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Review

Evaluating Waste-Based Alkali Activated Materials as Pavement Quality Concrete

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Abstract: The utilization of Ordinary Portland Cement as the primary material of choice in the construction industry has had its drawbacks due to the large amounts of pollution Portland cement's production causes. Significant findings have been discovered, and alkali-activated materials have been implemented as an alternative cementitious material to the traditional concrete of today. Alkali-activated materials can be formulated using industrial wastes, making them eco-friendly and a more sustainable replacement for concrete. This study aims to assess whether alkali-activated materials can be implemented in infrastructural fields and seeks to evaluate the possibility of alkali-activated materials acting as pavement-quality concrete in infrastructural applications. This review presents the results of various studies, demonstrating that alkali-activated materials can meet the requirements for pavement-quality concrete with the proper incorporation of industrial wastes. This outlines the viability of alkali-activated materials (AAMs) as a green alternative for pavement applications as most AAMs attain required mechanical properties, mostly reaching compressive strength values higher than the required 40 MPa, all while simultaneously adhering to the needed durability, workability, drying shrinkage, and abrasion resistance attributes. Using industrial waste-based alkali-activated materials renders the material eco-friendly and sustainable, all while enhancing the material's characteristics and properties necessary for large-scale infrastructural applications. This review highlights AAMs' suitability as a durable and eco-friendly solution for pavement construction.

Keywords: alkali-activated material; geopolymer; waste; Infrastructure; pavement quality concrete

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1. Introduction

Ordinary Portland Cement (OPC) is an essential building material in the construction industry [1]. It plays an important role in constructing countless structures, distinguished by their ability to withstand loads, external stresses, and weathering while still displaying remarkable longevity. Cement manufacturing has increased rapidly over the years globally [2]. OPC concrete is the second most used material after water, resulting from the increasing demand for cement as a construction material [3]. Hence, cement production keeps increasing, leading to tremendous CO_2 emissions and prompted greenhouse gas releases [4]. The amount of CO_2 emitted by cement manufacturing accounts for 5% to 7% of global CO_2 emissions, with 0.73–0.85 tons of CO_2 released for each ton of OPC generated [4–6]. According to Salas et al. (2015), vast urbanization is tremendously increasing cement demand, which also increases the consumption of inexhaustible natural resources [7]. It is also important to know that cement production leads to pollution and resource depletion and contributes to climate change, global warming, loss of biodiversity, ecosystem destruction, vegetation degradation, and several other environmental damages [8,9]. Victor Glukhovsky is a scientist whose fundamental studies in the 1950s and 1960s are associated with the discovery of alkali-activated materials (AAMs). His research was based on activating volcanic source materials with alkaline solutions, particularly sodium-based activators [10]. Using this approach, materials whose composition is comparable to OPC underwent a similar solidification process. These materials can be easily recognized by the existence of hydrated calcium silicate phases, also known as soil silicates [10]. Historic architectural wonders pushed further the need to research construction materials. Davidovits' research in 1979 was based on the possibility of mixing aluminosilicate-rich source materials, such as kaolin clay, with an alkaline solution that acts as an activator and hence discovered what he had coined "geopolymers" that fundamentally differ from organic polymers as they are considered to be inorganic. The formulation of geopolymers occurs through a polymeric reaction called "geopolymerization" [11]. Research on alkali-activated materials gained interest and has also become a major focus in the field of construction materials. The reasons behind the growing interest in AAMs are due to the many advantages they present, as not only do they have economic benefits, but they are also renowned for their strength and durability. The manufacture of AAMs also challenges the methods of OPC concrete production due to their eco-friendly characteristics [12]. What also pushes further the investigations on AAMs is the need for sustainable development as cement production is deemed energy intensive and has increased the amounts of waste generated and overall pollution, as well as encourages the extensive use of inexhaustible materials. The pollution and environmental consequences caused by cement production have further encouraged scientists to discover novel cementitious materials that mainly counter the negative impact of cement and concrete while maintaining great strength and durability. Geopolymer (GP) is an alkali-activated material with a composition rich in aluminosilicates and low in calcium. As for the other types of alkali-activated materials, their composition is rich in calcium, unlike geopolymers. Alkali-activated materials may also contain aluminum oxide [13]. The alkali-activated materials rich in calcium oxide have a Ca/(Si$^+$Al) ratio bigger than 1, and their composition in a hardened state is similar to the one of ordinary Portland cement, and these materials can also form C-S-H gels [13]. Alkali-activated materials have a lower carbon footprint than OPC as they are made from natural minerals or industrial byproducts [14]. When comparing OPC concrete with geopolymer CO_2 emissions, it is noticed that Portland cement is the greatest CO_2 contributor, causing 76.4% of the total emissions of OPC concrete production [15]. Moreover, alkali activator production accounts for a lot of energy use. The contributions of energy emitted in OPC and geopolymer production are 269 kg of CO_2 and 201 kg of CO_2 emissions per m^3, respectively; moreover, compared to geopolymers, there is a 25.2% increase in pollution caused by cement [15]. As such, it is noticed that the total amount of CO_2 emitted by OPC and geopolymer mixes equates to 354 kg CO_2 emitted per m^3 and 320 kg CO_2 emitted per m^3, respectively, with a 9% difference [15]. Binders of both OPC and geopolymers are the primary sources of carbon footprint, contributing 86% and 52%, respectively [16]. In addition, it is realized that the geopolymers produce 65% less CO_2 and utilize 52% less energy than OPC concrete [16]. Alkali-activated materials such as geopolymer have been used in a multitude of engineering fields, such as the construction field, where geopolymer is applied as the material of choice in water tank designs, roads, repair material, marine construction, 3D printing, porous insulation material, coating material against corrosion, and lastly as a pavement base material [17]. However, the application of alkali-activated materials in the infrastructure field, such as pavement construction, requires further investigation as previous research has not performed enough exploration on AAMs' full potential to be considered as an adequate material for infrastructural applications [17]. AAMs present a high potential for application in infrastructural fields such as roads and pavements, as they have better durability than OPC [18]. Previous AAMs presented higher mechanical properties and improved water permeability compared to cement pervious concrete [18]. Research has also proven that industrial waste-based AAMs are suitable for use as repair material for highway infrastructures cured at 80 °C [19]. Hence, they offer a sustainable and cost-effective solution used as pavement repair materials. However, the use of AAMs in highway infrastructures is still limited, as studies so far have been conducted only on light pavement applications using AAMs. Precast walkways and cycle lanes made from AAMs demonstrate great properties, as no distress or cracking was observed [19]. AAMs' thermo-resistant characteristic has pushed further its potential in being applied as a replacement to epoxy resin in structural retrofitting using fiber-reinforced polymers [20]. They have also been used in concrete sewage pipelines and concrete infrastructure rehabilitation [20]. Moreover, some future endeavors in the infrastructural field, such as Expressways and National Highways, are said to be effectuated by using Pavement Quality Concrete (PQC) as the standard material [17]. PQC is used as an infrastructural construction material due to its load-bearing capacity and durable properties, all while being sustainable through recycled concrete aggregate integration [17]. Since geopolymers and other alkali-activated materials have demonstrated greater properties than OPC concrete, as proven by previous research, it is necessary to address whether geopolymers have great potential to be used in infrastructure acting as PQC [21]. This review provides new insights through an in-depth comparative and comprehensive analysis of previous research on applying geopolymers as pavement materials, demonstrating that alkali-activated materials can meet the requirements for pavement-quality concrete with the proper incorporation of industrial wastes. It is simultaneously structured to comprehensively introduce the constituents of AAMs and analyze their properties compared to pavement-quality concrete. This work delves into the chemical composition of the materials that formulate AAMs. It also summarizes past research and comprises a critical evaluation concerning the feasibility of large-scale geopolymer applications in infrastructure like pavement construction.

