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Review

A Mini Review on Properties of Portland Cement Concrete with Geopolymer Materials as Partial or Entire Replacement

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Abstract: The main aim of this paper is to review recent studies over the past 10 years investigating the influencing factors for improving the mechanical properties of concrete. This focuses on concrete comprising of pozzolanic materials, partially or entirely replacing ordinary Portland cement, in the concrete mixture. Firstly, the effectiveness of main factors such as temperature, water to solid (W/S) ratio, and alkaline solution ratio was briefly discussed. Next, the effects of significant factors such as different superplasticizer and alkaline solutions and combinative materials on the improvement of concrete workability were reviewed and compared. Eventually, other concrete properties such as water absorption and durability were discussed in the last section. After reviewing all types of concrete additives, including mineral or chemical materials, the influence of these admixtures under different laboratory conditions were highlighted to objectively evaluate the benefits of each factor. As a whole, the significant reasons of such experimental tests arising from the usage of these materials, in accordance with the laboratory results obtained from these investigations, are discussed.

Keywords: fly ash; geopolymer concrete; Portland cement; pozzolanic materials; superplasticizers

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1. Introduction

Considering the high consumption of concrete and the increasing necessity for cement production, high attention to the environmental degradation effects of this substance is needed [1,2]. These effects include 7% of CO_2 emission and the considerable consumption of energy such as electricity and fossil fuels. Hence the provision of alternative products in order to move towards sustainable development is essential. Therefore, the use of an eco-friendly concrete enables the reduction of consumption of ordinary Portland cement (OPC) with activated pozzolanic binders as a replacement, leading to lower emission of CO_2 in the atmosphere [3].

Geopolymers are in the family of mineral polymers, in which their chemical combinations are similar to zeolite materials, whereas their microscopic structure is amorphous rather than crystalline. The use of polymers such as concrete adhesives result in the production of geopolymer concrete (GPC) that can be a suitable substitute for OPC [4,5].

Regarding other beneficial aspects of GPC, numerous studies have been presented in favor of usage of GPC as an alternative for Portland cement concrete (PCC). For instance, Albitar et al. [6] presented the arguments to emphasize that durability of GPC is typically superior to that of PCC under similar curing condition, and fly ash (FA) is more chemically stable compared to conventional concrete. Additionally, Liew et al. [7] advocated that the utilization of green concrete provides numerous environmental, technical and economic benefits such as high strength, increased durability, improved workability, reduced permeability, controlled bleeding, superior resistance to acid attack, and reduction of plastic shrinkage cracking. These properties promote faster concrete production, reduction of curing waiting time, reduction of construction costs, early project completion, reduction of maintenance costs, and increased service life of construction projects. The recent study by Li et al. [8] concluded that the green GPC made with a binder of ground granulated blast-furnace slag (GGBS), desulfurization gypsum (DG) and electric arc furnace reducing slag (EAFRS) as cementitious materials and W/S ratio of 0.32 have a high compressive strength, over 50 MPa at 28 days of age. The hydration mechanism of the GGBS-DG-EAFRS system was experimentally investigated utilizing isothermal calorimetry (IC), thermogravimetric analysis (TGA), X-ray diffraction (XRD), and scanning electron microscopy equipped with energy dispersive X-ray spectroscopy (SEM-EDX), which demonstrated that the combination of GGBS-DG-EAFRS pastes as the specific type of geopolymer materials have significantly lower hydration heat in comparison with OPC. GGBS was activated through $Ca(OH)_2$, available in EAFRS and gypsum from DG [8].

Most experimental programs have been carried out in this case, nevertheless what needs to be considered in the present research is the evaluation of the comparative study between GPC and PCC, as well as the assessment of the various combination of GPC, which is based on three central issues:

- The effects of chemical admixtures such as silicon dioxide (SiO_2) powder on the improvement of physical and mechanical properties of this concrete type.
- The efficiency of chemical activators at different molar concentrations for the performance of GPC concrete using various ratios of these solutions in the mix design.
- The effect of FA and other pozzolanic admixtures such as GPC content in concrete mix design in order to achieve optimal combination and the optimum ratio of alkaline activator.

