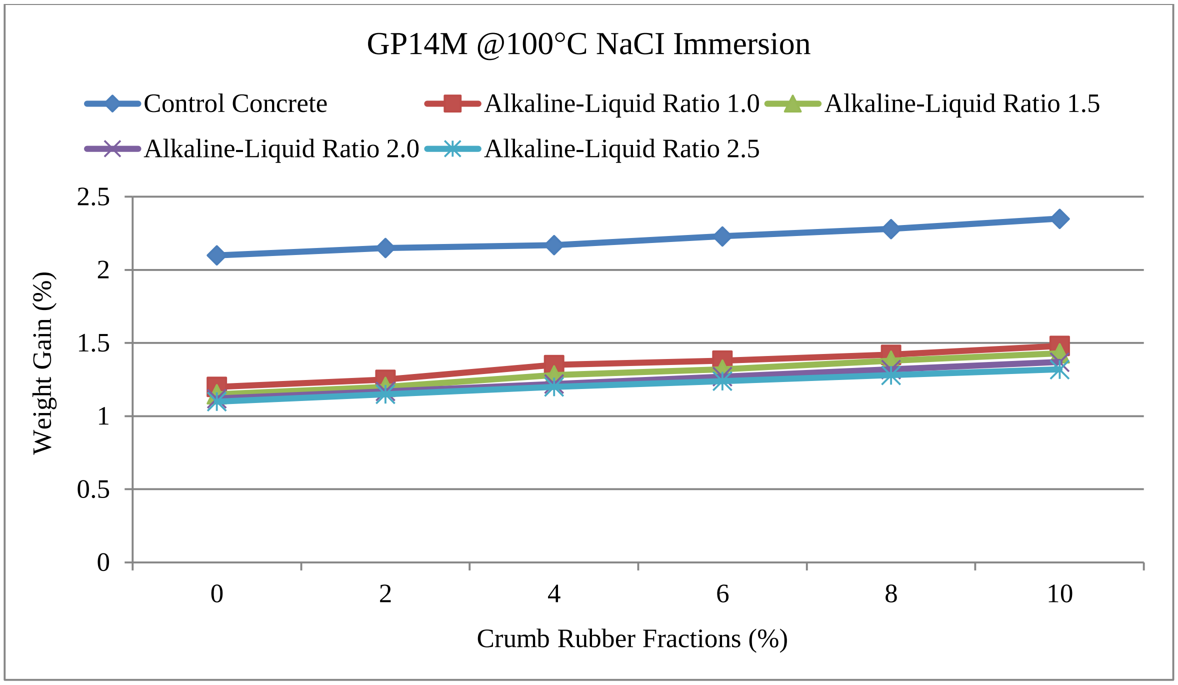
(a) Weight gain of cubes with 14M NaOH solution after immersion in $MgSO_4$



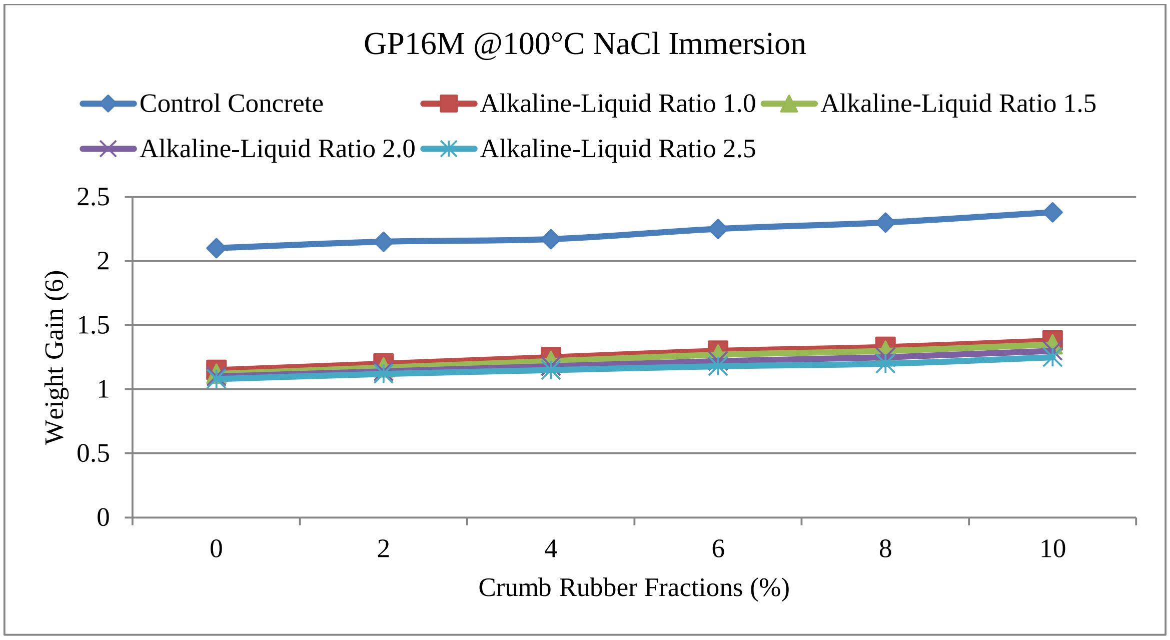
(b) Weight gain of cubes with 16M NaOH solution after immersion in $MgSO_4$

