

Review

The Effects of the Type and Quantity of Recycled Materials on Physical and Mechanical Properties of Concrete and Mortar: A Review

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Abstract: The reuse of industrial wastes to produce concrete and mortar is an environmental solution for their disposal as well as for the development of ecological and sustainable concrete. A large number of previous studies summarized in this review paper focused on adding different types of waste in the concrete and mortar mix in the form of fine aggregates, coarse aggregates or cement additives, and investigated the physical and mechanical properties of the enhanced material. Reusing waste in concrete and mortar mix design significantly affects the material's fresh and hardened properties. This literature review offers a general insight to the civil and industrial engineering community on ecological waste-based concrete and mortar that can serve as a basis for construction and future work in this field.

Keywords: industrial wastes; concrete; physical properties; mechanical properties; waste-based concrete; recycling



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1. Introduction

During recent decades, there has been an increase in awareness about environmental and ecological issues, greenhouse gas emissions, and the energy consumption of buildings, which has led to increasing interest in sustainable development. Although natural aggregate resources are not depleting currently, the accumulation of nonbiodegradable waste (such as hardened cement, bottles, polystyrene, used tyres, and glass) is a major source of environmental and economic problems. This accumulation is linked to the population explosion in developing countries with uncontrolled urbanisation, which has led to the production of large amounts of waste (e.g., used tyres, bottles, cans, various containers holding stagnant water, and so on). Sanitary waste is a fertile habitat for insects (e.g., flies and mosquitoes), and it exposes a large number of people to life-threatening diseases such as dengue and malaria. Other wastes generated from industries and factories such as fly ash from the combustion of coal in large industries and coal-fired power plant boilers, silica fumes formed during the production of silicon and ferro-silicon alloys, blast furnace slags, and bauxite residues from the production of steel and aluminium are also environmental threats if not disposed of in a proper manner. In this context, waste-based concretes represent a new way of recovering waste in construction materials and ensuring environmental protection. Wastes used in concrete can be classified into two categories: recycled aggregates and cement substitute materials.

For wastes that replace natural aggregates, researchers have evaluated the partial or total replacement of fine or large natural aggregates or both by using different types of aggregates (Table 1), especially in medium- and low-strength concrete. The durability and mechanical properties of recycled aggregate concrete are always poorer than those of control concrete because of the properties of recycled aggregate (Table 1) and other aspects, such as the type and content of recycled aggregate, water: cement ratio, mixing procedure, adjuvants, and additives.

Concretes made from glass, polystyrene, and plastic aggregates can easily slide and flow inside different parts of the formwork and generate remarkable consolidation within the targeted formwork owing to their own weight. They do not need external or internal vibration and leave no defects resulting from segregation. To obtain complete compaction, these concretes must be adequately fluid and cohesive. However, concretes made from rubber, brick, and demolition aggregates show firm fluidity due to their high absorption (Table 1) and rough surfaces. In contrast, the workability of concrete can be improved by mixing fine substances, such as silica fume, limestone powder, blast furnace slag, and fly ash, or by adding an appropriate dosage of viscosity-modifying adjuvants.

Table 1. Mechanical properties of different types of aggregates used in concrete.

Properties/Materials	Elastic Modulus	Poisson Ratio	Density	Water Absorption Coefficient
	E [GPa]	ν	ρ [kg/m ³]	(%)
Typical natural aggregates	20–70	0.2–0.45	400–2000	0.35–0.40
Demolition aggregates	-	-	1300–1700	3–5
Brick	14–16	0.15–0.18	1800–2100	8–9
Waste glass	60–69	0.18–0.30	2500	0
Plastic (polypropylene)	1.3–5	0.35–0.45	900–1500	0
Polystyrene	3–3.4	0.35–0.45	200–1500	0.30–0.40
Caoutchouc	0.001–0.1	0.5–0.6	970–1250	0.25–0.30

Cement is a major contributor to greenhouse gas emissions [1]; the cement production process is harmful to the environment as it generates carbon dioxide. In this regard, the use of by-products from other industries as additional cemented materials in concrete with cement is well known for reducing gas emissions from concrete [2]. Substituting cement with fly ash, silica fume, and blast furnace slag leads to a cement-like fineness (Table 2), and it has been used in several studies [3–5] to prepare geopolymer concretes (GPCs). Red mud and glass powder have also been used to partially replace cement in concrete [6]. Glass functions as a pozzolanic material when finely ground (Table 2). The properties of concrete are thus modified and there is decreased consumption of cement, which is the most expensive component of concrete.

Another major component of geopolymers is alkaline activators, which can be hydroxides, silicates, sodium, or potassium carbonates or a mixture of these; these are soluble in water. To obtain a high-performance final product, the precursor and the alkaline activator must be appropriately paired. Some precursors react preferentially or work effectively with a certain type of activator because of the differences in chemical compositions. For example, sodium hydroxide is preferred for the alkaline activation of fly ash. A sodium-in-silicate solution provides better activation for blast furnace slags than other types of alkaline activators.

A geopolymer can achieve strength comparable to ordinary concrete. GPC is a good fire-resistant material [7]. Some of the advantageous characteristics of GPC include rapid strength, dimensional stability, acid resistance, fire resistance, excellent adhesion to reinforcements and aggregates, and a lower cost of materials, which is approximately 10–30% compared to conventional concrete as it uses waste as a raw material, unlike cement concrete, which uses virgin materials [8–10]. Lan et al. [11] reported that GPCs experience very little creep and drying shrinkage and exhibit exceptional resistance to sodium sulphate. The application of GPCs in buildings and other structures is limited due to lack of structural design standards and codes [12]. More investigations into long-term behaviour and durability are required to enable the commercialisation of GPC.

Table 2. Fineness of cement and different types of waste replacing cement (m^2/g).

Cement	Fly Ash	Silica Fume	Blast-Furnace Slag	Red Mud	Glass Powder
0.3–0.35	0.22–0.4	0.28–0.70	0.25–0.4	0.1–0.3	0.3–0.35

This study comprehensively reviewed various state-of-the-art residues used in the formulation of concrete for recycling the maximum amount of waste, preserving natural resources, and ensuring environment protection. This paper can serve as a reference document and guide for the characterisation of parameters that affect the physical and mechanical properties of waste-based concrete. This paper aims to provide a comprehensive understanding of the parameters affecting the physical and mechanical properties of concrete formulated from waste. First, the effects of waste type and replacement rate on workability and air content of fresh concrete are presented. Next, the mechanical parameters, such as compressive strength and modulus of elasticity, are discussed. Finally, their development, evolution, and advantages and disadvantages are discussed in detail.

2. Properties of Concrete with Recycled Aggregates

Comprehensive understanding of the mechanical properties, including the workability of fresh concrete and the strength and stiffness of hardened concrete, of concrete containing industrial waste is essential to study delayed strain. These properties are affected by the rate at which aggregates are replaced by waste or cement additions, types of recycled materials, W:C ratio, and types of admixtures.

2.1. Properties of Fresh Concrete

- Workability

The slump test is used to evaluate the workability of fresh concrete. Typically, a workable mixture is more durable and exhibits better mechanical properties. The workability of a mixture also depends considerably on the properties of its constituents.

Typically, glass aggregates are used to replace fine aggregates in concrete. However, the workability of glass concrete decreases with the increase in the amount of glass (Figure 1a). Park et al. [13] determined that slump decreased by 23%, 32%, and 41% compared to conventional concrete when 30%, 50%, and 70%, respectively, glass aggregates were used as sand replacement. This decrease in slump can be attributed to the tendency of cement paste to cling to the surface of the waste glass. Therefore, a lower proportion of cement is available to fluidise the mix. Glass aggregate particles are also typically smoother and more angular than sand, which decreases the fluidity of fresh concrete.

Polystyrene aggregates are used to replace coarse aggregates, and this decreases workability. Tang et al. [14] showed that replacing coarse aggregates with polystyrene aggregates decreased sagging from 65 to 55 mm (Figure 1b). However, polystyrene aggregates did not absorb much water owing to their closed cell structures [15–17]. Polystyrene aggregates typically show a uniform distribution in the mortar and concrete matrix, and the cohesion of fresh mixes of polystyrene concrete appears similar to that of ordinary concrete [18].