In this paper, the mechanical properties of concrete are evaluated in the state of compressive and tensile, as well as flexural, separately. In fact, the mechanical behavior of concrete depends on various factors, including its internal structure, properties of cement gel, aggregate and the components used in the concrete production process. Therefore, the main aim of this review paper is to provide an integrated, synthesized overview of the current state of the innovation in the case of concrete mixtures with the involvement of pozzolanic (geopolymer) materials for improving concrete properties. For this purpose, the experimental works previously carried out in this field are assessed to reach a conclusion.

2. Concrete Additives

Admixtures are added to concrete to provide the desired properties in fresh and hardened concrete. Indeed, the utilization of additives in concrete mix design can help to enhance the concrete properties, such as compressive strength and durability, due to the reduction of water to cement ratio. Chemical admixtures such as superplasticizers (SPs) are the major additives added to the concrete mixture at around 2–3% of cement weight, whereas mineral admixtures are the powders that are added to concrete at 10–20% of cement weight or even more to ameliorate durability, strength, and workability in concrete.

An acidic alkaline activator solution consists of an alkaline solution such as sodium hydroxide (NaOH) alone, or with a two combinative solution, including an alkaline hydroxide along with a silicate solution such as sodium silicate (Na_2SiO_3) or potassium silicate (K_2SiO_3) with specific mole and weight ratios. Studies indicate that the alkaline hydroxide type of MOH (where M is alkaline cation), and its concentration (molarity), as well as the ratios of two combinative solutions including weight ratio of M_2SiO_3/MOH or mole ratio of SiO_2/M_2O, have notable effects on chemical and mechanical properties and the durability of geo-polymer concrete [9,10]. The changes in the properties of GPC are not only attributed to the activator solution, but to the reactive amounts of Si and Al in the powder along with the number of water molecules and total mole ratios, such as H_2O/M_2O, M_2O/SiO_2, and SiO_2/Al_2O_3. These ratios have a conclusive effect on the formation of M-A-S-H polymer gel, where A is aluminum oxide, S is silica oxide and H is H_2O. As a result, a geopolymeric combination can be expressed with the formula ($nM_2O.Al_2O_3.xSiO_2.yH_2O$) [11–13].

As discussed briefly, in modern concrete technology a wide variety of mineral and chemical admixtures and chemical activators can be used extensively in the production of concrete, especially GPC concrete. The most significant goals in this regard are:

- Optimal economic use of this type of concrete in the construction industry
- Preserving the environment
- Workability improvement in fresh concrete
- Increasing compressive strength and durability of hardened concrete
- Reducing hydration temperature in concrete

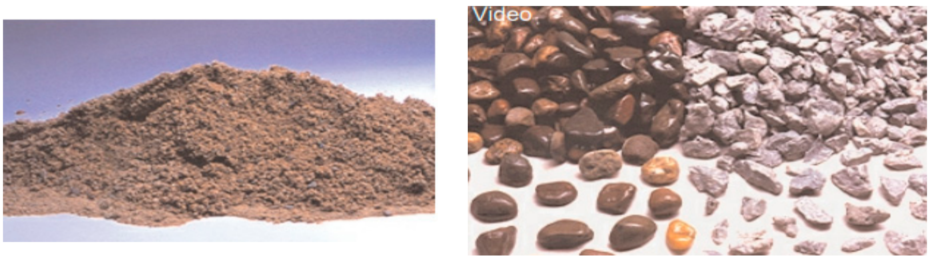
3. Specimen Preparation and Concrete Manufacturing Process

It is essential to point out that each laboratory programs discussed in this review paper utilized a specific standard (e.g., Australian standard, American Society for Testing and Materials (ASTM), British standard) for the preparation of concrete specimens. The number of combinative materials participating in concrete mix design have a notable role in the improvement of concrete properties, hence the limitations have been considered for utilizing the source materials of concrete types in a number of standards. For instance, the amount of silica in the case of ultra-high-performance concrete (UHPC), as the new generation of concrete with higher strength, should not exceed 11% based on German (DIN) standard. Therefore, in the laboratory program conducted by Winberg and Khosravani [14], the UHPC mixture was experimentally examined using an amount of only 10% microsilica in accordance with DIN EN 12390-3 and DIN EN 12390-5 [14,15].