Fig. 13 Change in weight after high-temperature curing and immersion in $MgSO_4$ solution

In the sulfate-exposed environment, a very slight increase in weight has been identified in RGP specimens, 0.43% to 0.54%, which is less than the control concrete, 0.628% to 0.684%. The magnesium ions may diffuse into the geopolymer alkaline solution. In the chloride-exposed environment, rubberized geopolymer specimens have been found to increase in weight by 1.07% to 1.50%, which is also less than the 2.08% to 2.36% of control concrete. However, in NaCl and $MgSO_4$ solutions, the alkaline-liquid ratio does not present any significant impact on durability. Among all four, the H_2SO_4 solution affects the cubes more adversely than the others in reducing/gaining the weight of concrete.



(a) Weight loss of cubes with 14M NaOH solution after immersion in NaCl

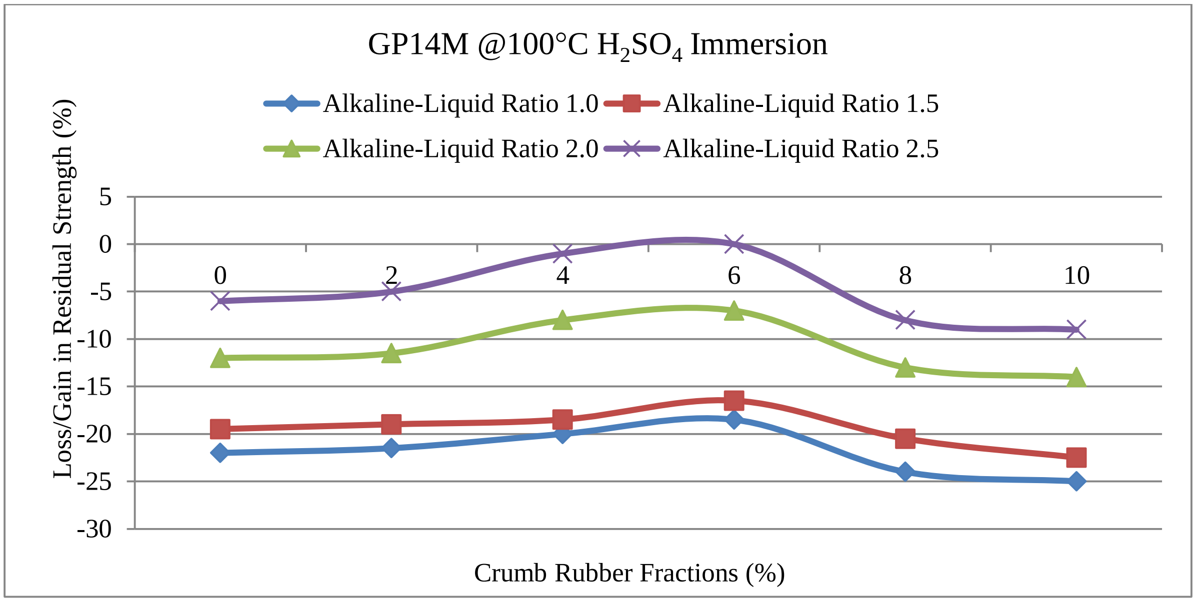


(b) Weight loss of cubes with 16M NaOH solution after immersion in NaCl

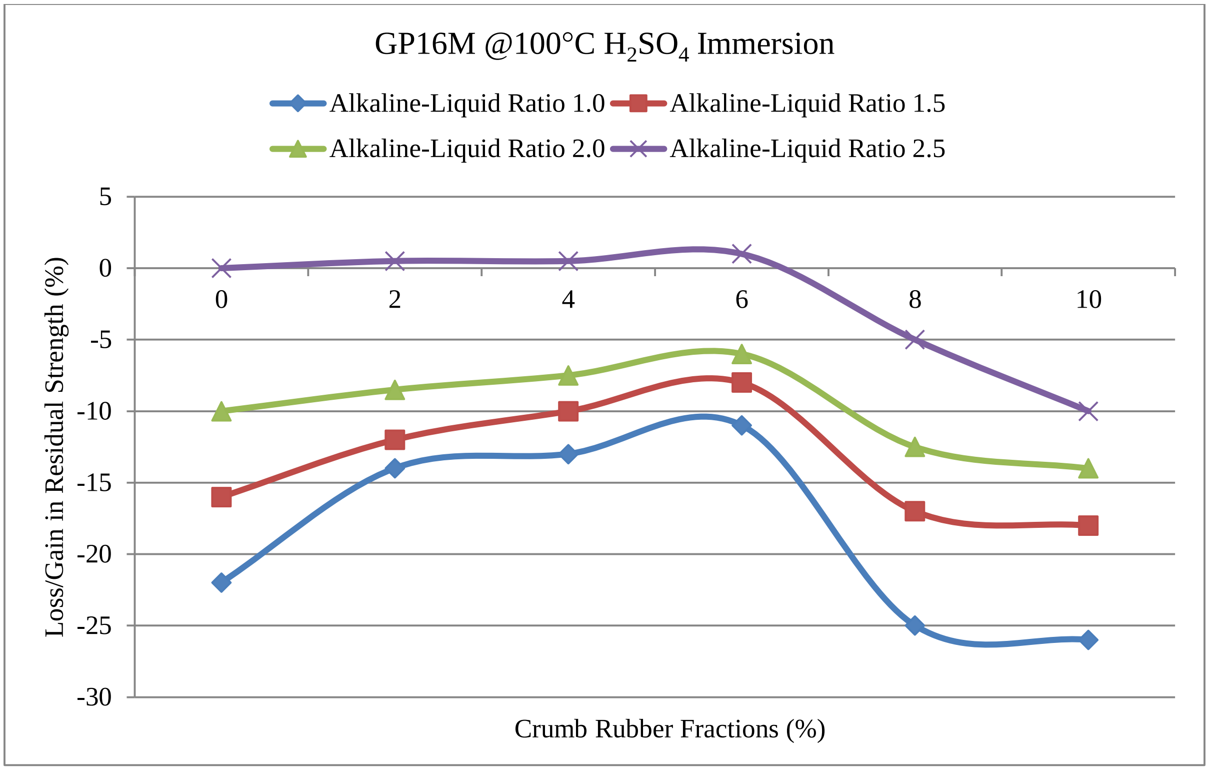
Fig. 14 Change in weight after high-temperature curing and immersion in NaCl solution

4.2.2. Change in Residual Strength

Residual strength is another important parameter utilized here to study the durability of fly ash-based rubberized geopolymer concrete. After taking out the immersed concrete cubes from different solutions and measuring their weights, the cubes are further subjected to a compressive strength test. The residual strength is then measured by subtracting the final compressive strength from the strength of conventional concrete cubes cured in water. The results are presented in Figures 15-18. Performance of FA-RGPC prepared with both 14M and 16M NaOH solutions is shown side by side in each figure for their easy comparison. Following the trend of mechanical properties, in Figures 15(a) and (b), FA-RGPC shows higher retention of strength with 6% CR replacement. A negligible gain in strength at 16M NaOH solution with 6% CR may be due to the filling up of pores by the materials formed in the reaction. With the increase in Alkaline-Liquid Ratio, the loss in strength significantly reduces as it neutralizes the acidic effect with the increase in alkalinity. Achievement of better results for the 16M NaOH solution-based FA-RGPC over the 14M solution is governed by a similar reason.