Using tyre rubber as a substitute for aggregates in a concrete mix also affects its workability and slump. Several studies [19–22] have determined that the workability of rubber–concrete mix decreases with increasing rubber content (Figure 1a,b). Zaher et al. [22] and Su et al. [23] reported that the workability of rubber–concrete decreased with a decrease in the size of the rubber particles due to the increase in the area of the angular size particles. Mechanically crushed rubber aggregates are more rough and provide higher surface area, and thus, they have lower workability values than crushed cryogenic rubber [22]. However, some researchers have reported conflicting results on the effect of rubber particle size. Senouci [21] and Reda Taha et al. [20] found that the workability of rubber–concrete decreased with increasing particle size due to increased friction between the angles of rubber particles, which also decreased the fluidity of larger-calibre rubber particles [24]. Studies have shown that pre-treatment of rubber particles may improve

the workability of concrete mixes containing rubber aggregates. For example, soaking the rubber particles in water for 24 h can increase the slump of rubber–concrete mixes. This is because the water adsorbed by the rubber aggregates facilitates relative displacement between the rubber particles and the other components of the concrete mix [25]. Similar workability improvement can be achieved by treating rubber particles with one of the following aqueous solutions: anhydrous ethanol, acrylic acid or polyethylene glycol. The molecular structures of these mixtures is similar to that of a polycarboxylate-based water reducer, and their behaviours are similar to those of concrete mixtures with treated rubber aggregates [26]. Treating rubber particles with sulphuric acid (H_2SO_4) also improves fresh concrete workability. Such treatment affects the surfaces of rubber particles, which increases workability and forms particles that are more porous, smaller, and rougher [27,28].

Plastic aggregates may also be used to replace sand or gravel in concrete mix. Most studies have determined that increasing the replacement ratio decreases the workability and slump values of fresh concrete [29–32]. Most studies have shown that increasing the percentage of plastic content decreases the sag. Mohammed et al. [33] replaced sand with recycled plastic aggregates at different percentages (2.5%, 5%, 7.5%, and 10%) relative to the weight of the aggregates and found that the optimum performance for flow diameter was 2.5% content of plastic aggregates. Some studies have shown that the shapes of plane particles can be an important factor in decreasing the flow and that these may thus behave as the retaining material, slowing the sag. This is mainly observed when round and smooth plastic particles are used as a replacement material [34].

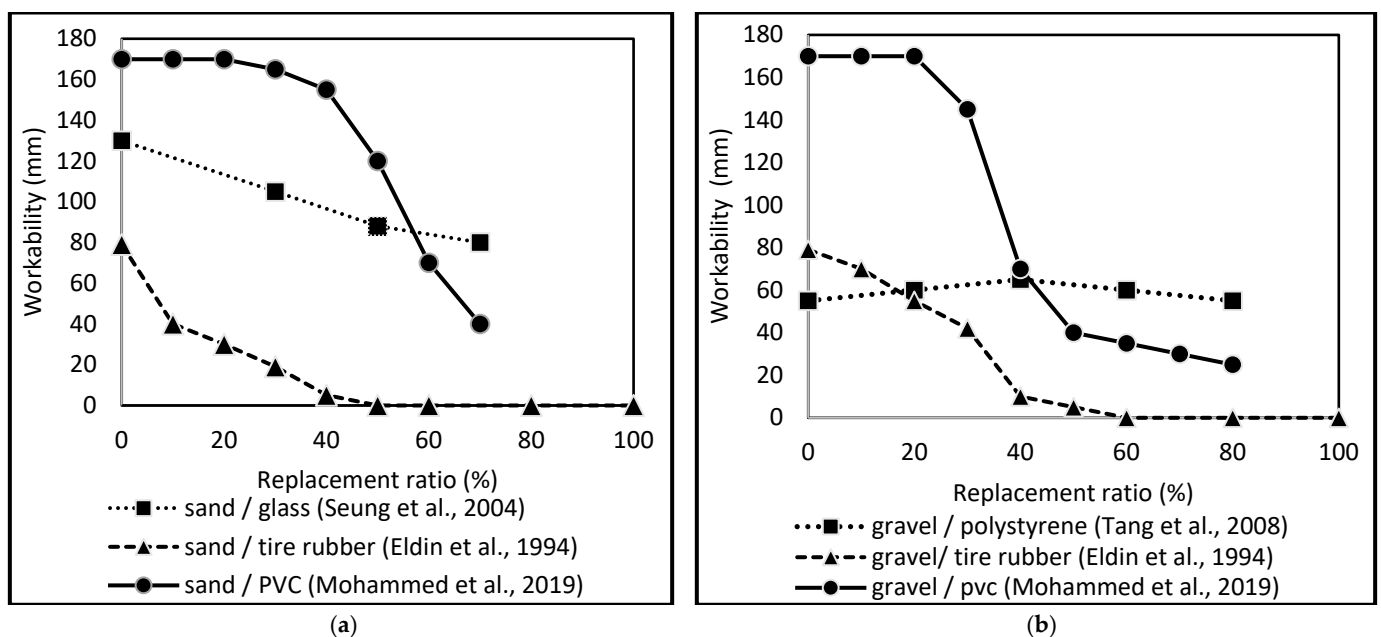


Figure 1. Variation in workability as a function of replacement ratio of (a) sand and (b) gravel [13,14,21,33].

From a workability point of view, all the wastes mentioned in this study negatively influence the workability of concrete. It is preferable to replace sand with glass and PVC, and gravel by polystyrene and rubber tyre.

- Air content

Handling fresh concrete always lets in a certain amount of air, which is called occluded air. For concrete that is not exposed to freezing and thawing, the air content should be between 1% and 4%, while for concrete exposed to freezing and thawing, the air content varies between 5% and 8% due to the addition of air-entraining additives. In the case of waste concrete, air content is higher than that of control concrete due to the irregular

size and shape of the waste aggregates. For example, concretes containing waste glass as aggregate, with replacement ratios of 30%, 50%, and 70%, show an average of 16.9%, 27%, and 36% increase in air content, respectively, compared to plain concrete (Figure 2). This trend of increased air content is attributed to the existence of more waste glass aggregates with larger grain sizes than sand, as well as their irregular shapes, which results in a larger relative surface area and thus more air [13].

The air content of polystyrene aggregate concrete increases considerably with the increase in polystyrene aggregate content (Figure 2), which increases the workability of the concrete [14]. Spherical air bubbles act as fine aggregates with very low surface friction and high compressibility [35]. However, the high trapped air content increases the presence of voids and decreases the strength of the concrete.

For concrete made with recycled brick aggregates, the amount of entrapped air increases with the increase in the percentage of recycled brick aggregates (Figure 2). This is attributed to the increases in water content due to the incorporation of this type of aggregate [36].

Sadrmomtazi et al. [31] studied the air content of concrete with plastic particles as a partial replacement for sand. The air content values of the mixes increased with the addition of recycled plastic aggregates (Figure 2). For the reference mix, the air content value was only 4.2%. With the incorporation of 15% plastic particles, this value increased to 5.8%.