In this part, the most common method typically utilized for preparing concrete specimens in all standards is briefly described as follows:

(A) coarse and fine aggregates along with PCC and pozzolanic admixtures such as FA were quantified before mixing. Fine aggregates (Figure 1a) [16] commonly consist of sand or crushed stone, including most particles with a size smaller than 5 mm (0.2 in). Coarse aggregates (Figure 1b) [16] consist of a combination of gravels or crushed stone with a size larger than 5 mm, which is between 9.5 mm and 37.5 mm based on ASTM standard [17].

(B) To make chemical solutions, sodium hydroxide (SH) pellets and sodium silicate (SS) powders were separately blended with water in the $Na_2SiO_3/NaOH$ ratio of 2.5 to produce alkaline liquid with different molarities. This liquid was provided 24 h before mixing day. The alkaline solutions should be mixed as it causes the polymerization to be more easily formed based on Davidovits [18]. Generally, the manufacturing process, which is approximately similar in all standards, can be categorized into three steps:



(a) (b)

Figure 1. (**a**) Fine aggregate (0–5 mm); (**b**) coarse aggregate (9.5–37.5 mm) [16].

Step 1: All solid materials were mixed around 3 min after quantifying by concrete mixer. The value used was considered based on the calculation of the number of specimens used in this part of laboratory work.

Step 2: The alkaline solutions previously prepared 24 h before blending materials were poured over the solid materials for the mixes containing diverse dosages of fly ash or other pozzolanic admixture as the replacement of Portland cement. Consequently, they were mixed together for approximately four minutes.

Step 3: Before casting fresh concrete, the workability was immediately measured through a slump test. Subsequently, the produced concrete was poured into the cube molds with the standard dimensions of 150 × 150 × 150 mm^3 to reduce the voids of concrete by compacting action on the vibrating table for 1–2 min. After this period, the specimens were exposed to the oven under the curing condition which was 110 °C, and the samples were removed from the oven after 24 h. Subsequently, theses specimens were kept at the usual temperature (room heat) between 14–17 °C for 4–5 h, and eventually the specimens were put in a water bath at a temperature of 21°–23 °C until commencing the compressive tests at 7, 28, and 90 days into this study.

As for the other concrete mixtures, the cube specimens were covered by a film to lessen water evaporation happening over the curing condition and were maintained in the molds for 24 h at room temperature (14–17 °C) to deter the drastic change of environment which can happen over this period. Consequently, the specimens were taken out from the molds and were kept in a water bath at a temperature of around 20 °C until the strength tests at 7, 28, and 90 days [15,19,20].

4. Mechanical Properties of Geopolymer Concrete

4.1. Influencing Factors on GPC Compressive Strength

The compressive strength of concrete, obtained by unidirectional loading on cubic or cylindrical cases, is called uniaxial compressive strength. If the compressive strength of concrete is measured in such a way that the specimen is under the compressive stresses in the orthogonal direction, this experimental test is known as biaxial compressive strength. These orthogonal compressive stresses will be able to enhance compressive strength by 27% in comparison to uniaxial strength. In this part, the role of effective factors such as alkaline solutions along with diverse laboratory conditions on the enhancement of GPC uniaxial compressive strength are evaluated. The following paragraphs attempt to demonstrate and support this hypothesis [21,22].