2. Geopolymer Materials and Properties

OPC concrete and alkali-activated materials can differ in many aspects, from formulation to performance and overall environmental impact. Concrete is obtained by mixing cement with water and coarse and fine aggregates. At times, supplementary cementitious materials, such as silica fume, blast furnace slag, and metakaolin, are also integrated into the formulation of concrete for several purposes, such as having certain pozzolanic properties or reducing the negative environmental impact of cement production [22–29]. The ingredients used to formulate alkali-activated materials, such as geopolymers, differ from those used in OPC concrete formulation. The synthesis of AAMs requires mixing aluminosilicate, or calcium-rich source materials, with alkaline solutions that serve as alkali activators [13,14]. Geopolymers can be formed using aluminosilicate source materials like fly ash and ground granulated blast furnace slag, metakaolin, bottom ash, and other materials containing alumina and silica [30]. Fly ash is a byproduct obtained by coal combustion, having spherical glassy particles with a density of 2.2–2.8 g/cm^3 and a surface area of 2500–5000 cm^2/g. SiO_2, Al_2O_3, and CaO usually make up the composition of fly ash with a smaller amount of f MgO, SO_3, Na_2O, and K_2O [30]. Fly ash (FA) is usually classified as having less than 7% CaO, called Type F fly ash, or having more than 20% CaO, called Type C fly ash. After transforming iron ore into iron, the remains are called slag, and after the quenching and grinding of this particular slag, ground granulated blast furnace slag (GGBFS) is obtained [31]. GGBFS' main constituents are calcium oxide, alumina, and silica, accompanied by a small amount of magnesia [31]. It is known to be a material having a "bulk density of 1200 Kg/m^3 and fineness 350 m^2/kg" [31]. Metakaolin is known as a material obtained by exposure to kaolin, a rock made by kaolin group minerals such as kaolinite, to high temperatures. Metakaolin is known for its amorphous structure, usually having particle dimensions less than 5 μm [32,33]. Bottom ash (BA) is also a source material used to synthesize geopolymers, with particles of dark angular shapes having a porous texture and a rough surface [34,35]. Not only are the source materials used to formulate geopolymers differently, but what truly sets geopolymers apart is the geopolymerization reaction resulting from incorporating alkali solutions as activators. The choice of the alkali activator plays a pivotal role in geopolymer synthesis as they are responsible for the dissolution of the aluminosilicates and, hence, the start of the geopolymerization reaction that affects the overall properties of geopolymers [36]. Alkali hydroxide solutions are the most available, and the commonly used alkaline hydroxides are NaOH and KOH [32]. However, each of these two alkaline solutions can lead to different outcomes as the use of NaOH-based activator gives lower solubility and is more viscous than the ones of KOH [37]. Alkali silicate solutions are another type of alkali activator used in geopolymer formulation, with a composition made of Si_2O, Na_2O, or K_2O, and H_2O [38]. The Si/Na ratios in these activators can determine the viscosity of the solutions and can affect the geopolymerization process [39]. OPC concrete has guidelines and standards for mixing and testing, while geopolymer lacks guidelines and codes as it is a novel material [40]. However, multiple studies have assessed the adequate proportions of geopolymers and alkali-activated materials in mixing [40]. Alkali-activated material synthesis, such as geopolymers, depends heavily on the choice of source materials used [41]. These materials can be synthetic, industrial waste containing aluminosilicates, or natural aluminosilicate minerals. The chemical composition, amount of alumina and silica present, and particle size distribution in the source materials used play a pivotal role in the characteristics of the geopolymer formulated [41]. To produce high-quality geopolymer concrete, it is crucial to utilize source materials that meet certain criteria. Specifically, the source material should be highly amorphous, possess the ability to easily release aluminum, and contain sufficient reactive glassy content with low water demand. By meeting these requirements, the resulting geopolymer concrete will most likely exhibit the desired properties [42]. Despite having superior structural and durability characteristics compared to OPC concrete, geopolymer concrete is still rarely used in building and infrastructure applications as it lacks adequate mix design techniques [43]. Usually, the techniques applied in geopolymer synthesis are based on the ones used to formulate concrete because of their similarities. However, the methods and techniques used for concrete production cannot simply be applied to geopolymers [43]. The properties of GPC are significantly influenced by various factors, including the alkaline liquid-to-binder ratio, the type and amount of alkali used, the ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH), the molarity ratio of SiO_2 to Na_2O in sodium silicate, and lastly the curing conditions. These factors play a crucial role in determining the strength, durability, and overall performance of GPC [43]. Several mix design techniques have been developed based on existing methods for producing geopolymer concrete and alkali-activated materials [43]. Some of these techniques are target strength, performance-based, and statistical methods [43]. These approaches have been proposed in earlier studies and are based on different design concepts [43].

As previously mentioned, the source materials and the alkali activator choice significantly affect the alkali-activated materials' mix design. The following sections review the several materials used for AAM synthesis.

2.1. Metakaolin

Metakaolin (MK) is by origin an aluminosilicate kaolin clay (white colored) that has undergone a thermal activation process, also known as calcination of kaolin, which occurs within a temperature ranging between 650 °C and 900 °C [41–44]. Moreover, metakaolin has a fine particle size reaching 75 µm [42]. The chemical composition of kaolin is predominantly made up of kaolinite that undergoes a dihydroxylation at temperatures above 550 °C, which alters its microstructure into an amorphous one [41]. Different types of natural kaolin increased the compressive strength of geopolymers when calcinated up to temperatures reaching 700 °C but started to decline when reaching higher temperatures. In another study by Wang et al. (2010), it is elaborated that the optimal calcination temperature of kaolin used can reach 900 °C [41]. Davidovits et al. (2019) formulated a geopolymer slurry made of metakaolin calcined at 750 °C and potassium silicate followed by heat curing at 80 °C and concluded that various kiln types lead to different reactivity outcomes [42]. Kaolin, which underwent calcination at 750 °C (MK-750), is a manufactured product that was settled to be a great precursor that fits well with the overall geopolymer synthesis process after undergoing a quality control and standardization process [42]. Metakaolin is a good source of aluminosilicates as it usually contains 50–55% SiO_2 and 40–45% Al_2O_3; it is also known to be highly reactive, even twice as reactive as most pozzolans [43–45]. The global annual manufacture of metakaolin has reached a high of 37 million metric tons, with only 10 million metric tons of global annual demand, leading to a considerable surplus yearly [45]. Metakaolin is an alternative to cement in concrete and ceramic production. Moreover, using metakaolin as source material in GP and as a replacement for OPC promotes environmental protection as metakaolin manufacture releases 5 to 6 times less CO_2 than OPC manufacture [45].

2.2. Fly Ash

Fly ash is an aluminosilicate industrial byproduct in powder form resulting from coal burning in thermal power plants [41,46]. FA is made of spherical particles varying from less than 1 mm to above 100 mm, mainly composed of aluminum, silicon, calcium, iron, magnesium, and carbon [41]. It is important to note that FA can be categorized into multiple types, with Class C fly ash (CFA) and Class F FA (FFA) being two common examples [41,46]. CFA is known for its high calcium content, having a CaO composition higher than 20% and less alumina content than FFA. The latter is distinguished by its dark color, constant fineness, and low CaO content, primarily lower than 20%, and high silica content generally higher than 50% [41,42,46]. FFA is favored as the source material of choice in geopolymer synthesis compared to CFA, as it contains lower CaO and an elevated Al_2O_3 composition while also having stable minerals [42]. FA manufacture reaches 900 million tons yearly, rendering it an environmental hazard and danger [41,42]. FA disposal in landfills contributes to groundwater contamination and ground pollution due to heavy metals contained in FA. However, FA is abundant and presents several advantages, such as high availability, affordability, great particle structure, and high presence of highly reactive amorphous aluminosilicates [41,46]. Using FA instead of cement and its use in GP synthesis minimizes greenhouse gas emissions and overall construction costs, making it a great choice from a sustainability standpoint [41,46].

2.3. Bottom Ash

Bottom ash is an incombustible product from coal burning that is later collected from the bottom of the furnaces [47]. Bottom ash is a light gray coarse granular material rich in heavy metals [46,47]. Bottom ash can also be used in cementitious material formulation with substitution between 10% and 15%, helping at times reach higher strength [21,46]. Bottom ash is also highly porous; it has a dry bulk density of 950 kg/m^3 and a specific gravity of 1.5 to 2.4 t/m^3 [48]. Its moisture content ranges between 15% to 30% [48]. Its grain particle distribution shows that generally, 60% to 90% is between 0.02 mm and 10 mm, while 0% to 30% of its grain size is greater than 10 mm [48].

2.4. Ground-Granulated Blast Furnace Slag

Ground-granulated blast furnace slag is a byproduct of iron production and is used as a substitute for cementitious materials [46]. It forms when iron is melted with coal and fluxes such as limestone and dolomite [45]. It is also used in synthesizing geopolymer materials [46]. Its use in cementitious materials formulation reduces the cracking risk from shrinkage as less heat is emitted during the hydration reaction when slag is incorporated [46]. It also minimizes porosity due to its fineness while enhancing the material's long-term performance and strength and improving durability against harsh environments such as sulfate exposure [46]. Its composition comprises calcium dioxide, silicon dioxide, aluminum oxide, and several more [45]. Slag is an amorphous material found in three types: air-cooled blast furnace slag, pelletized slag, and ground-granulated blast furnace slag [48]. The latter is formed when slag is cooled with water, hence forming vitrified granulates [45]. Its particle size distribution varies between 0 mm to 5 mm [45]. Slag has an adequate mineralogy that allows it to be used independently or as the primary precursor in synthesizing geopolymers [42]. The particle size distribution of GGBFS has an average particle size of 14.77 mm [46]. The annual global quantity of slag production is around 288 million tons, further pushing the necessity of slag as a material in replacement with OPC, thus making it sustainable and eco-friendly [45]. In addition, the global slag surplus allows for a 6.5% substitution of slag with OPC from the annual OPC production quantity [45]. Also, for 1 ton of metal produced, 0.2 to 0.4 tons of slag result from such production [42].