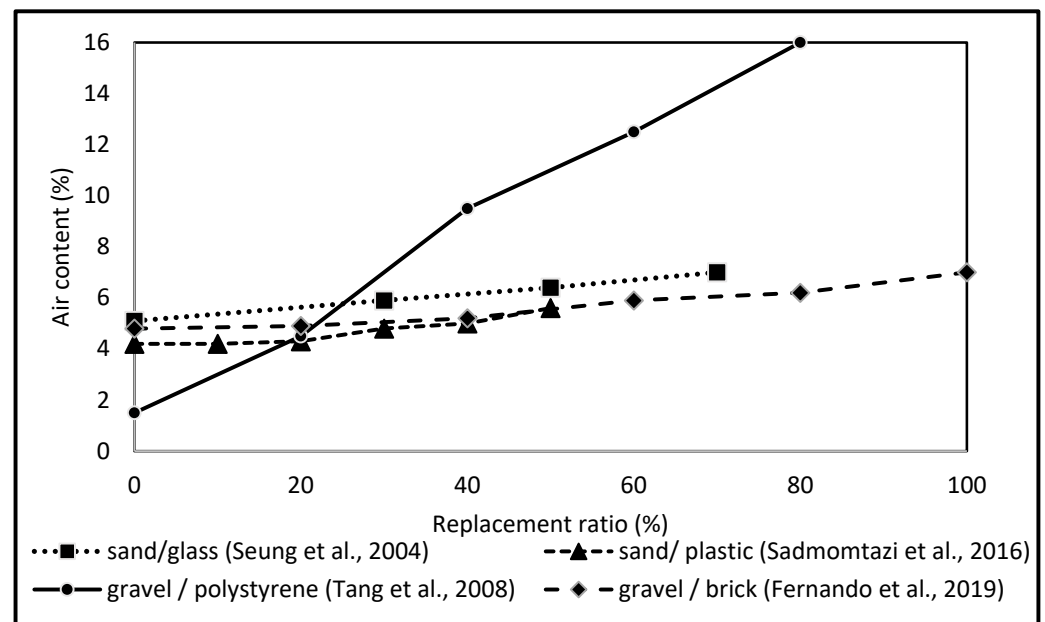


Figure 2. Variation of air content as a function of replacement ratio [13,14,31,36].

Although the air content increases with the addition of the various wastes, it is still acceptable for glass, plastic, and brick concretes. However, for polystyrene concrete, the addition should not exceed 40%.

2.2. Mechanical Properties of Concrete with Recycled Aggregates

• Compressive strength

The compressive strength of concrete is an essential property considered by engineers. Different codes require certain conditions of durability that must be satisfied according to the purpose of the concrete mixture. The compressive strength of concrete is largely affected by the stiffness and roughness of the aggregates, which improve the anchorage of the binder (i.e., cement paste for conventional concrete) as well as the matrix density [37].

Replacing gravel and sand in conventional concrete by another type of aggregate may therefore affect the compressive strength of the new material.

The effect of replacing gravel or sand by recycled aggregates on concrete compressive strength measured after ageing for 7 and 28 days is presented in Figure 3a,b, respectively. Replacing gravel or sand aggregates with rubber, polystyrene, plastic, brick aggregates, and demolition aggregates decreases the compressive strength of concrete at both 7 and 28 days. For rubber aggregates [20–22,38–40], strength reduction was attributed to: (i) the deformability of rubber particles in relation to the cement microstructure, leading to crack initiation in a pattern similar to that of air voids in normal concrete; (ii); the weak interfacial bonding between the rubber particles of the tyres and the cement matrix; and (iii) the possibility of decrease in the density of the concrete matrix, which further depends on the size, density, and hardness of the aggregate particles.

Water-washed rubber pre-treated with NaOH was shown to provide slight improvement compared to untreated concrete (4.7% and 3.1%, respectively); rubber particles pre-coated with cement and mortar showed considerable improvements of 15.6% and 40.6%, respectively [41]. Balaha [42] reported an improvement of approximately 13% in compressive strength in rubber–concrete containing crumbs of rubber pre-treated with NaOH. Soaking rubber particles in water is the most cost-effective method of pre-treatment. Mohammadi et al. [25,43] found that soaking rubber aggregates in water for 24 h provides a considerable compressive strength improvement in 28 days, as it helped remove air trapped in the rubber particles, thereby improving the adhesion of the rubber to the cement matrix.

A similar decrease in compressive strength was observed after 7 and 28 days when polystyrene [14,16,44,45] or plastic aggregates [29,30,34,46,47] were used to replace natural aggregates in concrete (Figure 3a,b) by Faraj et al. [44] and Iucolano et al. [35]. Faraj, et al. [29] reported 24% reduction in compressive strength by incorporating 40% plastic granules instead of sand at the same water: cement ratio. Sadrmomtazi et al. [31] reported that the strength of concrete containing 15% by weight of plastic aggregates decreased by 48.3%. Most researchers have attributed this decrease in strength to the low stiffness and density of the polystyrene and plastic aggregates compared to that of conventional aggregates. When samples are loaded, these aggregates behave as voids within the matrix, leading to crack initiation around the particles and decreasing strength and stiffness [30].

Perry et al. [45] studied the strength of polystyrene aggregate concrete over a density range of 850–1250 kg/m³ and found that the mechanical behaviour of polystyrene aggregate concrete is similar to that of concrete cells, as polystyrene aggregate mainly comprises air. Similarly, Chen, et al. [48] investigated the mechanical properties of polystyrene aggregate concrete at a constant water: binder ratio (0.37), producing a series of polystyrene aggregate-based samples with compressive strength of 10–25 MPa over a density range of 800–1800 kg/m³. Saradhi Babu et al. [16] studied the strength and durability of polystyrene aggregate concrete containing mineral admixtures with concrete densities in the range of 550–2200 kg/m³; the corresponding strength results were in the range 1–21 MPa. The density and strength of polystyrene aggregate concrete decreases considerably with increase in polystyrene content; therefore, this concrete can be used in areas where strength is not a crucial factor and in areas exposed to freezing and thawing.

Some researchers have also studied brick aggregates as an alternative for replacing coarse aggregates. All studies reviewed in this paper have reported linear reductions in concrete compressive strength when natural coarse aggregates are progressively replaced by brick aggregates (Figure 3a,b), as tested by Debieb and Kenai [49]. Figure 3b shows that at 28 days, the compressive strength decreased linearly at a rate of approximately 4% for each 10% replacement and reached a loss of 40% for 100% substitution. For low-strength concrete (strength < 25 MPa), de Brito et al. [50] observed a linear decrease in strength, but at a smaller rate of 2.2% for each 10% replacement of coarse aggregates. By replacing fine aggregates (sand) with brick aggregates instead of coarse aggregates in normal-strength concrete, Cachim [51] observed almost no decrease in compressive

strength for a replacement ratio of 50%, and compressive strength loss was <20% for a replacement ratio of 100%.

Torkittikul and Chaipanich [52] stated that the compressive strength of concrete made from ceramic aggregates was higher than that obtained with natural aggregates for fine fraction substitution percentages up to 50% (Figure 3a,b). The optimum result was obtained by Pacheco-Torgal and Jalali [53], who used ceramic sand with a low water absorption coefficient (6%). The replacement of natural sand by ceramic sand is a good choice because the concrete did not show any loss of strength and had excellent durability.

The addition of mineral admixtures such as fly ash and silica fume considerably improved the strength of recycled aggregate concrete due to the improved microstructure of the matrix [29,31]. The use of 10% silica fume in recycled aggregate concrete containing 15% by weight of plastic particles increased the compressive strength by 14% compared to the same mix with no silica fume content [31]. Faraj et al. [29] also reported that the compressive strength of recycled aggregate concrete increased by 5% with the addition of 10% silica fume, regardless of the plastic aggregate content.