In research by Neupane et al. [23], two major sorts of powder-activated GPC binders and OPC had been used as binding material in order to evaluate the considerable differences in terms of compressive strength between GPC and OPC objectively. In this study, the compressive strength and drying shrinkage of different grades (40, 50, 65 and 80 MPa) for GPC and OPC concrete with different workability levels (normal-workable and super-workable) were carried out based on Australian standard 1379. The notable point is the fact that all the concrete specimens were cured under the standard laboratory curing (ambient) condition involving three main steps: Initially, the process of concrete mixing along with the casting of specimens was conducted at standard laboratory temperature (23 °C). Next, both OPC and GPC cylinders were kept in a laboratory room for 24 h. After that, the GPC cylinders were wrapped by plastic sheet as the effective factor for preventing the moisture loss from concrete and were maintained under 23 °C until commencing the test day. On the other hand, OPC cylinders were kept under the moist cured condition in lime-saturated water at 23 °C until testing in accordance with Australian standard-1012.8.1 [24]. Two types of chemical admixtures were added in OPC concrete as normal (WR) and high-range water reducers (HWR), respectively, whereas no water reducer or superplasticizer was used for GPC concrete of both workability levels. The laboratory findings indicated that GPC concrete needed considerably less water for the same workability and 28 days compressive strength compared to OPC. The production of GPC for both normal and super-workable states can be conducted without needing any chemical admixtures. The development of compressive strength in the medium grade (40, 50 MPa) was partly lower than that of OPC in this study.

In another attempt by Nindyawati et al. [25], fly ash as an environmental concrete containing high silicate and aluminate reacted with alkaline solution in order to produce alumina-silica gel, binding the aggregates for manufacturing GPC. The alkaline activator was prepared for GPC one day before utilization through mixing SH with the molarity of 10M, and subsequently the solution was blended with SS considering the ratio of

Na_2SiO_3(SS)/NaOH(SH) = 2 between two alkaline activators. The results from the cylinder test indicated that the compressive strength of GPC is typically higher than the conventional concrete (OPC). Indeed, the average cylinder compressive strength for both GPC and OPC concrete was 31.1 MPa and 24 MPa, respectively. It can be concluded that the compressive strength of GPC is 26.78% higher than that of OPC, as the previous studies explained [25].

The studies of Farhan et al. [26] also acknowledged that the tensile and the compressive strength of fly ash-based geopolymer (FAGP) were higher than those in OPC, however, the elasticity modulus subjected to FAGP in the compression and direct tension state was lower than that of OPC with the same compressive strength at 7 and 28 days. In recent investigations by Zhang et al. [27], the effect of temperature on the characteristic of GPC was well documented. In this experimental program, pull-out tests were employed on GPC specimens under ambient condition and after exposure to 100, 300, 500 and 700 °C. The alkaline-silicate activator with the desired SiO_2/K_2O molar ratio of 1 was provided one day before the experimental test. The results showed that GPC has similar or better bond properties compared to OPC at ambient temperature (300 °C) and beyond 300 °C, which shows that GPC is able to be a practical alternative to OPC, especially in the case of high temperature where the resistance against fire is one of the significant design considerations.

Most early studies, as well as current research, focus on the fact that the process of OPC production is attributed to pessimistic aspects on environments due to CO_2 emission as a primary greenhouse gas; hence, Luhar et al. [28] conducted the study to show that the development of rubberized geopolymer concrete (RGPC) along with the improvement of GPC strength and durability are two main exigencies to be considered in this study. The following constituents were considered for the GPC mix proportioning in this study, based on Taguchi method:

- Ratio of Alkaline activator to fly ash by mass: 0.4
- Ratio of SS to SH: 2.5
- Molarity of SH solution: 14 M
- Additive dosage: 2%

This research indicated the assessment of strength studies, such as compressive strength, split tensile strength, flexural strength, and elasticity modules in addition to durability parameters like abrasion resistance of fly ash-based GPC, and subsequently compared the experimental observation with rubberized OPC concrete (ROPC), in which the compression of experimental outcomes proved that the RGPC has notable superiority in comparison with ROPC. This has also been explored in another investigation by Kwasny et al. [29], where the increase of parameters such as water to solid (W/S) ratio had a considerable factor in the reduction of compressive strength in geopolymer mortars (GPMs) in contrast with Portland cement mortars (PCMs). The W/S ratio was considered from 0.275 to 0.6 by keeping the constant value of paste or free water content (Figure 2). All constituent material in this investigation was placed in a dry location at typical temperature (20 ± 2 °C), except for mixing water which was maintained at 17 ± 1 °C. The comparison of GPMs and PCMs showed that the lower content of free water is needed for GPMs and rapid strength increments, as well as shorter setting time in this concrete mix proportion. Further details in relation to abovementioned research are summarized in Table 1.