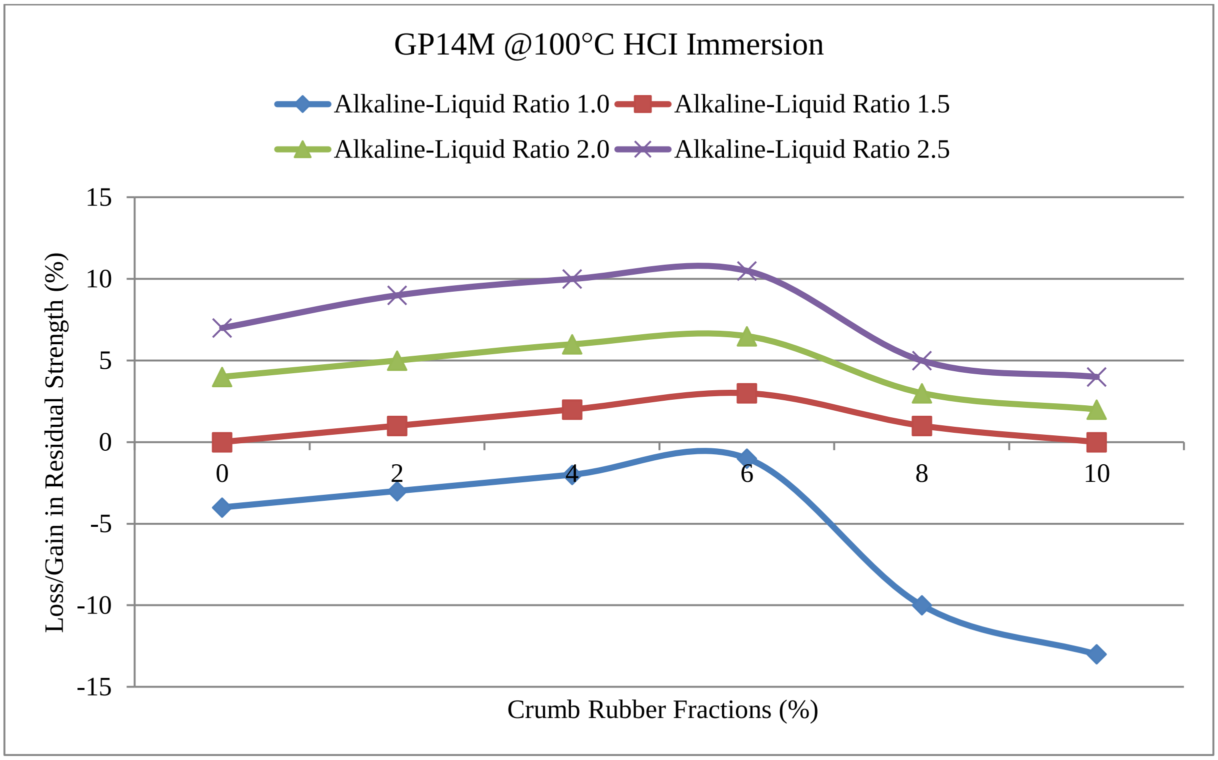


(a) Loss/Gain Of Compressive Strength Of Cubes with 14M NaOH Solution After Immersion In H_2SO_4

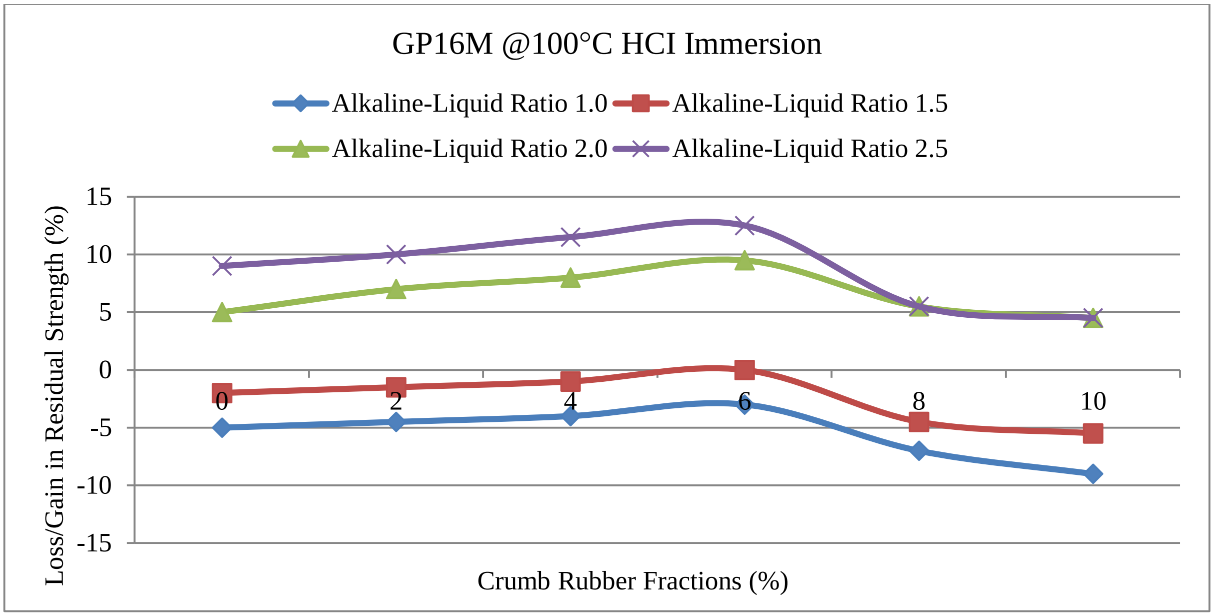


(b) Loss / gain of compressive strength of cubes with 16M NaOH solution after immersion In H_2SO_4

Fig. 15 Change in residual strength after high-temperature curing and immersion in H_2SO_4 solution