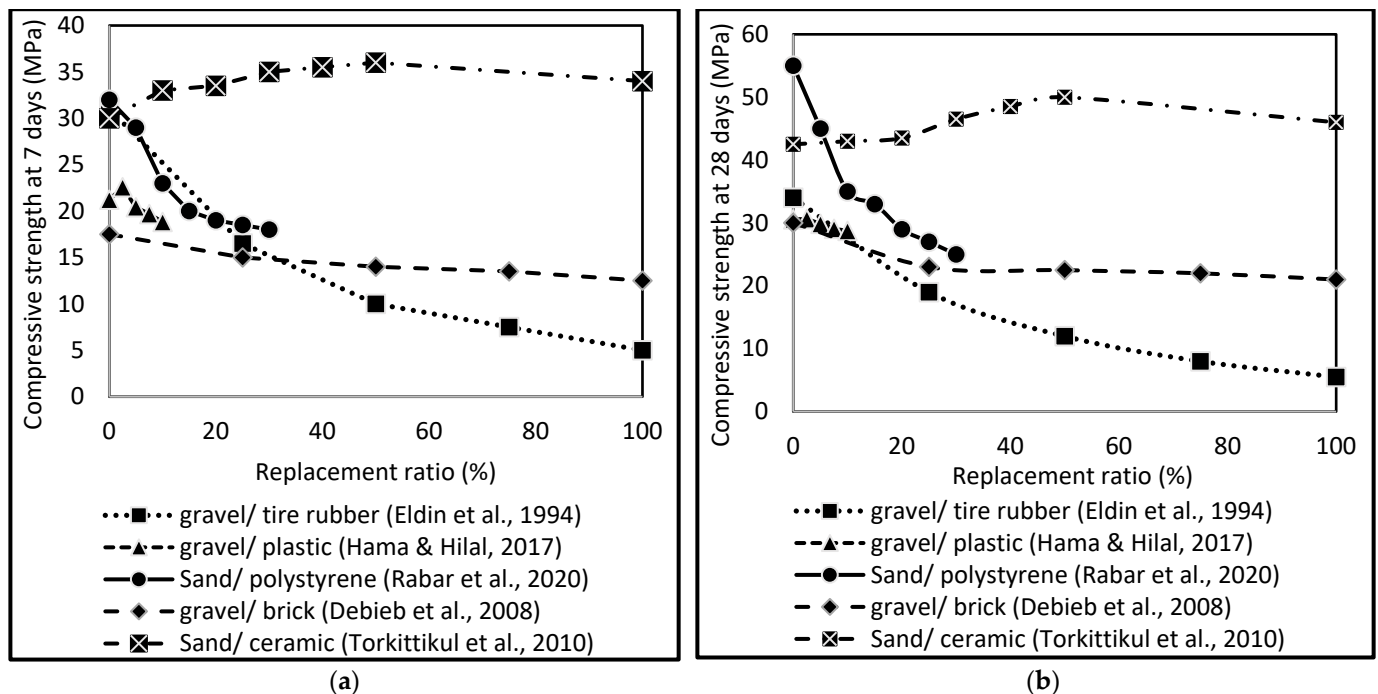


Figure 3. Variation of compressive strength as a function of replacement ratio at (a) 7 days and (b) 28 days [21,30,44,49,52].

Despite the decrease in compressive strength of waste-based concretes, it remains acceptable for brick and ceramic concretes at up to 100% replacement and for plastic at up to 15%. On the other hand, the polystyrene and tyre rubber concretes had a significant drop in compressive strength with the increase of the replacement.

- Elastic modulus

The modulus of elasticity (E_c) of concrete depends on many factors, such as W:C ratio, binder content, and type of aggregates. Table 3 presents the results of previous studies on the influence of percentage and the types of aggregates on E_c ; these were determined from the experimental stress–strain.

Tang et al. [14] reported that compared to control concrete, the E_c of concrete made from polystyrene aggregates decreased by 29% and 73% when 20% and 80% aggregates were replaced, respectively. Yang et al. [32] concluded that the E_c of lightweight concrete containing 15% polystyrene aggregates was 10% lower than that of the control mix. The modulus of elasticity of concrete is considerably affected by the properties of the aggregates,

the cementitious matrix, and the transition zone. The E_c is negligible in polystyrene aggregate-based concrete because the incorporation of polystyrene aggregates in the mix increases the elastic incompatibility between the polystyrene aggregates and the matrix, thus increasing the stress concentration at the bond interface [54]. As a result, the elastic modulus decreases considerably.

The modulus of elasticity of plastic aggregate concrete depends on many factors, such as the water: cement ratio, binder content, and the type of plastic aggregate. The elastic modulus of plastic aggregate concrete decreases with increasing plastic content. Faraj et al. [29] also reported that as the replacement ratio of plastic content increased from 0% to 40%, the static elastic modulus of high-strength concrete decreased by 22% on average. They also determined that adding silica fume improved the E_c regardless of the plastic aggregate content. Similar results were presented by Sadrmomtazi et al. [31].

Li et al. [55] examined the effect of particle size and the replacement ratio of coarse/fine aggregates by rubber aggregates on the elastic modulus. The elastic modulus increased with increasing particle size but decreased with increasing rubber replacement ratio. Similar findings were reported about the decrease in the elastic modulus with increasing rubber replacement ratio: Atahan and Yücel [56] and Yuan [57] determined that the elastic modulus of concrete containing smaller rubber particles increased by 17.1% and 17.4%, respectively, compared to rubber particles with larger sizes. At higher replacement levels, however, there was not a considerable difference in the effect of particle size on the elastic modulus.

Table 3 shows that the modulus of elasticity is strongly affected by the presence of aggregates of recycled bricks. The modulus of elasticity decreases with increasing percentage of brick aggregates. It follows a similar trend to compressive strength (Figure 3a,b). For a substitution percentage of 100% of brick aggregates, the elastic modulus decreased by approximately 60%. Cabral et al. [58] reported a 45% decrease for 100% coarse fraction substitution and a 12% decrease when replacing the fine fraction of medium-strength concrete (<35 MPa). Alves et al. [59] reported a decrease of 30% in medium-strength concrete (<50 MPa) for 100% substitution of fine fractions. Khatib [60] reported a decrease of only 15% in the dynamic modulus of elasticity for 100% substitution of the fine fraction in medium-strength concrete (<50 MPa). The decrease in elastic modulus occurs mainly because the recycled brick aggregate has lower stiffness than the natural aggregate. Moreover, the presence of the coarse fraction of recycled brick aggregates enhances this characteristic compared to the substitution of only the fine fraction.

Table 3. Mechanical properties of different types of concrete [31,32,54–61].

Material	Replacement Ratio	Modulus of Elasticity	Compressive Strength at 28 Days	Tensile Strength at 28 Days	Density
	%	E [GPa]	[MPa]	[MPa]	ρ [kg/m ³]
Concrete based on natural aggregates	100%	20–50	30 \mp 2	3	2200–2400
Concrete based on tyre rubber	25–100%	-	23–5.5	2.8–1.63	2150–1700
Polystyrene-based concrete	5–30%	-	45–25	4–2.8	1800–2150
Glass concrete	25–100%	16.5–18	52–55	-	2150–2450
Brick-based concrete	20–70%	36–16.5	55–43	3.87–2.52	2340–1870
Plastic-based concrete (polypropylene)	5–40%	41–34	78–62	4.4–5.8	1500–2000
Concrete made with demolition aggregates	25–100%	-	44.5–38.7	-	2210–2170

The modulus of elasticity was not determined for all the waste concretes cited in this study because of its sharp decrease with increasing waste quantity. This is also the case for the wastes listed in Table 3.

3. Mechanical Properties of Concrete with Alkali-Activated Concrete

Over the past few decades, extensive research has been conducted on energy-efficient and sustainable alternatives to Portland cement concrete. Compared to Portland cement concrete, the primary raw materials of geopolymers are mainly natural aluminosilicate-rich minerals, alkaline activators, and industrial wastes, rather than relying on calcium carbonate calcination (CaCO_3) (Table 4), which is a dominant source of CO_2 emissions in the production of Portland cement concrete [62]. Portland cement is totally replaced by another raw material in GPC; therefore, it is considered an environmentally friendly alternative to conventional concrete [63,64].

In GPCs, the binder can replace 100% of the Portland cement and provide better concrete physical properties and durability [6,65]. Various sources of raw materials can be used as binders in GPC. Contemporary raw materials that are commonly used in GPC are fly ash (FA), blast furnace slag ground granules (GGBFS), and metakaolin. These by-products have been preferentially used for GPC due to their availability and high content of silica and alumina, which are responsible of the geopolymerisation process when reacting with activators (typically sodium silicate, Na_2SiO_3 , and sodium hydroxide, NaOH). Silica fume (FS), which is a by-product of smelting silicon, is another source of silicate that can be used in concrete to replace Portland cement or to act as an additive for Portland cement concrete [66]. Silica fume comprises very fine particles (between 0.1 and 0.5 mm) [5], which leads to very high pozzolanic activity [67]. Bauxite residues (RBs) and glass powders are alternative sources of silica that can be used for geopolymers if they contain sufficient alumina and calcium [10]. GPC can be used as an industrial by-product of raw materials that have considerable potential to improve durability [68]. FA and blast furnace slag are preferentially applied to GPC due to their high availability and high content of silica (SiO_2) and alumina (Al_2O_3) [69]. Table 4 shows the typical chemical compositions of Portland cement, bauxite residue, FA, silica fume, glass powder, and blast furnace slag.