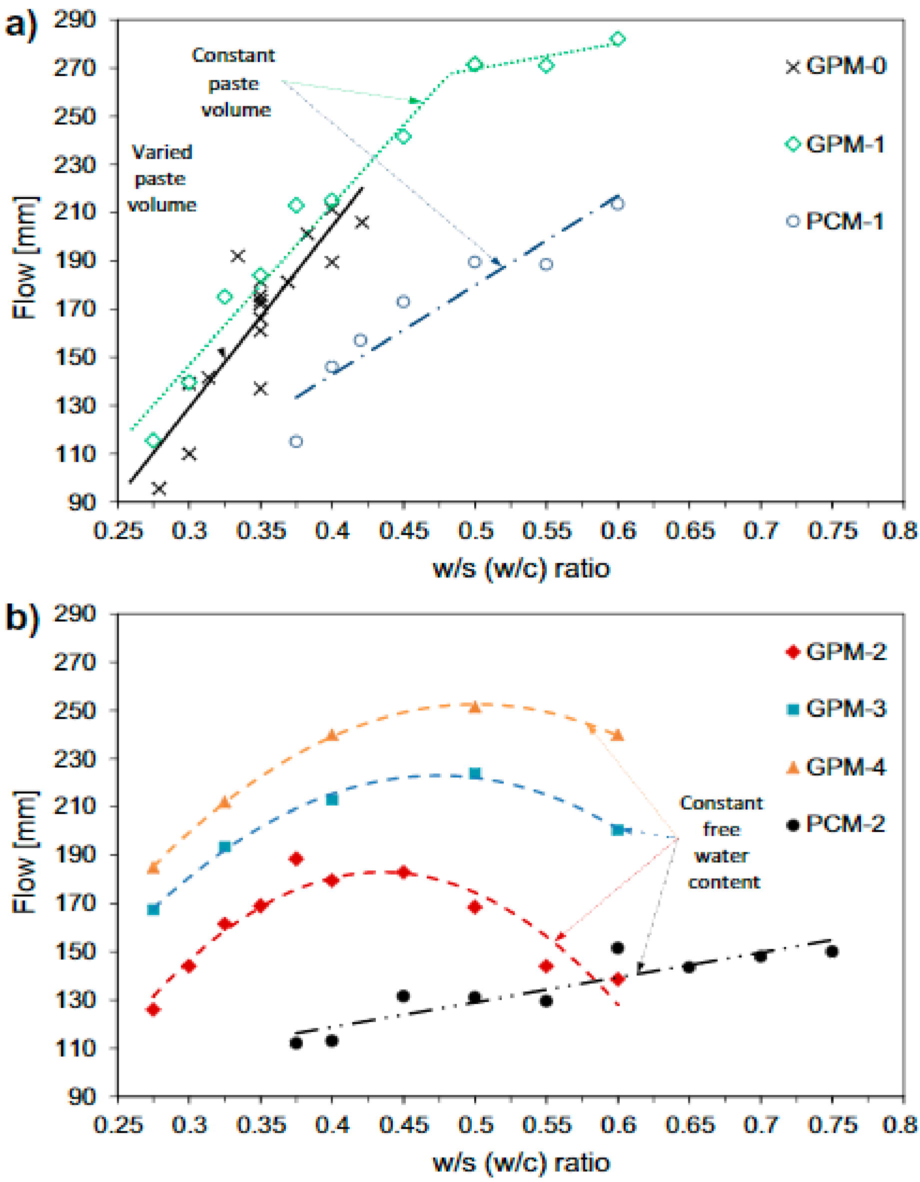


Figure 2. The effectiveness of w/s ratio and w/c ratio on the flow of geopolymer mortars (GPM) and Portland cement mortars (PCM) mixes: (**a**) the constant past value; (**b**) the constant free water content [29].