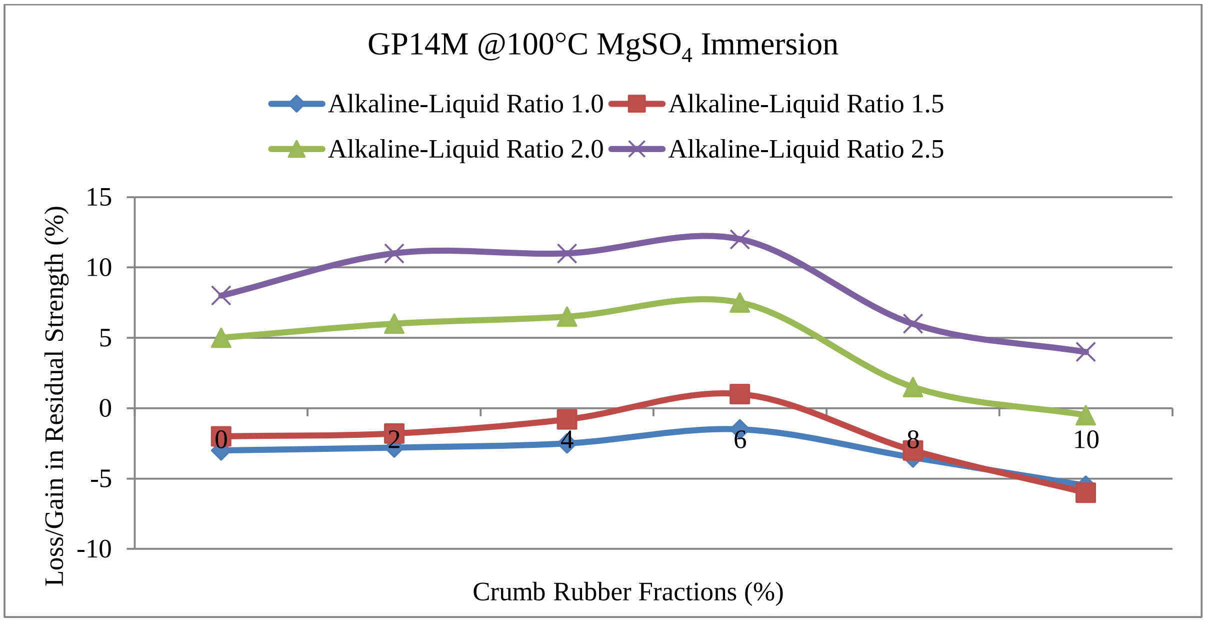
(a) Loss / gain of compressive strength of cubes with 14M NaOH solution after immersion in HCl



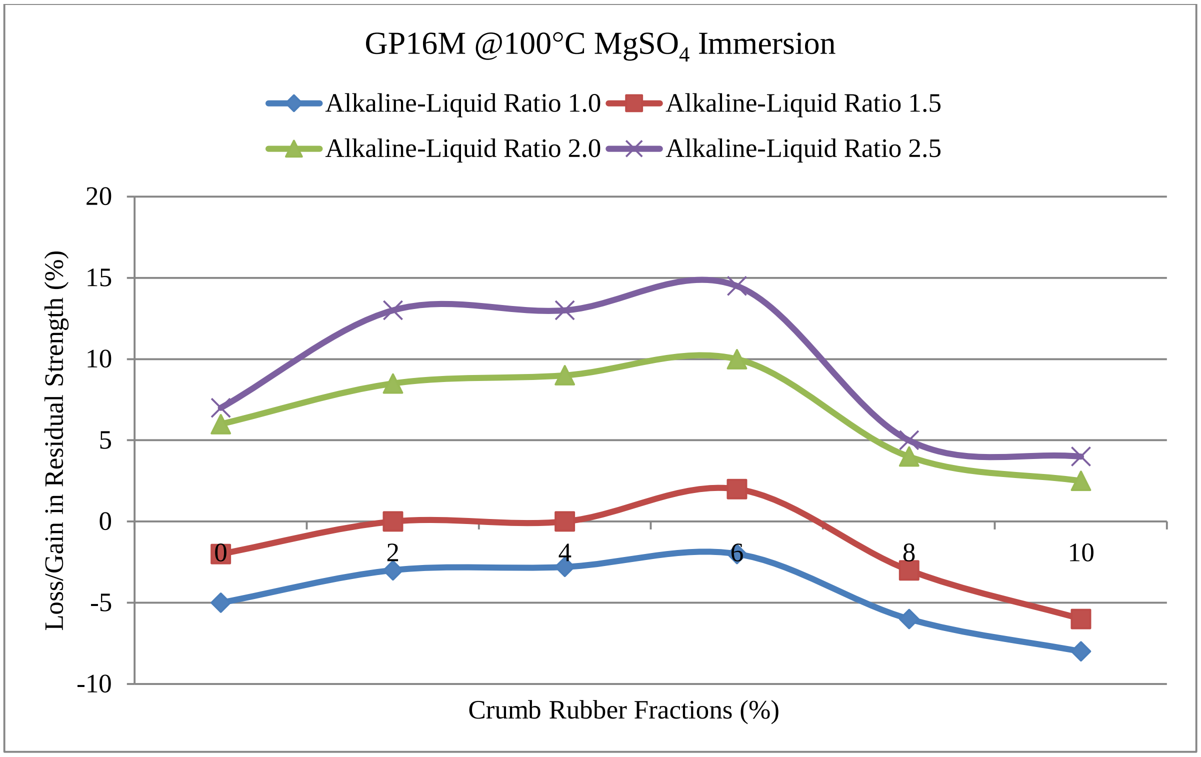
(b) Loss / gain of compressive strength of cubes with 16M NaOH solution after immersion in HCl

Fig. 16 Change in residual strength after high-temperature curing and immersion in HCl solution