Table 4. Chemical composition of cement as well as different types of industrial residues used in the manufacture of geopolymer concrete [5,6,62–69].

Composition (%)	Portland Cement	Bauxite Residues	Fly Ash	Silica Fume	Glass Powder	Blast Furnace Slag
CaO	61–70	1–4	1–40	0.1–0.15	8–10	40–45
SiO_2	20.0–25	8–15	15–60	91–97	70–72	35–38
Al_2O_3	3.5–7.5	20–24	5–35	0.2–0.3	1.5–5	10–12
Fe_2O_3	1.5–6	40–45	4–40	0.1–0.5	0.08–2.3	0.18–0.4
MgO	1.5–4	0.20–0.30	1–3	0.1–0.2	0.5–3.2	8–9
SO_3	0.05–3.5	0.60–0.8	0.1–0.4	0.12–0.45	0.08	-
K_2O	0.05–1.4	0.04–0.05	1–3	0.1–0.56	0.5–7	0.1–0.4
Na_2O	0.05–0.7	3.70–4	0.4–1.5	0.1–0.6	8–14	-
Chloride	0–0.1	-	-	-	-	-
Insoluble	0.05–1.2	-	2.0	-	-	-
Loss on fire	0.2–3	10	3–5	1.2–2.40	2–3	1.5
Free lime	1.0	-	-	-	-	-

The main reaction and activation products of GPC show the optimum mechanical properties and durability after high-temperature curing. Generally, FA requires a curing

temperature of 60–85 °C because the reactivity of FA is inadequate to be activated by alkaline activators at 20 °C room temperature [70]. Blast furnace slag can improve the curing properties of fly ash-based GPC at room temperature because of the presence of CaO in the blast furnace slag [71]. Thus, the use of FA/GGBFS-based GPC, which includes calcium silicate hydrate (C–S–H gel), calcium aluminosilicate hydrate (C–A–S–H gel), and sodium aluminosilicate hydrate (gel N–A–S–H) [5], can save energy, decrease CO₂ emissions, and facilitate the recycling of waste. These types of geopolymer also exhibit excellent mechanical properties [72,73], freeze–thaw resistance [74], corrosion resistance for embedded steel reinforcement [75], high temperatures resistance [76], and exceptional interfacial bonding properties of steel reinforcing bars [76].

Glass powder is also considered a source of silica for the production of GPC. It can limit the amount of sodium silicate (SS) and sodium hydroxide (SH), which are alkaline solutions that are typically used as geopolymer activators. Under certain conditions, these solutions can be completely eliminated for economic advantages in the production of alkaline geopolymers, which are the most expensive components of GPC mixtures [77]. Silica fume reacts with the calcium compounds of the raw geopolymer material (usually FA) and forms C–S–H gels, which increases the physical and mechanical properties and durability of GPCs [78]. Mijarsh et al. [79] used silica fume as a mineral additive for the production of geopolymers from palm oil fuel ashes.

Several studies have shown that the use of calcium hydroxide, Ca(OH)₂, is the optimum representative of pozzolanic reaction activity, and it is the criterion for the identification of a pozzolanic material [80]. In the past, two main types of pozzolanic materials have been used, namely, natural materials, which are rare materials generally produced by volcanic activities, and synthetic materials such as ceramic powder. Currently, the most frequently used pozzolanic materials with the same properties are FA, silica fume, and metakaolin [81]. Water-quenched slag also has suitable cementing and pozzolanic properties. However, the hydration of water-soaked slag decreases Ca(OH)₂ in concrete, which can reduce its permeability, improve its resistance to chemical attack, enhance its durability, and decrease the reaction of alkaline aggregates. Thus, this concrete is more compact, and its strength may increase after long-term use [82].

Bauxite residues have also been used in GPCs. The chemical composition of bauxite residues can be variable and depend on its nature. In general, bauxite residues contain iron, titanium, silica, and the aluminium that was not extracted during refining and metal production. These may also contain sodium, in the form of hydrated aluminium silicate and sodium of a zeolitic nature, hematite (α -Fe₂O₃), goethite (α -FeOOH), magnetite (Fe₃O₄), boehmite (γ -AlOOH), quartz (SiO₂), sodalite (Na₄Al₃Si₃O₁₂Cl), and gypsum (CaSO₄·2H₂O). A small amount of calcite (CaCO₃) and gibbsite (Al(OH)₃) may also be present in bauxite residues [83]. Olivia and Nikraz [6] indicated that the percentage of CaO is less variable, and thus, bauxite residues do not have cementitious properties. However, when added to concrete with Portland cement, bauxite residues may react with water and cement and acquire cementitious properties.

3.1. Properties in a Fresh State

- Workability

Generally, an alkaline solution (NaOH, Na₂SiO₃) of geopolymer activators is used in the liquid form. Investigations into the effects of different alkaline solution concentrations (35%, 40%, and 45%) on the performance of GPCs based on blast furnace slag have shown that the slump of GPC is maximised when the concentration of the alkaline solution is 45% [84]. However, the increase in SH concentration decreases the slump of the GPC [85], which may be attributed to the penetration of more SiO₂ and Al₂O₃, which accelerates the geopolymer process and improves the stiffness of the system.

The workability of fly ash-based GPC is also considerably affected by the Na₂SiO₃: NaOH ratio, and different Na₂SiO₃: NaOH ratios can cause unstable variations in the workability of GPC (Figure 4) [86]. The viscosity of GPC increases with increase in the

Na_2SiO_3 : NaOH ratio, and generally, the slump of GPC decreases with increasing Na_2SiO_3 content [84].

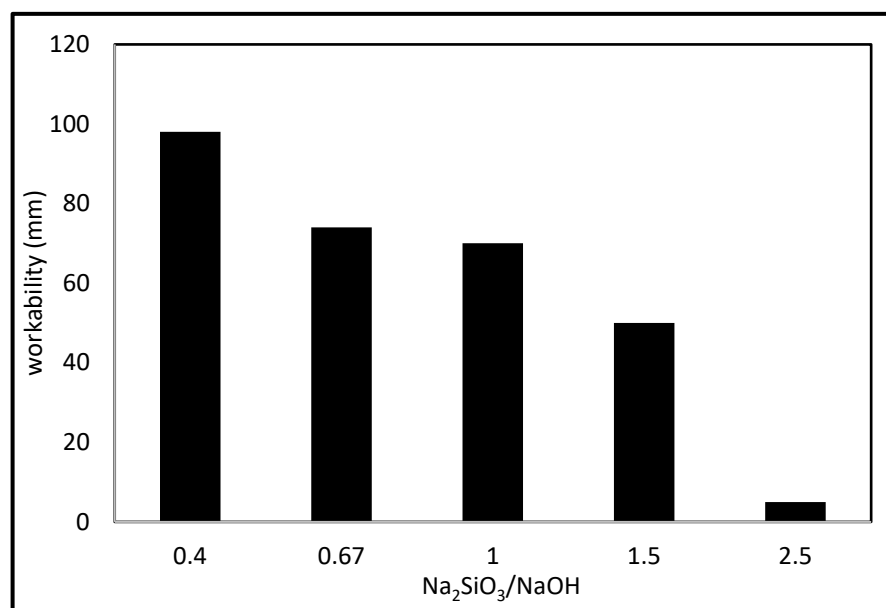


Figure 4. Effect of Na_2SiO_3 : NaOH ratio on the slump of GPC [84].

For GPC mixed with FA and blast furnace slag, Laskar and Talukdar [87] and Venu and Gunneswara Rao [88] revealed that replacing part of the FA with blast furnace slag would decrease the slump of GPC. This may be due to the high calcium content in the blast furnace slag, which accelerates the reaction of the geopolymers by forming an amorphous Ca–Al–Si gel [89].