Table 1. Geopolymer concrete (GPC) compressive strength and influential factors on the improvement of GPC strength.

Author	Aim	Results
Neupane et al. [23]	Investigation on compressive strength improvement of ambient cured GPC concrete compared to OPC concrete	GPC and OPC concretes of four different grades and workability levels at standard curing (ambient) conditions (23 °C) were experimentally studied. The compressive strength of GPC at early ages (1-3 days) was significantly lower than that of OPC. From 28 to 90 days, the growth of the strength enhancement in GPC was considerably higher than that of OPC.
Ninyawati et al. [25]	Evaluating the compressive strength for both ordinary and GPC concrete with cylinder specimens	GPC cylinder specimens with the SH concentration of 10 M and the ratio of SS/SH = 2.5 had 26.78% higher compressive strength than ordinary concrete cylinders.

Table 1. *Cont.*

Author	Aim	Results
Farhan et al. [26]	Investigation of engineering properties of fly ash-based GPC with different SH concentrations compared to OPC	The compressive strength of GPC with the SH concentration values of 14M and 12M were higher than those of OPC specimens at 7 and 28 days. The elasticity modules of GPC under uniaxial tension were around 7–8% less than that of OPC. The elasticity modules of GPC under compression were about 12–13% less than that of OPC.
Zhang et al. [27]	The comparison of temperature effect on compressive strength of GPC and OPC	The degradation in concrete strength was seen for both GPC and OPC beyond 300 °C. The relatively better bond properties were found for GPC specimens with the SiO_2/K_2O molar ratio of 1 compared to the similar levels of compressive strength for OPC.
Luhar et al. [28]	Evaluating the strength of RGPC compared to ROPC based on percentage of waste rubber fibers	The compressive strength in both RGPC and ROPC was decreased while increasing the percentage of waste rubber fibers at all ages. The elasticity modules of RGPC and ROPC was sharply decreased by 36.34% and 34.54%, respectively, while increasing fiber content from 0 to 30%.
Kwasny et al. [29]	The effect of W/S ratio on behavior of GPMs and PCMs	The increment of W/S ratio led to the decrement of compressive strength at each age (1, 7, 28 days). GPMs mixes had very rapid and higher strength, approximately three times that of equivalent PCMs, achieving 55–66% of their strength at 28 days in the first 24 h after mixing.

4.2. Factors on Workability of GPC and PCC

One of the most significant drawbacks of geopolymer concrete (GPC) is low workability due to high viscosity and cohesion in this type of concrete. Diverse methods are employed to improve concrete workability. The simplest method to increase the workability of fresh concrete is adding water and raising the water-cement ratio. Alternatively, keeping the ratio of water to cement constantly in a controlled range and appending plasticizer or superplasticizer to concrete content can be considered the best method in terms of the improvement of workability in this kind of concrete.

GPC workability as an important topic of the literature review needs to be assessed in this section. In a study by Xie and Kayali [30], the effect of superplasticizer (SP) for the workability enhancement of fly ash-based GPC was evaluated using a slump test and mini flow results, as well as rheology behavior. The results indicated that the effect of both superplasticizers in GPC was remarkably less beneficial than that in OPC. Their efficacy on fly ash was distinct in each category. The effectiveness of Polycarboxylate (PC) on class C was more considerable compared to class F fly ash, which is attributed to high-value calcium ion participating in the content of class C fly ash.