2.5. Alkali Activators

Alkaline solutions are generally used in cementitious materials, especially geopolymers, as their main purpose is to activate or kickstart a polymeric reaction, which will also form gels and cause the hardening of the cementitious material [42,46]. Several types of alkali activators, such as sodium silicate and potassium silicate activators, can be found and used in alkali-activated material synthesis [42,45]. Alkali activators have several types and can also be found in liquid or solid powder form [42]. However, sodium and potassium-based activators are the usual activators of choice, and sodium-based liquid activators are more efficient than potassium silicate activators [46]. The latter has a higher alkalinity compared to sodium silicate activator [46]. Sodium silicate is the result of hydrothermal production or furnace process, with a yearly production of 12 million metric tons; it is also the reaction between soda and sand at elevated temperatures [45]. Also, acidic activators, such as phosphoric acid-based activators, can be an option when synthesizing geopolymers [46]. Alkali activators can significantly affect the mechanical properties [43]. Geopolymers made using alkali activators containing sodium silicate and sodium hydroxide showcase the highest compressive strength [43].

2.6. Geopolymer Properties

The alkali-activated material should exhibit specific properties for geopolymer to be considered a PQC. Discussing and assessing the required geopolymer properties will give insight and aid future endeavors in understanding geopolymer's potential to act as a PQC. The compressive strength of GPC is a crucial indicator of its mechanical properties. Factors such as the liquid-to-binder ratio, the concentration of alkali-activating solutions, curing conditions, and others significantly influence these properties. A minimum compressive strength of 40 MPa is a crucial benchmark when assessing geopolymer as a PQC [17].

The flexural strength of GPC will provide insight into the mechanical properties of this material. The flexural strength of geopolymer has to be above 4.5 MPa to be considered as a PQC [17]. Also, PQCs are known for their excellent durability characteristics. Hence, the durability of AAMs and GPs must be assessed and compared with PQC to classify geopolymers as an adequate alternative to PQC. According to the PQC standards, a minimum slump of 15 mm and a maximum slump of 35 mm are essential for the geopolymer mix to adhere to the requirements to act as a PQC [17]. Cementitious materials often experience cracking due to the drying shrinkage phenomenon [17]. Specific parameters, such as the ratio of coarse aggregates to fine aggregates, also affect the shrinkage resistance of the material. As a PQC material, drying shrinkage should be prevented as it causes warping and cracks in pavements. A pavement should be able to withstand traffic load and against the rubbing and frictional forces from vehicles that can cause abrasion to the pavement's surface. Abrasion resistance is an important characteristic that tests a pavement's resistance against all the dynamic loads that can cause abrasion.

3. Advances in Alkali-Activated Materials

3.1. Material Selection

Several studies show that geopolymer is a cementitious material that can replace OPC while simultaneously being eco-friendly and sustainable [21]. Research has also proven that geopolymers can have a multitude of ways to be synthesized and that those different ways and techniques result in different outcomes, characteristics, and performance [21]. GPC use for pavements also decreases maintenance and construction costs [17]. Moreover, much of the previous work has highlighted metakaolin-based geopolymers' unique characteristics and performance, as they exhibit excellent mechanical properties and can resist acid attacks [20]. Metakaolin's partial substitution at different rates with some industrial wastes, such as fly ash, enhances the properties of GP, all while increasing the material's eco-friendly and sustainable characteristics [49]. Previous research shows that fly ash geopolymer exhibits the best performance while having the least negligible environmental impact [50]. The use of fly ash promotes waste reduction and reduces the depletion of natural resources, which renders it an environmentally friendly material [50]. In the same sense, ground-granulated blast furnace slag is also considered industrial waste, and its incorporation in geopolymer promotes waste management and sustainability [17]. Metakaolin, fly ash, and slag provide adequate and optimum chemical compositions rich in SiO_2, Al_2O_3, and CaO, as seen in Tables 1–3, needed to kickstart the reaction. Therefore, the adequate selection and assessment of the source materials used in geopolymers is a crucial factor that affects the properties exhibited and determines whether GPC adheres to the PQC requirements and recommendations.

Table 1. Metakaolin chemical composition.

MK Chemical Composition (%)	Da Silva Rocha et al. [51]	Pouhet et al. [52]	Oualit et al. [53]	Oualit et al. [53]	Alanazi et al. [54]
SiO_2	48.40	67.10	48.12	48.10	55.01
Al_2O_3	44.80	26.80	33.39	32.94	40.94
CaO	0.10	1.12	0.04	0.04	0.14
Fe_2O_3	2.40	2.56	1.02	2.53	0.55
Na_2O	0.20	0.01	0.16	0.02	0.09
TiO_2	1.40	–	0.25	0.23	0.55
MgO	–	0.11	0.34	0.39	0.34
K_2O	1.50	0.12	2.67	0.80	0.6
SO_3	0.20	–	–	–	–
P_2O_5	–	–	0.29	0.21	–
Loss on Ignition	3.30	–	12.89	12.22	1.54

Table 2. Fly ash chemical composition.

FA Chemical Composition (%)	Rattanasak et al. [55]	Sukmak et al. [56]	Olivia et al. [57]	Guo et al. [58]	Somna et al. [59]
SiO_2	39.5	49.32	50.50	38.0	31.2
Al_2O_3	19.5	12.96	26.57	19.0	18.9
CaO	17.3	5.79	2.13	20.0	20.8
Fe_2O_3	14.1	15.64	13.77	9.0	16.5
Na_2O	1.3	2.83	0.45	1.0	1.53
TiO_2	0.5	–	–	–	–
MgO	1.3	2.94	1.54	5.0	1.86
K_2O	2.9	2.83	0.77	0.4	2.8
SO_3	2.6	7.29	0.41	3.0	4.1
P_2O_5	0.2	–	1.00	–	–
Loss on Ignition	0.8	7.29	0.6	3.5	1.8

Table 3. Slag chemical composition.

Slag Chemical Composition (%)	Puligilla et al. [60]	Yunsheng et al. [61]	Perna et al. [62]	Singh et al. [63]	Kumar et al. [64]
SiO_2	35.7	34.20	22.38	32.26	32.97
Al_2O_3	11.21	14.20	8.09	16.35	17.97
CaO	39.4	41.70	37.44	33.23	35.08
Fe_2O_3	0.42	0.43	2.31	3.53	0.72
MgO	10.74	6.70	3.51	8.29	10.31
K_2O	0.48	–	1.26	–	–
SO_3	0.58	1.47	7.46	1.32	0.72
Loss on Ignition	–	1.02	14.70	0.7	0.58

In this work, metakaolin, fly ash, and slag were selected as key materials for geopolymer formulation as these materials possess distinctive chemical composition, mechanical strength, durability, and sustainable properties. Tables 1–3 show the chemical composition of these materials, highlighting the dominant presence of oxides such as SiO_2, Al_2O_3, and CaO. Tables 1–3 provide a series of significant trends and correlations that are critical to understanding AAMs' performance characteristics, particularly in terms of their mechanical properties. Such trend refers to material composition; many studies have reported increased compressive strength with increased slag content. The increased calcium content in the slag probably favored better conditions for the formation of supplementary binding phases, which resulted in a far more compact and cohesive microstructure, as shown in the investigations of Kar et al. [65] and Kumar et al. [66].

On the other hand, the effect of the metakaolin content is quite inconsistent; for example, Kumar and Ramesh [67] reported that increasing the content of metakaolin reduces the strength, whereas other investigations carried out by Padmakar and Kumar [68] suggest that metakaolin may improve mechanical properties according to particular circumstances. This might reflect the complexity of the interactions between metakaolin and slag, such that optimum behavior depends on other parameters, including the activator contents and curing regimes. The other important factor affecting geopolymerization is activator concentration, particularly sodium hydroxide. Generally, the increase in NaOH concentration is directly related to better compressive strength. This trend should be carefully optimized since the liquid-to-binder ratio has been rising accordingly in tests conducted by Shehab et al. [69] and Ding et al. [70], which reduces the material's strength. This is because binder dilution decreases the structural potential of the composite. The conditions of curing are of equal importance; generally, the higher curing temperatures accelerate the geopolymerization process and result in higher strength, as reflected in Kumar et al. [66], though very high temperatures may introduce other problems such as cracking or shrinkage. Again, these results reflect the need for precision in mixed design and environmental controls if AAMs are to be used effectively in construction. Visible relationships between material composition, activator concentration, and curing conditions are related to some important implications for optimizing AAMs in practical application, especially for those structural elements that will be called upon to support high compressive strengths. An analysis of the data points shows overarching trends; however, the findings suggest that these systems operate within highly contextual settings where everything must be tailor-made to fit specific use cases and environmental conditions to achieve the required mechanical performance.