Generally, GPCs have a lower slump than Portland cement concrete. Fly ash-based geopolymers, where the slag has low calcium content, have workability similar to that of Portland cement concrete [9]. Rangan [65] showed that workability can be increased by using a superplasticiser product based on naphthalene (SP). The recommended amount of naphthalene (SP) for a 44% solid solution is approximately 2–4% of FA mass. Umniati, et al. [90] reported that the increase in FA-to-sand ratio leads to the increase in GPC workability. However, the cohesion and the slump of GPC increase with the increase in the SiO_2 : Na_2O ratio in the sodium silicate solution. Shadnia et al. [91] found that the slump of GPC increases when the molarity of NaOH is decreased with varying ratios of alkali activator solution to FA [92,93]. Mehta and Siddique [94] showed that the use of NaOH as an alkali activator alone, without SH, can considerably reduce the slump of GPC, which can be attributed to the high viscosity of Na_2SiO_3 . According to Ramujee and PothaRaju [95], among the factors that act on the slump of GPC, the alkali solution-to-FA ratio, the fineness of FA, the ratio of Na_2SiO_3 : NaOH solution and liquid to FA considerably affect the workability of GPC.

Few works have investigated the fresh state properties of geopolymer concrete. However, from previous studies, it can be concluded that geopolymer concrete has a firmer slump than Portland cement concrete. On the other hand, there are solutions to liquefy the geopolymer concrete mix, as mentioned above.

3.2. Properties in the Hardened State

- Compressive strength

Various material residues are used in the production of GPCs, and their dosage has a crucial effect on the concrete's mechanical properties. Consequently, the strength of GPC varies according to the type of residues used, the curing temperature, the curing duration,

and the selected raw materials, such as the types of superplasticiser: water: solid ratio, Na_2O : SiO_2 ratio, Na_2SiO_3 : NaOH ratio, and the particle size distribution [96].

The curing of GPC at high temperature can facilitate its subsequent reaction and generate more material in the geopolymer gel phase, thus improving the material strength [97,98]. However, the curing time at high temperature should not be very long. The main reason is that high-temperature curing for a long time would generate thermal stress within the geopolymer matrix, producing microcracks in its internal structure, which decreases the compressive strength of the samples [97–99]. Guo et al. [100] also concluded that there is a critical value for the high-temperature curing time of GPC, and a too long curing time at high temperature can damage the geopolymer structure.

High-temperature curing of geopolymer-based concretes produces their maximum compressive strength after one day without further increase in compressive strength over time. In fact, nearly 90% of this final strength is developed in a few hours if curing is done at 80–90 °C. However, GPC cured under ambient temperature gains strength over time, which is observed with ordinary concrete. Increasing the curing temperature is also beneficial for discharging the water generated in the system, as it accelerates the growth of the gel phase material in GPCs [4,98]. Hence, this can rapidly form a high-strength hard structure. Therefore, a high curing temperature of 80 °C can improve the compressive strength of GPC. In general, a large number of water molecules are deformed at the beginning of the geopolymerisation process; the water molecules evaporate during high-temperature curing [97,101], and then leave voids in the internal structure and the external surface of the matrix. Therefore, under appropriate conditions of curing temperature, all incompletely reacted blast furnace slag and FA particles are tightly enveloped by the generated gel phase material, and the bond between the particles and the matrix becomes compact and dense.

All curing regimes (ambient or higher temperatures) produce long-term strength [65], and the curing temperature simply changes the time to reach the ultimate strength of the mix under study. Curing at excessive temperature is not beneficial to the compressive strength of GPC. The main reason is the weakening of the microstructure and the formation of micro- and macro-cracks [98,100]. As an example, curing at 100 °C causes loss of humidity and a decrease in strength because the geopolymerisation process requires humidity to obtain good mechanical properties [4].

As for the effect of the residues on the compressive strength, on one hand, Nasvi et al. [4] reported that the fly ash-based geopolymer did not acquire a considerable increase in strength above 60 °C, and on the other hand, some researchers found that the optimal curing temperature for higher strength was 75–85 °C [98,102]. These conflicting results could be attributed to the type of activators and the level of alkalinity of the activators [4,103]. Several researchers have mixed blast furnace slag with FA at different percentages (Figure 5). Fang et al. [8] added blast furnace slag (GGBS, 0–30%) in FA concrete [104] or they added 0–50% FA in blast furnace slag concrete (GGBF). This gave better results at lower temperatures [8,104]. Some highly reactive very fine fly ashes do not require slag addition to achieve high strengths [105].

Studies have reported that the increase in the concentration of alkali activator affects the strengthening of the resistance while the increase in molarity leads to a better dissolution rate of the aluminosilicate sources, thus improving the geopolymerisation process [106,107]. Due to the increase in the activator: binder ratio, the water content increase resulted in high dissolution of the ions [108]. The compressive strength of GPC decreases with the increase in the superplasticiser: binder ratio [108].

The molar ratios, water: solid ratios (w:s) of the mixtures, and the Na_2O : SiO_2 ratio increased as the Na_2SiO_3 : NaOH ratio decreased. A higher Na_2O : SiO_2 ratio corresponded to a higher compressive strength of the samples. This may be due to the increased amount of Na_2O in the mixture, which improves the mechanical properties of the geopolymers [109]. The strength decreases as the alkali solution content increases due to the high liquid content w:s of the mixture, which hinders the polymerisation process as well as the increase in the amount of oligomerisation reaction products [110]. Although the Si: Al ratio in the total

binder increases as the alkali activator content increases, the water: solid ratio was the key factor affecting compressive strength.

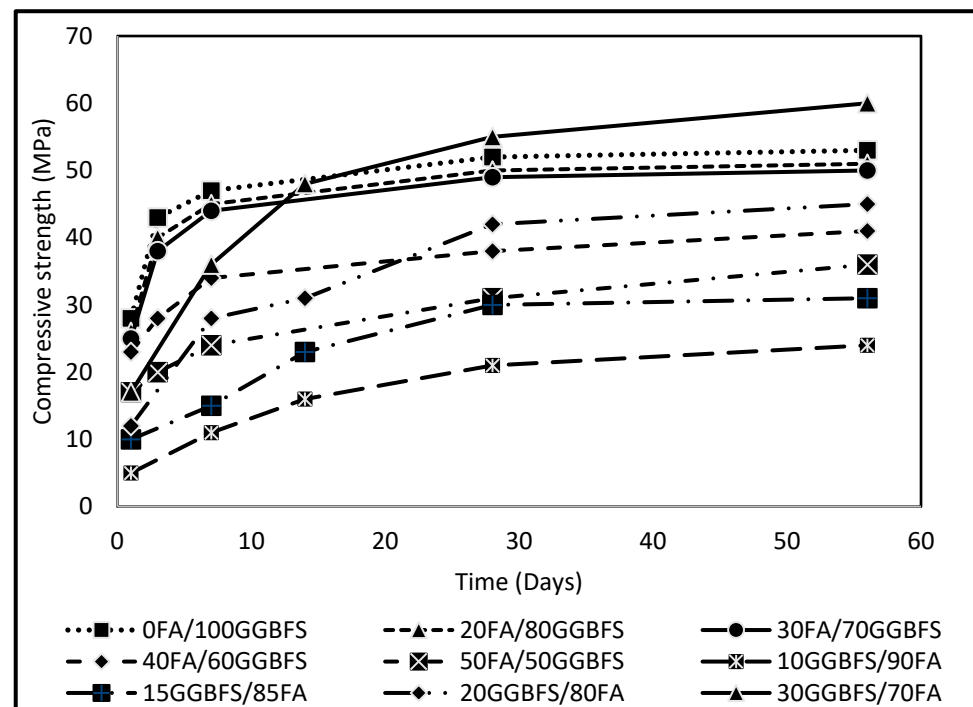


Figure 5. Variation of compressive strength as a function of time [8,104].