As for another type of superplasticizer, Naphthalene, investigated in this study, no significant difference associated with its effect on two types of fly ash was observed, however, the effect of this type of superplasticizer was slightly better than that of PC while testing on class F type. In addition to the results mentioned above, the performance of these two superplasticizers respective to other experimental factors was examined in other studies. Nematollahi and Sanjayan [10] have expressed a similar view in terms of concrete workability for GPC. In this study, naphthalene, melamine, and modified Polycarboxylate was investigated for increasing workability and strength in class F fly ash GPC paste which was activated by two different activators composed of 8 M sodium hydroxide solution along with a multi-compound activator, including 8 M sodium hydroxide and sodium silicate with SiO_2/Na_2O ratio of 2. The laboratory results demonstrated that these types of activators and superplasticizers are effective factors on workability and strength of fly ash-based GPC.

In Nath and Sarker [31], the efficiency of GPC under different curing conditions was explored in order to evaluate the setting and workability of fly ash GPC, as well as concrete strength at the early age. The laboratory results showed that the test specimens cured in an ambient temperature had a higher proportion for desirable workability and compressive strength compared to heat curing. The inclusion of class F fly ash in the content of this concrete mixture led to a significant increase in the value of compressive strength compared to that of OPC.

In an experimental program by Almuwbber et al. [32], the interaction of mineral and chemical admixture with different cements for self-compacting concrete (SCC) was investigated. Diverse characteristics in the cement combination was sufficient to influence the properties of SCC. The laboratory observation indicated that the compatibility of cement and admixtures are deeply attributed to molarity ratio of chemical combinations, such as C_3A, C_2S/C_3S, participating in concrete structure and specific surface area available in cement, as well as the superplasticizer type utilized in this case. Similarly, in another attempt, Alrefaei et al. [33] presented the investigations to point out the effect of various SPs involving naphthalene (N), melamine (M) and polycarboxylate (PC) on workability, and compressive strength of the concrete mixtures consisted of alkaline-activated material (AAM), such as FA, which was considered a sustainable contender for OPC. The results showed that SP type along with water/precursor (W/P) ratio were two dominate factors affecting on the improvement of compressive strength concrete workability.

As for the combinative usage of sustainable material in concrete production, Xie et al. [34] conducted a laboratory program to investigate the efficiency of combined ingredients such as ground granulated blast furnace slag (GGBS) and fly ash combination, considering water to binder (W/B) ratio on the concrete properties including workability (slump) and compressive strength in the case of alkali activated geopolymeric recycled aggregate concrete (GRAC). The results showed that GGBS and FA are significantly responsible for the workability and mechanical properties, respectively. GGBS/FA ratio has a remarkable role on the fresh and hardened GARC properties. More details are summarized regarding the discussed literature reviews in Table 2.

Table 2. Effective factors on the improvement of GPC properties and workability.

Author	Aim	Results
Xie and Kayali [30]	Effect of superplasticizer on workability enhancement of Class F and Class C	The used superplasticizer was less effective in comparison with its behavior in OPC mixture. Based on workability results, PC had the effective role for Class C compared to Class F. Naphthalene had a similar effect for both fly ash types.
Nematollahi and Sanjayan [10]	Effect of different superplasticizers and activator combinations on workability and strength	The mixture containing activated fly ash with multi-compound activator ($Na_2SiO_3/NaOH = 2.5$) had higher workability and strength compared to NaOH-activated fly ash. In activated fly ash by NaOH solution (8M), Naphthalene SP led to an increase of 136% in workability with no drawback effect on concrete strength.
Nath and Sarker [31]	The effect of ambient temperature (20–23°C) on improvement of GPC workability and compressive strength.	Workability was enhanced when alkaline solution was increased along with the reduction in compressive strength. SS/SH ratio of 2.5 indicated less workability comparable to those with 1.5 and 2.
Almuwbber et al. [32]	The effect of variation in cement characteristics on SCC workability and strength	The slump values of cement were commonly enhanced while adding FA up to certain extent and then remained constant. The decrement in compressive strength was observed while increasing FA concentration regardless of superplasticizer dosage.