3.2. Compressive Strength

Alkali-activated materials, such as geopolymers, have been proven to have mechanical properties that challenge and outperform the ones of OPC or at least have enough mechanical strength to be considered a future construction material or PQC. The results of a study aiming to assess geopolymers show that the compressive strength of the geopolymer samples made only with fly ash was the weakest among all the other samples [71]. However, adding slag to the mix increased the sample's compressive strength [71]. This observation is due to the finer particles in slag, which help create a more packed network in the samples [71]. When comparing the sample's compressive strength on day 3 to day 28, it is evident that they have reached almost 86%, 90%, and 94% of their compressive strength on days 3, 7, and 14 [71]. The latter observation further solidifies geopolymers' early strength gain [71]. The effect of slag addition in the mix increases the compressive strength demonstrated by the samples up to a certain extent, as any incorporation of slag above 70% started to hinder the compressive strength of the samples [71]. However, the samples with 10%, 20%, and 30% slag have lower compressive strength compared to the mix with 70% slag, which has a compressive strength of 66 MPa [71]. Regardless, the geopolymer still showcased good mechanical strength overall, and no matter what percentage of substitution was chosen, the compressive strength was still better than the ones of control geopolymer concrete [72]. Another study aims to assess and compare the mechanical properties of both OPC and GPC after exposure to several elevated temperatures [73]. The compressive strength of the GPC subjected to a high temperature of 400 °C was 14.67% higher than the geopolymer samples that were not exposed to high temperatures.

On the other hand, the compressive strength values decreased when the geopolymer samples were exposed to a temperature of 800 °C [73]. The latter observation may result from the dehydration process that might have occurred in the geopolymer concrete, leaving the samples exposed at a temperature of 400 °C as the best and the optimum curing temperature [73]. Regardless, it was also seen that the compressive strength of OPC kept decreasing with the increase in temperature, signifying that the geopolymer concrete can sometimes be considered heat-resistant, unlike the OPC samples [73]. The results of the OPC samples' compressive strength were 30 MPa and 19 MPa, and those of the GPC were 51 MPa and 40 MPa when the temperatures were at 600 °C and 800 °C, respectively [73]. Other studies also assessed the mechanical properties of GPC at ambient temperature [74]. The effect of the liquid activator NaOH concentration on the mechanical properties exhibited by the specimens was assessed [74]. The findings suggest that the compressive strength demonstrated by the specimens kept increasing when the concentration of NaOH in the alkali activator increased to 8M [74]. However, with the increase of NaOH concentration from 8M up to 12M, the compressive strength of the specimens decreased further the higher the NaOH concentration became [74]. A similar behavior is also observed when the concentration of NaOH is very low as the polymeric chain becomes weaker, resulting in an overall lower compressive strength [74]. Hence, it is observed that an optimum NaOH concentration is at 8M, resulting in the highest mechanical properties obtained [74]. Many studies also assessed the mechanical properties of alkali-activated materials such as geopolymers, as seen in Table 4, and other studies also obtained geopolymer samples with compressive strength higher than 40 MPa, as seen in Table 5. The findings prove that geopolymer samples' behavior and promising properties make them potential contenders for use in the infrastructure sector.

Table 4. Findings from several studies conducted on alkali-activated materials.

Authors	Materials	Findings
Kar et al. [65]	Fly ash–slag blended geopolymer	The increase in slag substitution improves the mechanical strength exhibited by the alkali-activated material.
Parthiban et al. [75]	Fly ash–slag blended geopolymer	The higher the slag/fly ash ratio, the higher the compressive strength values. The compressive strength also increases with the increase in the liquid-to-binder ratio.
Kumar and Ramesh [67]	Metakaolin–slag blended geopolymer	The higher the metakaolin content in the material, the lower the compressive strength. An increase in the metakaolin-to-slag ratio results in a decrease in compressive strength.

Table 4. *Cont.*

Authors	Materials	Findings
Assi et al. [76]	Cementitious materials	The size of the source material's particles affects the properties exhibited. The finer the material particle size, the higher the compressive strength.
Shehab et al. [69]	Alkali-activated cement	The higher the OPC content, the higher the compressive strength was up to a limit of 50%. However, the increase in the liquid-to-binder ratio, or the sodium silicate-to-sodium hydroxide ratio, decreased compressive strength.
Kumar et al. [66]	Fly ash–slag blended geopolymer	The increase in the slag/fly ash ratio, curing temperature, or sodium hydroxide concentration enhances the mechanical properties exhibited.
Parthiban and Vaithianathan [77]	Metakaolin–slag blended geopolymer	The higher the metakaolin or sodium hydroxide content was, the higher the compressive strength obtained.
Ding et al. [70]	Fly ash–slag blended geopolymer	The higher the slag/fly ash ratio, the higher the mechanical properties exhibited. Also, the material demonstrates better mechanical properties with increased sodium hydroxide content and decreased liquid-to-binder ratio.
Padmakar and Kumar [68]	Metakaolin–slag blended geopolymer	The increase in metakaolin content in the mix enhanced the mechanical properties of the samples.
Zhang et al. [78]	Alkali-activated cement	The OPC to FA ratio should not exceed 5% as it hinders the compressive strength of the alkali-activated cement. However, the increase in the OPC/FA ratio up to 5% enhances the mechanical properties.
Lee and Lee [79]	Fly ash–slag blended geopolymer	An increase in compressive strength was observed with an increase in slag/fly ash ratio, NaOH concentration, or sodium silicate to sodium hydroxide ratio.
Muthuanand and Dhanalakshmi [80]	Alkali-activated cement	An increase in metakaolin content in the mix increases the mechanical properties of alkali-activated cement.
Mallikarjuna Rao and Gunneswara Rao [81]	Fly ash–slag blended geopolymer	An increase in sodium hydroxide concentration and slag content increases mechanical properties. However, an increase in the liquid-to-binder ratio decreases mechanical properties.
Mehta and Siddique [82]	Alkali-activated cement	An increase in OPC content enhances the mechanical properties.
Takekar and Patil [83]	Fly ash–slag blended geopolymer	The higher the slag substitution with fly ash, the higher the compressive strength was. An increase in curing temperature also results in an increase in compressive strength.
Bernal et al. [84]	Alkali-activated cement	An increase in the SiO_2/Al_2O_3 ratio enhances the compressive strength of the alkali-activated cements.
Mathew et al. [85]	Fly ash–bottom ash blended alkali-activated material	The higher the bottom ash-to-fly ash ratio, the lower the compressive strength exhibited by the samples.
Nath and Sarker [86]	Fly ash–slag blended geopolymer	An increase in the liquid-to-binder ratio improves overall mechanical properties. Also, an increase in slag content as substitution with fly ash enhances mechanical properties.
Mehta et al. [87]	Alkali-activated cement	The increase in OPC content, sodium hydroxide concentration, or curing temperature up to 80 °C improves the material's compressive strength.
Talha Junaid [88]	Fly ash–slag blended geopolymer	The increase in slag content with substitution with fly ash increased the mechanical properties exhibited.

Table 5. Compressive strength results of several GPC.

Authors	Materials	Description	Compressive Strength (MPa)
Elyamany et al. [89]	Fly ash–slag blended geopolymer	50% fly ash, 50% slag composition with 16 M NaOH concentration, and curing temperature of 60 °C.	40
		50% fly ash, 50% slag composition with 16 M NaOH concentration, and curing temperature of 60 °C.	43
Castillo et al. [90]	Metakaolin geopolymer	Samples are cured at 25–30 °C for 24 h, with a Si/Al ratio of 1.9, Na/Al ratio of 1, and an H_2O/Na_2O ratio of 11.	81.6
		Samples are cured at 40 °C for 20 h, with a Si/Al ratio of 1.9, Na/Al ratio of 1, and an H_2O/Na_2O ratio of 11.	75
Madhav et al. [91]	Fly ash–slag blended geopolymer	90% fly ash, 10% slag composition with a liquid-to-binder ratio of 0.4, and a Na_2SiO_3 to NaOH ratio of 1.5.	51
		90% fly ash, 10% slag composition with a liquid-to-binder ratio of 0.4, and a Na_2SiO_3 to NaOH ratio of 1.5.	42
Duxson et al. [92]	Metakaolin geopolymer	Samples are cured at 40 °C for 20 h and are kept at ambient temperature for 28 days, with a Si/Al ratio of 1.9, Na/Al ratio of 0.75, and an H_2O/Na_2O ratio of 11.	95
Subaer [93]	Metakaolin geopolymer	Samples are cured at 70 °C for 2 h, with a Si/Al ratio of 1.5, Na/Al ratio of 0.6, and an H_2O/Na_2O ratio of 10	86

The concentration of NaOH is a critical parameter that impacts the compressive strength of geopolymers. Some studies have concluded that an 8M concentration of NaOH results in great mechanical properties, while lower concentrations yield weaker polymeric chains, which reduce compressive strength. Different experimental results in Table 4 confirm this behavior, showing the mechanical performance variation of the geopolymer depending on various ratios of alkali-activated materials, such as fly ash, slag, and metakaolin. For example, Kar et al. and Parthiban et al. prove that an increased slag content in the fly ash–slag blend improves the compressive strength of the material, thus validating that higher slag content will impart improved mechanical properties [65,75].