Al Bakri et al. [108] also reported that water content is the most important factor for a geopolymerisation process and for the dissolution of SiO_2 and Al_2O_3 and hydrolysis [111]. Consequently, the water content increases with the increase in the activator: binder ratio, which leads to more efficient dissolution of ions.

High compressive strength is related to the leaching of silica and alumina with a high-molarity alkaline solution. The dissolution process and the binding of the particles are related to the NaOH concentration. Therefore, the use of a high concentration of NaOH solutions leads to a better dissolution and a more efficient geopolymerisation process [112,113].

The polymerisation of GPC is controlled by the dissolution and precipitation processes. As pH increases, the diffusion-controlled polymerisation reaction process of GPC becomes faster than the hydration reactions of Portland cement concrete, and GPC has a higher compressive strength at the beginning of the drying period. Hydration products for Portland cement concrete are mainly calcium hydroxide ($\text{Ca}(\text{OH})_2$), C-S-H gel and ettringite (AFt), and those for blast furnace slag-based GPCs comprise a geopolymer gel and a C-S-H gel [114]. The structure of GPC is also denser than that of Portland cement concrete. The interfacial transition zone of GPC is very dense and uniform, and particle roughness has been shown to improve the mechanical integrity of GPC [93,115] and recycled GPC [116].

Some researchers have reported that increasing the amount of silica fume in fly ash-based geopolymer blends decreases strength due to their low Al_2O_3 and CaO content. Silica fume also decreases the alkalinity of the mixtures and the solubility of the FA [117]. Others report that the resistance increases under the effect of silica fume may be related to its pozzolanic nature. $\text{Ca}(\text{OH})_2$ is formed with the reaction of the alkaline solution and CaO, which is very high in FA. Silica fume is a highly reactive pozzolan; it reacts with $\text{Ca}(\text{OH})_2$ and forms calcium silicate hydrate (C-SH) gels, resulting in increased resistance [118].

Xuan et al. [10] analysed the mix effect of glass powder and NaOH concentration in GPC. For a low concentration of NaOH (6 mol/L), they observed that the increase in the amount of glass powder up to 20% increases the compressive strength of geopolymer

up to 45 MPa. For a large proportion of glass powder ($\geq 50\%$), the compressive strength decreased. However, at a concentration of 10 mol/L NaOH, the use of 50% glass powder could still increase the compressive strength up to the highest measured value. This was attributed to the better dissolution of the glass powder in the alkaline environment, which is related to the NaOH concentration. The authors of [107,119] reported that partially dissolved glass powder develops a silica-rich gel on the surface of the glass particles that prevents complete dissolution, and therefore, a higher glass powder replacement ratio can limit the reaction and decrease mechanical properties.

Bernal et al. [3] evaluated the compressive strength of GPC with different blast furnace slag contents (300, 400, and 500 kg/m³) and compared these with a Portland cement concrete with the same contents. They observed that compressive strength increased with the binder content (slag for GPC and cement for ordinary concrete). Regardless of the blast furnace slag content, GPC had a higher compressive strength than Portland cement concrete [3]. Sas et al. [7] studied the compressive strength of GPC with different contents of blast furnace slag (GGBS) and bauxite residue (BR). As presented in Figure 6, for different ratios of BR and GGBS (mixtures named XXRB/YYGGBS, where XX and YY are the percentage of BR and GGBS, respectively), they found that compressive strength decreased with increasing percentage of bauxite residue in the mixtures cured at ambient temperature. For all four studied mixtures, the compressive strength increased with time, but the strength at 2 days was generally very close to the strength measured after 28 days.

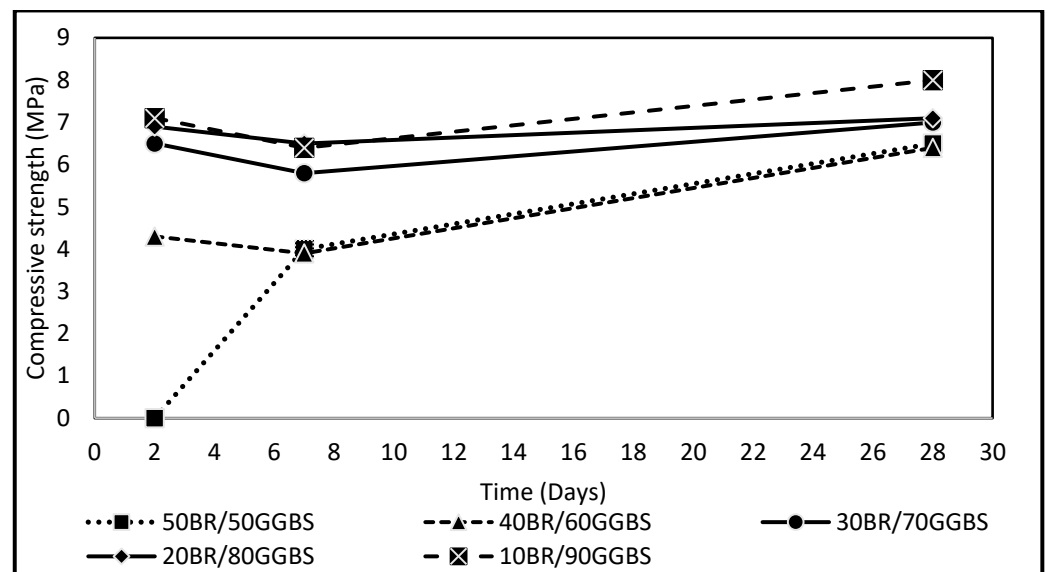


Figure 6. Variation of compressive strength of Portland cement concrete with blast furnace slag (GGBS) and BR, as a function of time and for different BR: GGBS ratios [7].

Few researchers have studied GPC with recycled aggregates. The authors of [64,120] found that geopolymer paste comprises a more homogeneous substance and is denser than Portland cement concrete paste, which modifies the defects caused by the demolition aggregates. Shi et al. [116] also reported that GPC made from recycled aggregates had higher mechanical strength than its counterpart ordinary Portland cement concrete made from recycled aggregates [64,121].

Some researchers have studied the combination of fly ash (FA) and silica fume (SF) with irradiated polyethylene terephthalate (PET) waste and ordinary polyethylene terephthalate (PET) waste in a cementitious grout [122]. The results show that the compressive strength is significantly reduced at all curing ages, although the pozzolanic characteristics of FA and SF combined to increase the compressive strength. Khan et al. [123] studied the influence of replacing ordinary Portland cement (OPC) with irradiated polyethylene terephthalate

(PET) waste and silica fume in cement grouts. The experimental results show a loss of compressive strength.

In general, the compressive strength of geopolymer concretes varies according to the type of residues used, the curing temperature, the curing time, and the raw materials used. Geopolymer concretes can be produced by mixing several wastes at the same time. This considerably improves the mechanical properties of the concrete.

- Modulus of elasticity

The elastic modulus of alkali-activated GPC was studied and compared to that of conventional Portland cement concrete by several authors. Generally, GPC has a lower modulus of elasticity than conventional Portland cement concrete [124–126]. The main reason could be that for the intrinsic modulus of elasticity of sodium aluminosilicate hydrate gels formed in fly ash/GGBS, geopolymerisation is slower than that of calcium silicate hydrate gel [73,127]. However, many parameters of a GPC mix affect its elastic modulus.

Figure 7 presents the effect of the curing time at 80 °C on the elastic modulus for three different mixtures of GPC with GGBS and FA [128]. The effect of curing temperature on the elastic modulus for the same mixtures was examined by Wang et al. [128], and the results are presented in Figure 8. The mixtures were named as XXGGBS/YYFA, where XX and YY are the percentage of GGBS and FA used, respectively. Figures 7 and 8 show that as the substituted amount of FA increased, the elastic modulus decreased. Increasing the curing time and curing temperature up to 80 °C also increased the elastic modulus. The smaller growth of elastic modulus after 24 h indirectly reflects that the geopolymerisation reaction is almost completed [128]. A similar effect of curing time and temperature was observed by Nasvi et al. [4] and Wang et al. [128] for GPC with Portland cement recycled aggregates. The reason for this improvement in the elastic modulus of concrete depends on the concrete components, including the paste, aggregates, and the interfacial transition zone [129,130]. The gel phase of the geopolymer became stronger and the hydration reaction in the GPC matrix increased further with increasing curing duration and curing temperature [73]. It was also noted by Xuan et al. [10] that the addition of glass powder may increase the elastic modulus of GPC. However, most studies have shown that for a given compressive strength, GPC has an elastic modulus lower than that of a control Portland cement concrete sample [112].