The reduction in residual compressive strength is found to be comparatively less, between 0.44% to 4.63% in HCl-exposed geopolymer specimens, compared to 2.23% to 9.40% in control concrete. While observing the residual strength of rubberized geopolymer specimens exposed under H_2SO_4, it is found that there is a 4.14% to 26.54% reduction in strength compared to the compressive strength of the geopolymer specimen. The control concrete attains 16.88% to 29.58% less strength than the compressive strength of conventional concrete. The reduction in compressive strengths for $MgSO_4$ immersion is observed between 0.06% to 2.82% in all the geopolymer specimens (Figures 17(a) and (b)), and for control concrete, the reduction is from 2.02% to 3.28%. The reason for the strength reduction is that diffusion of magnesium and movement of alkali ions in the solution may have happened simultaneously. It stimulates the cracks in the geopolymer specimen and causes strength reduction. In the chloride environment, the strength reduction is identified between 0.20% to 3.38% in the geopolymer specimen (Figures 18(a) and (b)), and 1.81% to 3.46% in the control concrete. Further, the strength reduction of GP16M is less than that of GP14M. Higher molar concentration and higher alkaline ratio have contributed to its effective results under a chloride and sulphate environment.

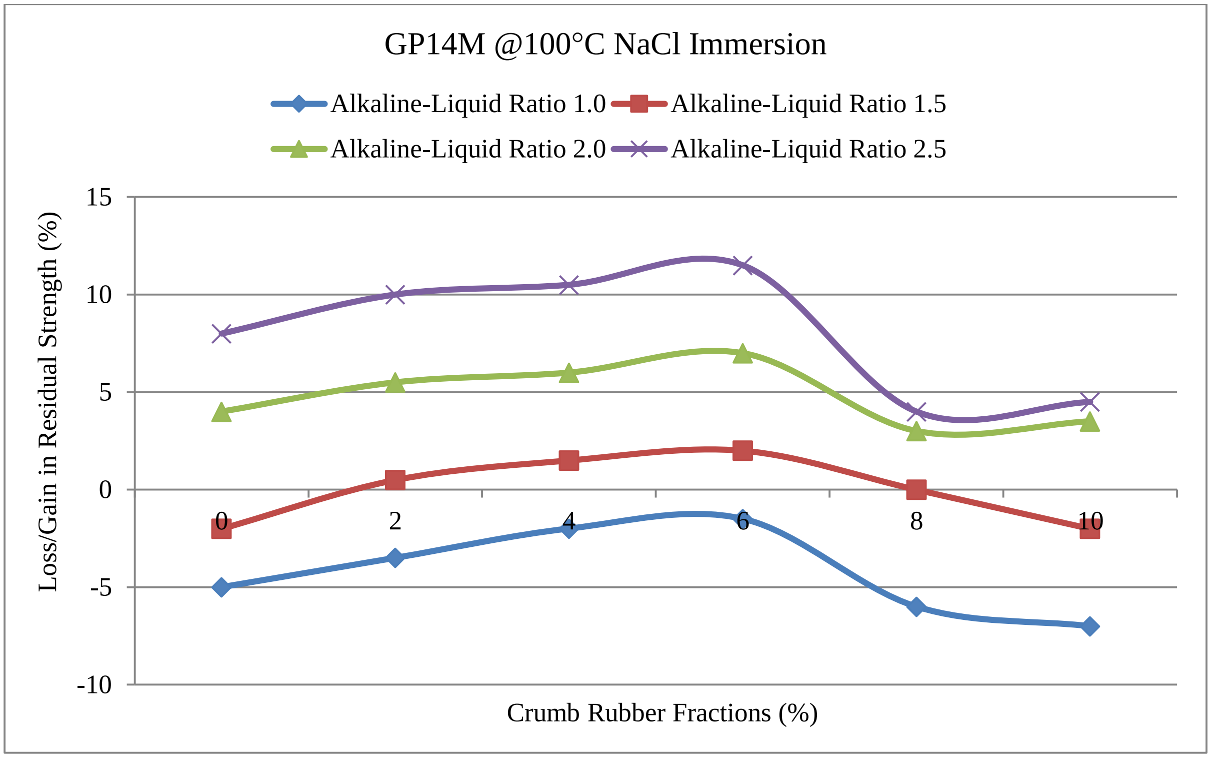


(a) Loss / gain of compressive strength of cubes with 14M NaOH solution after immersion in $MgSO_4$