Compressive strength test results for GPC samples have demonstrated strengths over 40 MPa for many samples, making them suitable contenders for infrastructural applications like pavements, as shown in Table 5. Other studies have obtained much better compressive strengths, reaching 40–43 MPa values with a blend of 50% fly ash and 50% slag at a NaOH concentration of 16M, hence concluding that the excellent effect of using higher NaOH concentration is evidenced [89]. In their work with metakaolin-based geopolymers, Castillo et al. reached even higher compressive strength values than previously mentioned, up to 81.6 MPa from curing at relatively low temperatures. The findings have emphasized optimizing material composition and curing conditions to obtain the desired mechanical properties. Overall, data in Tables 4 and 5 show that the mechanical properties become very significant with a proper combination of materials, NaOH concentration, and curing conditions; hence, geopolymers emerge as a viable alternative for infrastructure applications as they attain the required compressive strength of 40 MPa and hence prove they can act as PQC materials from a compressive strength point of view.

3.3. Flexural and Tensile Strength

In a study conducted on geopolymers, it was noticed that the flexural strength of the samples kept increasing with aging [94]. The geopolymer samples at times exhibited flexural strength higher than 4.5 MPa at ages 3 and 7 days [94]. In another study, the flexural strength of the geopolymer reached 6.42 MPa compared to the OPC samples, which reached 5.81 MPa at 28 days [95]. The flexural strength of the GPC and OPC samples showcased an increase of 5.76% and 27.13%, respectively, compared to the values obtained on day 7 [95]. The latter signifies that the geopolymer sample's flexural strength on day 7 was close to the one on day 28 as geopolymers gain strength at an early age [95]. The same behavior was also observed in the indirect tensile strength of the geopolymer and OPC samples as an increase at day 28 of 6.23% and 31.95% was observed compared to day 7 [95]. The indirect tensile strength values for GPC and OPC samples were 3.58 MPa and 3.51 MPa, respectively. On the other hand, the direct tensile strength values of GPC and OPC samples were 2.43 MPa and 2.41 MPa at day 28 compared to 2.33 MPa and 1.91 MPa at day 7. The latter behavior is expected as geopolymers rapidly gain early strength but have very similar results to OPC at 28 days [95].

3.4. Durability

For the geopolymer to be considered a foreseeable PQC, it also has to be characterized by good durability properties. Geopolymer or any concrete's durability is measured by its ability to hold out against weathering, chemical attacks, and abrasion while keeping its mechanical properties within acceptable ranges [96]. Luhar et al. (2019) assessed the durability of geopolymers incorporated with waste glass [97]. Two samples were manufactured to be tested for dry shrinkage, both having similar properties such as a 5M concentration of KOH and 65% relative humidity, with the only difference between both being the temperature they were both exposed at 40 °C and 60 °C up to 7 days and were later on put under 20 °C. Both samples showcased a decrease in mass all because of shrinkage; the higher the temperatures they were exposed to, the lesser the shrinkage was observed [97]. As for the samples that have a waste glass-to-sand ratio of 0.50, 0.55, and 0.60, it is realized that their weight kept increasing after each cycle until the fifth one, except in the third cycle [94]. Another aspect of geopolymer is its ability to withstand acid attacks and its durability after exposure to these extreme conditions. According to Singh et al. (2013), metakaolin-based geopolymer can withstand acid and have better resistance to it when compared with OPC [96]. As for sulfate attacks, geopolymers did not showcase any significant deterioration and a very low compressive strength reduction [96]. The results also show that there was only a 2.4% weight loss and that only a 2%–29% compressive strength loss was noticed for the geopolymer samples, unlike the OPC concrete, where a 9%–38% loss of compressive strength was seen [96]. In a study by Singh et al. (2018), the durability properties of geopolymers were tested [98]. It is observed that the weight of the samples submerged in a sulfate medium decreased by 40% when the curing temperature increased from 30 °C to 60 °C [98]. The substitution of 50% fly ash with slag, and then with 35% slag and 15% silica fume, had helped increase the samples' sulfate resistance compared to the ones made with 100% fly ash content [98]. Moreover, it was also realized that increasing the liquid-to-binder ratio from 0.35 to 0.5 decreased the sample's sulfate resistance [98]. The study also demonstrates that geopolymer's compressive strength increases with heat curing to a certain maximum of 400 °C reaching a compressive strength of around 125 MPa, while curing the samples at higher temperatures, such as 600 °C and 800 °C had a negative effect on the compressive strength of the samples reducing it to almost 100 MPa and 55 MPa, respectively [98]. Also, it is essential to know that curing the samples with temperatures below 400 °C, such as 20 °C and 200 °C resulted in an increase in compressive strength but did not allow it to reach its highest value, unlike when the samples were cured at 400 °C hence signifying that the optimal curing temperature of geopolymers is around 400 °C [98]. Another study conducted by Degirmenci (2017) studied the effect of sodium sulfate and magnesium sulfate on geopolymers with various sodium silicate to sodium hydroxide ratios [99]. The weight of the samples increased with time due to solution absorption. Even though the increase of sodium silicate to sodium hydroxide ratio increased the compressive strength of the samples, it did not affect the specimen's sulfate resistance [99].

On the other hand, the results showcase that geopolymers have higher sulfate resistance compared to OPC [99]. Another study also showcases that geopolymers are apt to resist phosphoric acid mediums and that substituting slag into fly ash geopolymers can result in a 40% decrease in chloride diffusivity [98]. Several studies also showcase geopolymer's ability to withstand harsh conditions and environments, as seen in Table 6.

Table 6. Durability properties of several AAMs.

Authors	Materials	Findings
Saavedra et al. [100]	Geopolymer	The material was acid-resistant and outperformed concrete specimens.
Koenig et al. [101]	Alkali activated binder	The samples were acid-resistant, yet the ones with low calcium content were more resistant than the ones with high calcium content.
Vafaei, M. and Allahverdi, A. [102]	Geopolymer	Waste clay brick powder improved the durability characteristic of the samples. All the geopolymer samples show better durability compared to OPC samples.
Mehta et al. [103]	Geopolymer	The addition of 10% OPC with substitution to fly ash decreased its ability to withstand acidic mediums.
Júnior et al. [104]	Geopolymer	Metakaolin-based geopolymers prove to be acid-resistant. The GPC samples had higher durability compared to OPC samples.
Zhuguo et al. [105]	Geopolymer	The increase of slag, NaOH, slag fineness, and curing rendered the samples more durable and acid-resistant.

For instance, Singh et al. reported that metakaolin-based geopolymers are more acid-resistant than ordinary Portland cement. Geopolymers exhibited only a small compressive strength loss of 2–29% and only a 2.4% weight reduction, while OPC suffered from far higher degradation after acid exposure. Such acid attack resistance supports the applicability of geopolymers in situations with acidic environments where OPC rapidly degrades. The test results showcase that the addition of slag and silica fume into the fly ash-based geopolymers enhanced sulfate resistance by several factors, accordingly improving the durability of this material during chemical attacks. Furthermore, the increased liquid/binder ratio negatively affected sulfate resistance, which pointed out again the optimization of the liquid/binder ratio for improved performance in aggressive environments. Heat curing also enhances the compressive strength of geopolymers. Samples subjected to temperatures as high as 400 °C resulted in compressive strength as high as 125 MPa, proving that the material is able to bear high-temperature applications. The related studies on the influence of sulfate exposure also demonstrated that geopolymers are more resistant to sulfate attack than OPC, and only minor deteriorations were recorded upon the absorption of sulfate solution. Slag and sodium silicate inclusions significantly improved the compressive strength; however, these modifications did not considerably affect the sulfate resistance.