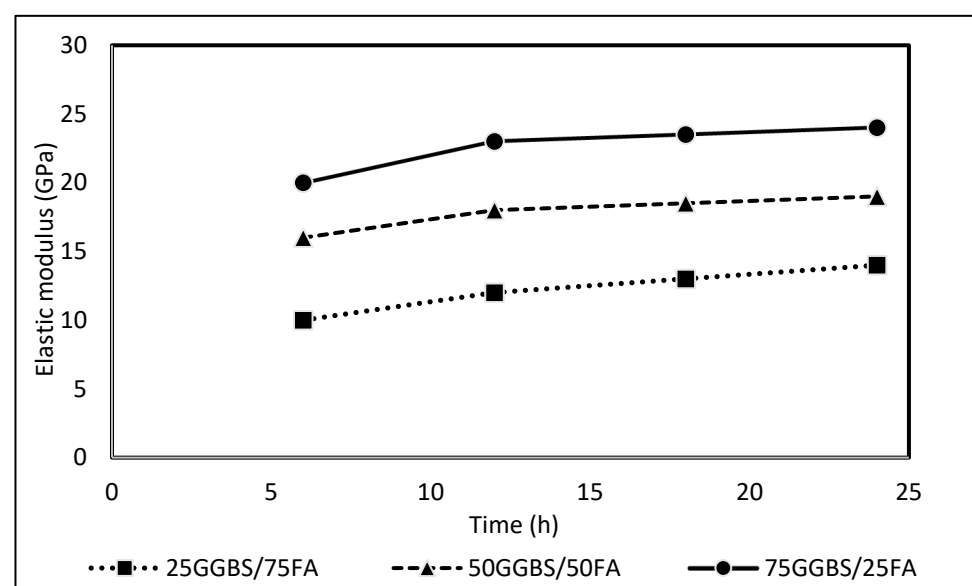


Figure 7. Modulus of elasticity as a function of curing time of GPC after 7 days at a curing temperature of 80 °C [128].

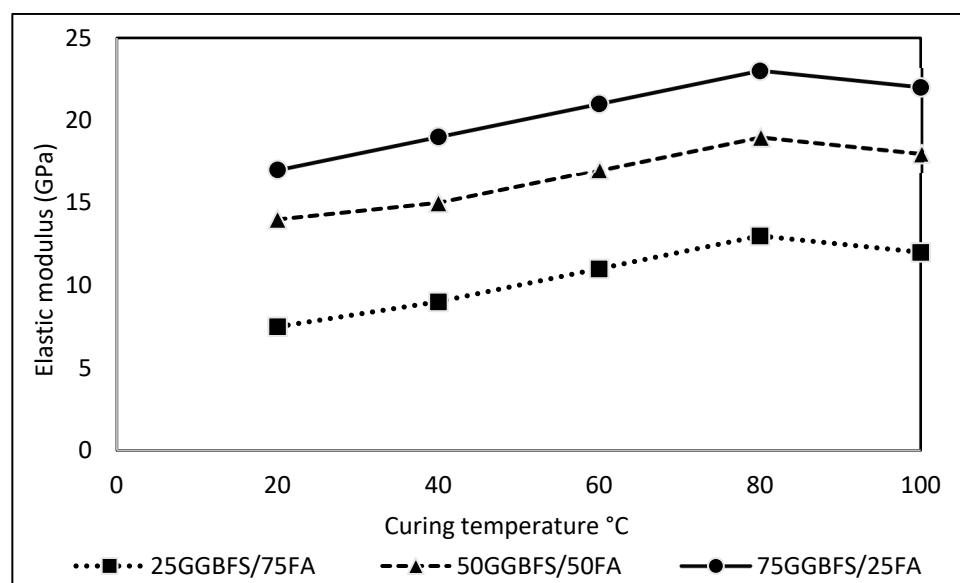


Figure 8. Modulus of elasticity as a function of curing temperature after 7 days with a curing time of 24 h [128].

Generally, the elastic modulus of geopolymer concrete is always lower than that of its reference concrete. However, it could be improved, by increasing the temperature and the curing time.

4. Discussion and Conclusions

Several researchers have studied the properties of mortar and concrete containing different types of waste. A complete review of previous studies on concrete made from different types of wastes is presented herein. Based on an extensive review of research data, the following points should be highlighted:

- Various admixture chemicals such as superplasticisers and viscosity modifiers, as well as mineral admixtures and industrial wastes, could be effectively used to improve the physical and mechanical properties of concrete. However, the type, form, and the level of replacement considerably influence the mechanical properties. The latter can be attributed to the decrease or increase in adhesive strength between the surface of the type of aggregate used and the cement paste. For example, the addition of recycled plastic, glass, tyre rubber, or brick aggregates in planar form can decrease the slump and the strength of concrete, while the compressive strength may increase with the addition of these recycled aggregates in spherical form.
- The use of waste aggregates considerably decreases the fresh and dry density of concrete regardless of the type of waste and the amount of substitution. Due to the unit weight, the concrete made by recycled aggregates is substantially lighter than concrete made by natural aggregates. The incorporation of different types of pozzolanic materials, such as silica fume, FA, glass powder, and blast furnace slag, increases the density of concrete and improves the microstructure of the matrix. As a result, the strength and mechanical properties of the concrete are considerably improved.
- Brick, ceramic, glass and demolition aggregates can be used at up to 100% replacement in a concrete mix. However, plastic, tyre rubber and polystyrene aggregates cannot exceed 20% replacement in a concrete mix.
- GPC is a relatively inexpensive material to produce since the essential component is an industrial by-product. The properties of GPC depend on the chemical product, the composition of the binders, the type of used admixture, the curing conditions, the pouring processes, and the environmental conditions. GPC has all the elements of de-

sirable mechanical and structural properties that make it an ideal choice for industrial construction. Generally, GPC elements show more durability than traditional repair materials in thermal resistance and under acid sulphate attack.

- The mixing of FA with other pozzolanic materials such as silica fume, blast furnace slag, or glass powder improves the strength of the concrete, and allows the use of other much finer by-products with FA, each giving its advantage. In addition, the use of both by-products also offers environmental benefits that help decrease the use of Portland cement while improving the properties of concrete.
- The mechanical properties of concrete containing recycled materials decrease due to the increased surface area of the waste, and its irregular shape results in rigid concrete that is difficult to handle.
- The unit weight values of concrete containing waste are lower than those of ordinary concrete. This decrease in weight is due to the nature of the waste used, which makes the concrete less dense and less resistant compared to conventional concrete.
- The increase in Na_2SiO_3 : NaOH ratio, fly ash: blast furnace slag ratio, or silica fume or glass powder, the hardening at very high temperature, and the temperature application time, affect the setting time, the end-of-setting time, and the physical and mechanical properties of the GPC.
- Recycled aggregate concrete is a clean product obtained from industrial waste as a more environmentally friendly building material. Concrete made from mineral additives has many important characteristics; it does not produce harmful greenhouse gas emissions, hardening periods between 3 and 8 h can produce concretes with excellent strength and high-performance durability in an aggressive environment, and cost-effectiveness and environmental friendliness make it a potential sustainable material in the construction industry.

Further research must be conducted on the application recommendations of waste-based concrete. Other properties, such as sound attenuation, vibration control, thermal insulation, heat release upon hydration, shrinkage, creep, fatigue resistance, fire resistance, and environmental impact, must be considered for the complete evaluation of waste concrete. For well understanding of the mechanical behaviour of GPC, the microstructure/nanostructure and chemical reaction of geopolymers should be studied. More creep tests on different designs and mixing conditions of GPC are needed to expand the creep database.

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