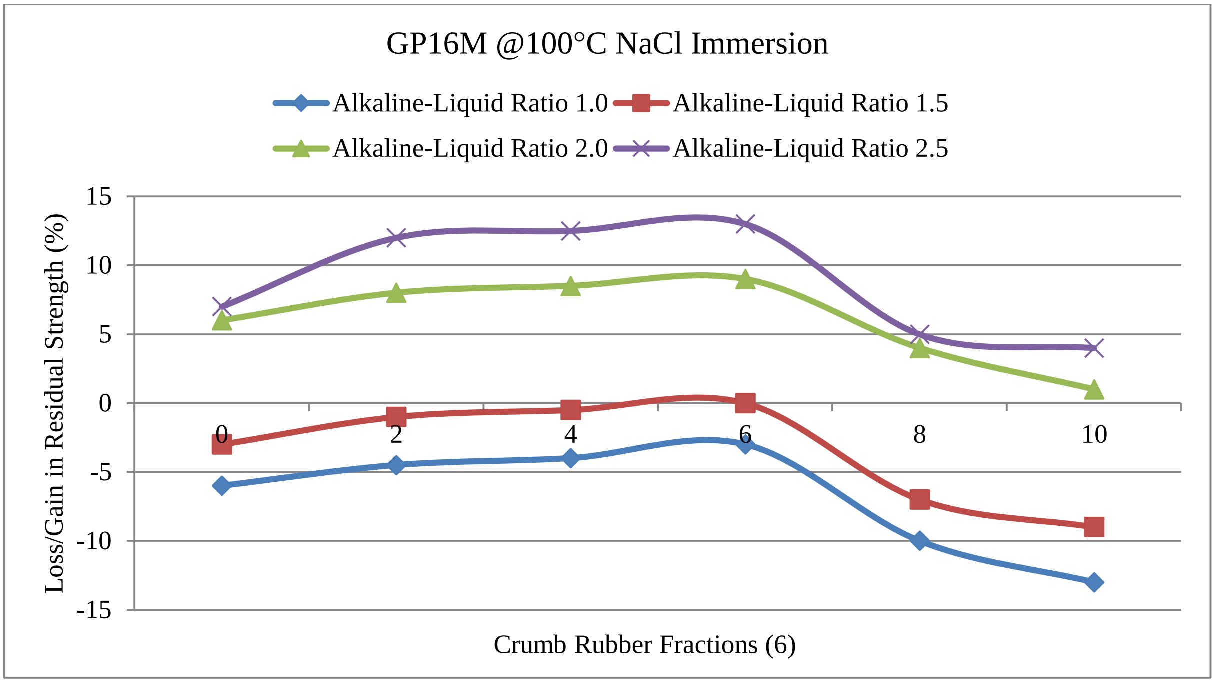


(b) Loss / gain of compressive strength of cubes with 16M NaOH solution after immersion in $MgSO_4$

Fig. 17 Change in residual strength after high-temperature curing and immersion in $MgSO_4$ solution



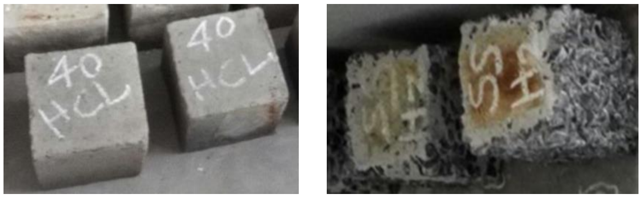
(a) Loss /gain of compressive strength of cubes with 14M NaOH solution after immersion in NaCl



(b) Loss / gain of compressive strength of cubes with 16M NaOH solution after immersion in NaCl
Fig. 18 Change in residual strength after high-temperature curing and immersion in NaCl solution

4.2.3. Physical Observation

Concrete cubes immersed in different reactive solutions are surface cleaned and examined for their physical changes at the surface. These are shown in Figures 19 and 20. There is no change found in the physical appearance of the geopolymer specimens after HCl exposure (Figure 19(a)). Most of the specimens immersed in HCl solution retain their shape and color, except for a few specimens that are found to have mustard yellow color in some places. It is the footprint of an acidic reaction with the concrete matrix.



(a) Physical changes of cubes after immersion in HCl **(a) Physical changes of cubes after immersion in H_2SO_4**
Fig. 19 Physical changes of cubes after high-temperature curing and immersion in HCl and H_2SO_4 solutions

(a) Physical changes of cubes after immersion in $MgSO_4$ **(a) Physical changes of cubes after immersion in NaCl**
Fig. 20 Physical changes of cubes after high-temperature curing and immersion in $MgSO_4$ and NaCl solutions

H_2SO_4-exposed specimens shown in Figure 19(b) exhibit surface deterioration in all the geopolymer specimens, and a deep brownish yellow color is observed on the surface. The cubes have also become softer than their normal condition. During $MgSO_4$ exposure (Figure 20(a)), the specimens' shape and size are found to be intact. However, the colour of the surface is changed to dark brown and black in many cubes. The appearance of the NaCl-exposed geopolymer specimen remains unchanged, as shown in Figure 20(b). The identified black and dark brown appearance in the sulphate exposure of geopolymer specimens may be due to the reaction of the iron content available in the base materials (GGBS).