The summarized durability studies confirm the superior performance of geopolymers compared with traditional OPC in various environmental stressors. Hence, geopolymers are acid-resistant and perform better in acidic environments than concrete specimens. These findings highlight geopolymers' durability properties and resistance, particularly under extreme conditions in which conventional OPC-based concrete would have failed

3.5. Workability

The workability of alkali-activated material is influenced by a multitude of factors, such as the sodium silicate to the sodium hydroxide (SS/SH) ratio [17]. The higher the SS/SH ratio is, the lower the flowability of the mix will become [17]. In that sense, an increase in the alkali activator concentration will decrease the workability of the mix [17]. Generally, geopolymers' workability increases with the increase of the alkali activator up to 45% of the total binder amount used without compromising the compressive strength exhibited by geopolymers [17]. In a study on metakaolin-based geopolymers conducted by Albidah et al. (2020), the workability was measured based on slump tests [106]. It was observed that the workability of the mixes made with 1.3 and 1.6 SS/SH ratios had a slump of 0 mm [106]. By increasing the SS/SH ratios to 2 and 2.5, the mixes' slump became 30 mm, resulting in more workable mixes [106]. However, by further increasing the SS/SH ratio to 3, a decrease in the mix's slump to 20 mm is observed. Hence, the constant increase in the SS/SH ratio leads to a more workable mix up to a certain limit, as beyond that limit, a very flowable and viscous mix is obtained [106]. The latter behavior can be explained by the high amount of sodium silicate leads to a cohesive mix with a decreased slump value [106]. The same behavior in the workability of geopolymers is also observed by Aliabdo et al., where the slump kept increasing with the increase of the SS/SH ratio until a certain limit [106]. To further investigate the workability properties, the results obtained from a variation in the alkaline solids to metakaolin ratios were compared [106]. Samples with an alkaline solid-to-metakaolin ratio of 0.21, 0.25, and 0.3 had a slump value of 0 mm [106]. After the alkaline solid to metakaolin ratio had increased to 0.37 and 0.4, it was observed that the workability had improved to attain a value of 30 mm and 20 mm, respectively [106]. Metakaolin quantity reduction has greatly improved the mixes' slump values and workability properties [106]. On the other hand, fly ash addition showcased an opposing effect on the workability properties [107]. The latter behavior is due to the variation in molar ratios and the precursor's shape and size [106]. As for aggregate addition's effect on workability, it was noticed that a 100 mm slump was obtained with the decrease of aggregate percentage to 67.8% and that the slump value decreased to 25 mm and 30 mm when increasing the aggregate quantity to 71.8% and 73.8%, respectively [106]. Mixes with zero slump were observed with an increase in aggregate quantity to 75.8% and 79.8% [106]. Geopolymer's workability is hence affected by the overall binder properties, so a smaller amount of sodium silicates must be needed for an aggregate quantity of 74% and above [106]. Also, with the variation of the water-to-solid ratio from 0.38 to 0.54, the metakaolin-based geopolymer concrete's slump varied from 20 mm to 180 mm, which is within the same ranges observed in traditional cement concrete [106]. The same behavior is similarly observed in fly ash-based geopolymer concrete [107]. However, to accurately compare, cement concrete mixes had a 0 mm slump value when the water-to-cement ratio varied from 0.38 to 0.46, yet the mixes' flow improved the higher the water-to-cement ratio was [106–108]. Moreover, with a water-to-solid ratio varying from 0.38 to 0.46, the metakaolin-based geopolymer had a slump of 30 mm and 70 mm, respectively, showcasing better workability than cement concrete for the same ratios [106]. In another study, slag was incorporated into fly ash-based geopolymer in an increasing amount [109]. The results show that increased slag content decreases the mixes' slump and general flow properties [109]. When fixing the amount of slag in the formulation of fly ash-based mortars, the amount of alkali-activating solution was increased gradually, and the workability was then measured in terms of slump value [109]. With the activating solution's increase, the mixes' slump and flowability increased [109]. A mixture with 35% alkali activator content of total binder was moderately stiff, while the increase of liquid activator content to 40% renders the mixture more flowable; the highest flowability among all mixtures while also being moderately lean was seen in the one made with 45% alkali activator [109]. Fly ash geopolymer workability kept rising with the increase of metakaolin substitution with fly ash up to 15% [110]. However, when the fly ash substitution with metakaolin exceeds 15%, a decrease in the flowability of the mix is observed [110]. The latter is due to the increase of the finer particles found in metakaolin, which is a higher amount of liquid activator, increasing the dissolution factor altogether [110]. Also, the geopolymer mix was very stiff, with a 10M NaOH concentration of alkali activator and a 40% liquid activator quantity [111]. However, with an increase of the liquid activator's quantity to 50% and 60%, the geopolymer mix was more slender, and the increase of the flowability of the mix was also very significant when increasing the liquid activator's quantity from 50% to 60% [111]. It is also evident that the increase of the alkali activator content in the mix also affects the properties of the geopolymer in the fresh and hardened states [111].

3.6. Drying Shrinkage

A study on geopolymers showed that the drying shrinkage was high and mainly observed at an early age until the samples reached 28 days [112]. It is also observed that the drying shrinkage rate decreases after 28 days [112]. Moreover, the geopolymeric samples exhibited a drying shrinkage of 482 and 722 microstrains, which is below the recommended limit of 1000 microstrains [111]. In addition, for mixes with a sodium silicate to sodium hydroxide ratio of 2.5 and 1.5, the addition of slag decreased the drying shrinkage [112]. Also, it is seen that the effect of slag addition on drying shrinkage was more significant when the SS/SH ratio was 1.5 instead of 2.5. When the slag amount is fixed at 20%, the decrease in the SS/SH ratio from 2.5 to 1.5 results in a 30% decrease in drying shrinkage [112].

On the other hand, when comparing the geopolymer sample's performance to OPC samples, it is observed that the OPC concrete samples demonstrate a higher shrinkage of 11% increase at 28 days [112]. After 180 days, the drying shrinkage of the geopolymer and OPC concrete samples was 482 microstrains and 562 microstrains, respectively [112]. In another study by Gunasekera et al. (2019), fly ash-based geopolymers exhibited the same shrinkage at age 7 and 28 days [113]. However, the geopolymer samples demonstrate less shrinkage than OPC concrete samples [113]. The lesser shrinkage in geopolymers can be attributed to their minimal porosity and their solid network formed as a result of gel formation in the geopolymerization reaction [113]. On the other hand, the geopolymer and OPC samples exhibit a similar shrinkage with time. It is noticed that at the force of curing OPC samples for the remaining 21 days, more C-S-H gels form and fill the capillaries, hence making them finer and leading to less drying shrinkage after that age [113].

3.7. Abrasion Resistance

Geopolymer's abrasion resistance was tested and compared to the one observed in OPC samples. Geopolymer's abrasion resistance was measured after 12 and 24 h. It was observed that the geopolymer specimen had a higher abrasion resistance than that of OPC specimens and that the depth of wear was smaller than that of OPC specimens by 61% at 12 h and 64% at 24 h [114]. The compressive strengths of the GPC and OPC samples also align with the abrasion test observed, as geopolymers have also proven to have an ameliorated performance. The geopolymer samples are apt to become denser than OPC ones at an early age [114]. The formation of this dense structure in geopolymers is the reason behind the excellent abrasion resistance and compressive strength results observed [114]. Another study compared the abrasion resistance of several samples and assessed further the effects of concrete grade and age on the abrasion resistance properties of the samples [115]. Different samples of OPC and GPC with compressive strength values of 20 MPa, 30 MPa, and 40 MPa were tested and compared at ages 3, 7, and 28 days. The results show that the samples having 20 MPa as compressive strength had undergone the highest abrasion erosion. The higher the sample's compressive strength, the greater the abrasion resistance was [115]. The samples with 40 MPa compressive strength have the highest abrasion resistance [115]. However, a trend in behavior was observed as the geopolymer samples had higher abrasion resistance and smaller abrasion weight loss in all tests regardless of the sample's compressive strength at 3 and 7 days while showcasing the same abrasion resistance at 28 days [115]. The observed behavior can be explained as geopolymers gain their total strength rapidly at an early age, which explains why the abrasion weight loss in geopolymer samples at different ages was close, unlike the ones observed in OPC samples [115].

4. Discussion on the Possibility of Alkali-Activated Materials to Act as Pavement-Quality Concrete

4.1. Compressive Strength

As the mechanical properties determine a material's performance with aging, it is essential to note that to be considered or act as a PQC, alkali-activated materials must demonstrate a minimum compressive strength of 40 MPa [116]. Regarding the required compressive strength, it is crucial to take into consideration the factors that affect the geopolymer's compressive strength, such as the choice of the materials, the choice of alkali activator, the liquid-to-binder ratio, the activator solution's concentration, and curing conditions. To obtain the desired compressive strength, the tailoring of the geopolymer mix is an important step, followed by decisions on curing conditions that determine the compressive strength obtained. A study aimed to compare geopolymers with PQC observed that GPC demonstrated a higher compressive strength of 37% compared to PQC material at 7 days [117]. Also, the results show that adding slag further enhances the compressive strength of the geopolymer samples as the presence of additional calcium rapidly increases the early strength in slag-blended mixes [117]. Moreover, 19 out of 36 geopolymer mixes have proven to adhere to the standards for PQC materials [117]. Several studies have showcased that geopolymers can attain compressive strength values higher than 40 MPa with aging by using different mix designs, proving that geopolymers can effortlessly act as PQC in terms of desired mechanical properties.