5. Conclusion

In this study, an extensive investigation is conducted for the comprehensive characterization of Fly Ash-Based Rubberized Geopolymer Concrete (FA-RGPC) at elevated temperature. A detailed investigation of FA-RGPC is conducted to address the dual environmental challenges of cement-related CO_2 emissions and the disposal of waste tires by establishing its practical applicability. Through this experimental approach, the effects of Crumb Rubber (CR) content, NaOH molarity, and curing temperature on the fresh, mechanical, and durability properties are systematically evaluated. The key findings obtained from this work are highlighted as follows:

1. The study identifies an optimal CR fraction of 6% as volume replacement of fine aggregate. At an Alkaline-Liquid Ratio of 2.5 and a curing temperature of 100°C, it achieves a 28-day compressive strength of 33 MPa and

35.2 MPa, respectively, for 14M and 16M NaOH solutions. It demonstrates that the Geopolymerization process with rubber can also effectively mitigate the strength reduction typically associated with rubberized concrete, even at elevated temperature curing.

2. Notably, the reduction in tensile and flexural strength is less severe than in compression. The compressive strength of GP14M reduces by 6.17% in 6% CR replacement with an alkaline-liquid ratio of 2.5. With similar CR content and alkaline activator ratio, the reduction in split tensile strength is obtained as 3.69% and 2.88% for flexural strength. This unique property profile makes FA-RGPC an ideal material for applications demanding high energy absorption, such as seismic-resistant elements, pavement overlays, and machinery foundations.
3. A key finding of this research is the exceptional performance of FA-RGPC under accelerated durability tests. A significant difference in retaining weight is observed between control concrete and FA-RGPC. This difference is as high as 0.8% for GP14M and 2.05% for GP16M for an alkaline-liquid ratio of 2.5. With the increase of CR fraction, the weight loss gradually increases in all cases.
4. The effect of the alkaline-liquid ratio is found to be negligible under sulphate and chloride exposure conditions. The retention of weight is also significantly higher than that of the control concrete in both of these exposure conditions.
5. Crumb rubber varying from 2% to 10% with increments of 2% and an alkaline-liquid ratio of 2.0 and 2.5 shows better residual strength than the control concrete, regular strength. The durability performance in terms of residual strength also establishes 6% CR replacement as optimal.

In summary, this research establishes the practical applicability of FA-RGPC. It may facilitate the application of a theoretically viable concept to real-world implementation as a high-performance construction material. It addresses the challenges of waste management and the environmental impact of cement production and advances the industry with the evolution of a superior combination of mechanical resilience, thermal resistance, and environmental sustainability. The findings of this study provide a suitable option for the industry to manufacture durable and sustainable infrastructure with the advancement of construction materials in a smart way.

5.1. Recommendations for Future Work

While the present study establishes a strong foundation of FA-RGPC, further research is recommended in the future to facilitate full-scale implementation:

- Further investigation on the long-term performance of FA-RGPC under real-world conditions, including resistance to acid and sulfate attack, carbonation, alkali-silica reaction, and freeze-thaw cycles, is necessary.
- Validation of the properties needs to be performed with full-scale implementation of FA-RGPC in beams, columns, and slabs under static, cyclic, and impact loads.
- The efficacy of suitable surface treatment methods in the presence of crumb rubber, for example, NaOH soaking, silica fume coating, etc., can be studied to further enhance the mechanical and thermal properties.
- A comprehensive cradle-to-gate Life-Cycle Assessment (LCA) with detailed cost-benefit analysis is also required to quantitatively demonstrate the environmental and economic advantages of FA-RGPC over conventional concretes.

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Annexure-1

Table 1. Details of specimens

Series ID	Specimen ID	NaOH concentration	% replacement as FA	No. of cubes	No. of cylinders	No. of prisms
FR0	FR00	14M	0	9	9	9
	FR02		2	9	9	9
	FR04		4	9	9	9
	FR06		6	9	9	9
	FR08		8	9	9	9
	FR10		10	9	9	9
FR1	FR00	16M	0	9	9	9
	FR02		2	9	9	9
	FR04		4	9	9	9
	FR06		6	9	9	9
	FR08		8	9	9	9
	FR10		10	9	9	9

Table 2. Representative mix proportion (per m³) for control geopolymer concrete specimen

Trial Mixture	Aggregates				Fly Ash (kg)	Alkaline liquid (kg)	Alkaline liquid ratio	NaOH solution		Sodium Silicate (kg)	Super plasticizer (kg)	Temperature (°c)
	20mm	6mm	Crusher Powder	Crumb Rubber				Mass	Molarities			
GP14M 1.0	776	518	554	Replaced 2-10% fractions from 554 kg	394	158	1.0	31.86	14M	78.80	3.0	100
GP14M 1.5	776	518	554		394	158	1.5	25.49		94.56	3.0	
GP14M 2.0	776	518	554		394	158	2.0	21.24		105.07	3.0	
GP14M 2.5	776	518	554		394	158	2.5	18.21		112.57	3.0	
GP16M 1.0	776	518	554		394	158	1.0	35.02	16M	78.80	3.0	
GP16M 1.5	776	518	554		394	158	1.5	28.01		94.56	3.0	
GP16M 2.0	776	518	554		394	158	2.0	23.35		105.07	3.0	
GP16M 2.5	776	518	554		394	158	2.5	20.01		112.57	3.0	