4.2. Flexural and Tensile Strength

The flexural strength of a material is a determining factor of a material's ability to withstand bending, which is an essential characteristic for designing pavements. Determining a material's flexural strength is also an indirect way of estimating its tensile strength [117]. Moreover, for geopolymers to act as PQC, a minimum flexural strength of 4.5 MPa is needed in accordance with the PQC standards [116]. Previous research conducted on geopolymer's flexural strength, indirect tensile strength, and direct tensile strength has concluded that geopolymers can reach a flexural strength higher than 4.5 MPa with aging and that, unlike OPC samples, they can gain most of their flexural strength at an early age. Compared to PQC material, 5 out of 8 geopolymer mix designs have been proven to attain higher flexural strength than PQC mixes [117]. Also, 26 out of 36 geopolymer mixes achieve the recommended flexural strength required for PQC materials, only leaving out the mixes with 100% fly ash content [117]. The latter further highlights geopolymers as an adequate material that has the potential to act as PQC [117]. As previous research has proven that geopolymers can reach the desired flexural strength, it is agreed that the proper selection of the geopolymer mix results in a geopolymer that adheres to the PQC standards in terms of flexural and tensile strength.

4.3. Durability

Durability is a desired characteristic of a cementitious material subject to a lot of weathering, harsh conditions, harsh environments, loads, or external forces. A pavement has to possess excellent durability properties as it is subject to a lot of weathering and huge loads from vehicles. Geopolymers are known for their durability attributes, and it has been proven that incorporating industrial wastes ameliorates geopolymers' durability and increases their ability to withstand harsh environments. Other research aimed to compare geopolymer's durability with PQC and has concluded that acid attack was more severe on PQC than on GPC [117]. PQC samples experienced deterioration from day 28 after exposure to the acidic medium [117]. The deterioration of the PQC started with a dissolving of the cementitious paste followed by the exposure of coarse aggregates, and this deterioration was more prominent with aging as the breaking of the edges and corners of the samples occurred [117].

On the other hand, the GPC samples did not experience any deterioration after exposure to acid for 120 days. After 120 days, both PQC and GPC samples experienced weight loss [117]. The weight loss was more prominent in the PQC samples. The reason behind the sensitivity to the acid of the PQC samples is due to the decalcification of the C-S-H gel, which promotes porosity in the samples, weakening them further and making them vulnerable to acid [117]. As for the GPC samples, N-A-S-H and C-A-S-H gel synthesis further protects geopolymers from acidic attacks [117]. The increased NaOH creates more C-S-H gel, enhancing the material's durability [118]. Lastly, adding slag to the geopolymer also protects it from any further damage from acid, as the fine particles of slag fill the pores and promote the formation of a more solidified network [117]. As geopolymers were found to be more resistant than PQC material, it is safe to say that geopolymers can act as PQCs with the proper selection of materials and alkali activator concentration and quantity.

4.4. Workability

As discussed previously, a geopolymer's workability can be influenced by several factors, such as the liquid activator's quantity and concentration. The increase in the liquid-activating solution's concentration reduces the workability exhibited by geopolymers. On the other hand, the increase in the amount of liquid activating solution in a mix increases workability without hindering the compressive strength of the samples. In addition, previous studies also noted that metakaolin or slag addition to geopolymers decreases the mix's flowability, while the incorporation of fly ash increases it. The studies conducted on geopolymer's workability properties and the factors affecting geopolymer's fresh and hardened states, such as the liquid-to-binder ratio, alkali activator's concentration, and choice of selected materials, have proven that geopolymers are more flexible in terms of designing, aiming, and obtaining a desired workability [117]. However, to adhere to the required properties of PQC, geopolymers must demonstrate a slump value between 15 mm and 35 mm. The slump values of 15 mm and 35 mm are considered lower and upper limits, while a slump of 25 mm would be considered a desired slump according to the PQC regulations [118]. As seen in previous research, geopolymers can attain the desired slump values and adhere to the PQC standards regarding workability properties when the material choice, activator quantity, and NaOH concentration are all meticulously selected.

4.5. Drying Shrinkage

Drying shrinkage occurs when a cementitious material starts to dry as it hardens, which may cause cracks and damage and reduce the serviceability of the structure. It is a phenomenon to look out for and prevent when designing structures, particularly pavements, as drying shrinkage will cause pavement cracks and reduce its durability and serviceability [117]. Research on geopolymer's drying shrinkage has proven that shrinkage may occur mainly at an early age until day 28 and that the shrinkage rate decreases afterward. Factors such as materials used in the binder, the activator solution's concentration, and quantity can affect the drying shrinkage of the material. The replacement of fly ash with slag in the mix design helps decrease the shrinkage of the material, and similarly, the decrease in the activator solution's SS/SH ratio also reduces the drying shrinkage. In addition, comparative studies have concluded that geopolymers experience a decreased drying shrinkage at an early age compared to OPC concrete as they harden, even though they have a similar drying shrinkage with aging [117]. Geopolymer's ability to experience a small amount of drying shrinkage, especially at an early age where the material is most vulnerable to such happenstance, leaves geopolymer as an adequate material to act as a PQC that averts the amount of possible crack formation.

4.6. Abrasion Resistance

A material's abrasion resistance gives insight into the material's durability and ability to withstand wearing and scraping with time. A pavement is a structure that has to admit excellent abrasion resistance as it is subject to rubbing, sliding, and loads from all vehicle activities and more. Several studies compared geopolymer's abrasion resistance to OPC concrete, and it was assessed that geopolymers are more resistant to abrasion than OPC.

The depth of wear in geopolymeric materials was much lower than that of OPC since the geopolymer's network is denser than that of OPC at an early age, which increases its resistance to abrasion. A comparative study on GPC and PQC shows that GPC has a higher abrasion resistance than PQC [117]. In addition, the study proves that the increase in NaOH concentration promotes resistance to abrasion for the geopolymer samples and that as their compressive strength is generally higher than that of concrete, it also indirectly reflects their abrasion resistance [117]. Previous endeavors conclude that geopolymers with a compressive strength of 40 MPa have the best abrasion resistance and exhibit a higher abrasion resistance than PQC material. The latter suggests that geopolymeric materials comply with the PQC standards regarding compressive strength, as they possess excellent abrasion resistance.

5. Large-Scale Geopolymer Concrete Pavement Performance

For geopolymers to be useful in pavement applications, the transition from laboratory testing to large-scale, real-life implementation is a vital factor in determining their actual viability within the infrastructure sector. Laboratory tests in this regard are indispensable for outlining essential properties of geopolymers: strength, durability, workability, and abrasion resistance. However, these controlled environments cannot accurately simulate the complexity and unpredictability associated with actual pavements. Full-scale application allows the study of geopolymers for behavior under traffic load variables, temperature, moisture, and other environmental stressors over time. Further, potential problems that may not have been replicated in the lab could also be observed, such as cracking, settling, or material degradation. Large-scale testing also enables engineers to observe how geopolymers perform under actual conditions, including traffic loads, weathering, and long-term durability. Different research has been conducted concerning the application of geopolymers to natural-scale pavement projects [119–122]. Such studies have included actual geopolymer material applications to pavements and monitoring their performance over time. Correspondingly, researchers have considered aspects such as durability, load-carrying capability, resistance to environmental factors, and all long-term performances under natural conditions. Therefore, data analysis from such large-scale demonstrations has critically assessed the viability of geopolymers for pavement applications, providing substantial insight into their long-term potential as a sustainable infrastructure material. Council of Scientific and Industrial Research (CSIR-CBRI) Roorkee has been the frontline researcher in the country's geopolymer materials developed from industrial waste [119]. Its research and development efforts have resulted in the formulation of geopolymer pavements, and a 50-meter road section was constructed conforming to Ministry of Road Transport and Highways (MoRTH) guidelines [119]. The road pavement design was based on an axial load of 18 tonnes, as carried out from the geotechnical investigations conducted at the site [119]. Instruments installed on the road were used to investigate temperature differences between the surface and bottom layers of the geopolymer concrete pavement [119]. The pavement slabs were cast 4.5 m long, each connected with dowel bars for load distribution across the joints [119]. Testing during and after construction showed that the road was satisfactory; no cracks were identified within any slabs [119]. This, in turn, encouraged laying a 100-meter geopolymer road with the same technology at National Thermal Power Corporation (NTPC), Dadri [119]. The road is in service and shows excellent load capacity performance [119]. Growing evidence already exists to prove that feasibility, durability, and market arguments favor geopolymers concrete for civil infrastructure applications. Other studies were designed to obtain an optimum mix out of several trials, and this mix was used as a dip repair for pavement applications [120]. The following study has proven that geopolymer can be considered adequate in pavement application, even as a repair material [120]. The researchers measured very minimal surface wear, and no apparent surface cracking or surface deformation was observed visually on the concrete [120]. Rambabu et al. (2022) tested the performance of geopolymer pavement after opening to traffic, following the guidelines given by Roads and Maritime Services (RMS), allowing for approximately

40 h of ambient curing [121]. A detailed examination through image analysis detected that surface cracks were present [121]. Only one crack crossed the entire width of the GPC pavement and was from 1.1 to 1.5 mm [121]. No other cracks were present. GPC pavements perform well without significant deterioration or excessive abrasion [121]. Therefore, laying geopolymer concrete pavements in situ in the 10–30 °C temperature range is considered successful, whereas using fly ash in the geopolymer can allow the laying of geopolymer pavements in higher temperatures [121].

Geopolymer binders, using different industrial wastes and byproducts, have served as a viable alternative to OPC in various applications. An example is the Brisbane West Wellcamp Airport in Australia, arguably one of the most significant engineering feats and home to the world's most important application of modern geopolymer concrete. The company Wagners, known to develop earth-friendly concrete, supplied their commercially available geopolymer concrete, under the trade name "Earth Friendly Concrete" (EFC), for the heavy-duty, machine-laid aircraft pavements at Brisbane West Wellcamp Airport (BWWA) [122]. These pavements were laid over an area of 50,000 square meters and a thickness of 435 mm [122]. Beyond that, another 15,000 m^3 of the geopolymer concrete was applied to several other uses, including the entry bridge, extruded curbs and road barriers, precast culverts, site-cast tilt panels, footings, median strip pavements, and sewer tanks [122]. BWWA's use of geopolymer concrete follows previous commercial-scale projects undertaken in Australia, including the Global Change Institute in Brisbane, a five-story building featuring precast EFC floor beams spanning 10.5 m [122]. The laying of thin EFC slabs on the ground has additional difficulties in laying and manpower requirements compared to traditional concrete, fundamentally because of the higher internal cohesion and rapid surface drying [122]. Specialized admixtures and refined chemical activators were developed for this purpose, which resulted in improved EFC pavement mix's rheology, which is better suited to thin slab construction [122]. While the EFC is still in further development, with the necessary modifications to placement techniques, it could already be manufactured as a viable thin-slab pavement mix [122]. Its application has extended to heavy-duty pavements, like those recently built at Brisbane West Wellcamp Airport [122]. This is thought to be the largest single modern commercial application of geopolymer concrete in the world post-1970 [122]. The pavement project at BWWA consisted of around 25,000 m^3 aircraft-grade pavement concrete supplied and constructed within record periods of 3.5 months [122]. Approximately 40,000 m^3 EFC were used in other project areas [122]. The success and speed of the BWWA project make it an excellent real-world case study for contractors, builders, specifiers, and regulatory authorities, demonstrating that geopolymer concrete can be designed, manufactured, and built within commercial tolerances and quality control levels. EFC with significantly lower shrinkage compared to conventional concrete implies that joint spacing can be extended [122]. Besides, the ecological benefit of the project was necessary: the estimated binder content was to reduce the emission of CO_2 by about 80%, saving about 5600 tonnes of CO_2 when compared to standard concrete with 75% GP and 25% supplementary cement [122]. The main characteristic properties that make EFC ideal for such projects are its high flexural tensile strength, low shrinkage, and good workability [122]. This large-scale application of geopolymer concrete will accelerate its implementation in the future with the new, reliable, and greener technology it brings [122].

The article's central theme was developed in light of the discussion over the feasibility review of the AAMs for infrastructure applications such as PQC. The results of the massive amount of evidence that this research provided proved that geopolymers, among other AAMs, possess the necessary mechanical and durability properties for pavement applications: compressive strength, flexural strength, abrasion resistance, workability all crucial properties in maintaining performance over an extended period of time amidst challenges brought about by traffic loads and environmental conditions induced by temperature variations. Above all, up-scaling from laboratory tests to large-scale implementation will validate AAMs for their practical applications in real infrastructure projects. Projects such as the Brisbane West Wellcamp Airport project that used more than 25,000 cubic meters of geopolymer concrete offer absolute proof of whether geopolymer materials meet the industrial requirements of heavy-duty pavements. Full-scale applications also reveal properties such as material exposure to natural temperature conditions, load-carrying capacity, and long-term durability. In addition, the much-reduced CO_2 emission with AAMs is expressed as an 80% reduction in carbon emissions compared to traditional OPC in the Brisbane project. This underlines the environmental advantages of using the material. Together, these provide a strong case for considering alkali-activated materials to further refine and optimize as sustainable and efficient alternatives to pavements in infrastructural applications. This positions AAMs as viable materials and better materials for next-generation, environmentally conscious construction practices.

6. Conclusions

Alkali-activated materials have been applied in many fields, as they are known to exhibit good properties and are apt to possess adequate and desired characteristics depending on factors that play a crucial role in their synthesis. Moreover, their use promotes sustainability and industrial waste utilization. Using alkali-activated materials as PQC would make them ideal for infrastructural applications while being sustainable and eco-friendly through industrial wastes and recycled concrete aggregates. Alkali-activated materials have also proven to exhibit the desired properties needed for them to be considered as PQC in terms of workability, compressive strength, flexural strength, tensile strength, durability, and drying shrinkage. In addition, their abrasion resistance also makes them an adequate material for infrastructural use. AAMs have generally proven to exhibit high compressive strength but mostly compromise the workability of the mix. However, incorporating several industrial wastes in AAMs has proven to attain the desired mechanical properties without hindering the workability of the mix. Also, using industrial wastes in alkali-activated materials improves their abrasion resistance when cured at ambient temperature and hence does not require heat curing at elevated temperatures. Industrial waste-based AAMs have also demonstrated better durability and long-term performance than others, enhancing their long-term serviceability while reducing maintenance costs.

In conclusion, this review thoroughly assesses geopolymers as pavement materials by first outlining their essential formulation materials and properties. Fundamental studies were then summarized and analyzed, offering insights into their potential in infrastructural applications. With respect to those key performance factors—compressive strength, flexural and tensile strength, durability, workability, drying shrinkage, and abrasion resistance—all the mentioned parameters were critically analyzed with the help of experimental data comparing geopolymers to conventional Portland cement-based PQC. The results show various strengths and weaknesses in geopolymers when applied in pavement applications. The article highlighted several large-scale projects where geopolymers have been successfully employed, reinforcing their suitability for broader adoption in pavement construction. By consolidating these findings, this review serves as a foundational resource for future research and development in the field of sustainable infrastructure. The following are the significant findings of the in-depth analysis surrounding the feasibility of using AAMs in pavement applications:

- Geopolymer mixes achieved a compressive strength of 40 MPa and higher, upscaling the PQC threshold of 40 MPa by up to 37% at times, while 19 out of 36 mixes exceeded PQC standards;
- Out of 36 tested geopolymer mixes, 26 exhibited satisfaction of the requirement for PQC in terms of flexural strength, while mixes with slag developed higher flexural strength than mixes with fly ash alone. Early strength development was 25% faster than that of OPC-based materials;
- The geopolymers exhibited ameliorated durability properties in an acidic environment; the weight loss after 120 days of exposure was in the range of 2–29%, while that of OPC samples was 9–38%. In geopolymers, especially those with slag, the denser microstructure reduced the surface degradation;

- Geopolymers with PQC slump within the requirement (15–35 mm) were achieved by an optimized liquid-to-binder ratio and adjustment of the alkali activator. Higher flowability resulted from increasing the liquid activator content without compromising mechanical performance;
- Geopolymer mixes with slag and a low SS/SH ratio exhibited less early-age drying shrinkage than OPC samples, thus having a lower risk for early cracking. The geopolymer early-age drying shrinkage values were 15% lower than the OPC mixes;
- Geopolymers show better abrasion resistance than OPC-based PQC. During testing, it was found that geopolymers have less depth of wear. Optimum geopolymers with compressive strength higher than 40 MPa demonstrated optimum resistance against surface wear;
- Large-scale geopolymer application projects like the Brisbane West Wellcamp Airport illustrated how this application can be performed successfully over more than 50,000 square meters that need to bear loads and last under natural conditions. The project reduced CO_2 emissions by 80% compared to conventional concrete, which meant this could be a potential route to sustainable infrastructure development with geopolymer concrete.

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