Table 2. *Cont.*

Author	Aim	Results
Alrefaei et al. [33]	The effect of different SPs on Alkali Activated Pastes	PC was effective for relatively high W/P ratio (≥0.36). In contrast, N had better performance in the case of low W/P ratio in AAMs containing Na_2SiO_3. Reducing water content in AAMs with Na_2SiO_3 had negligible effect on compressive strength.
Xie et al. [34]	The effect of combinative material (GGBS, FA) on workability and concrete strength	GGBS dosage lower than 25% had a slight effect on the workability and strength of GRAC. The optimal mechanical performance and workability in terms of GRAC was obtained by using 50% FA and 50% GRAC with W/B ratio = 0.5.

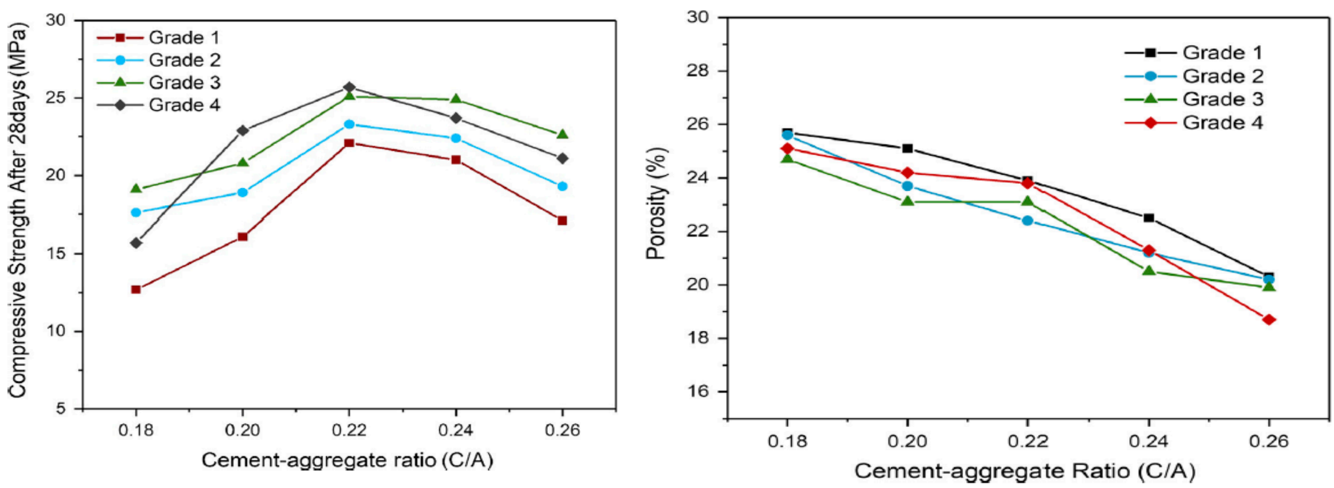
4.3. Concurrent Efficiency of Fly Ash and OPC on Mechanical Properties

The use of FA in concrete mixtures has always been of interest to researchers for decades due to its ability to improve concrete durability and decrease CO_2 emissions. Hence, a large number of investigations were carried out to explore the role of FA in cement hydration and pozzolanic mechanism. Although FA does not participate in the early hydration stage, it can help to increase the cement hydration rate due to a filler effect promoting cement hydration. This occurs through seeding effects by preparing additional nucleation sites for hydration productions on filler surfaces, enhancing the efficient W/C ratio to ensure adequate space for the growth of hydration product, which results in the improvement of mechanical properties of this concrete type [35,36]. Therefore, the achievement of this optimal combinative concrete comprised of geopolymeric and Portland cementitious materials is one of the main motivations of current investigations conducted in this field.

A more comprehensive description can be found in the recent studies related to this topic. For instance, in research carried out by Mehta and Siddique [37], it was shown that the compressive strength can be enhanced with replacing the mix design of conventional concrete (OPC) with low calcium fly ash. Other observations also demonstrated that co-existence of hydrated products along with the structure of geopolymeric alumina silicate polymer can improve some mechanical properties, such as water absorption and porosity in this concrete mixture type. In an investigation conducted by Moon et al. [38], the effect of physicochemical properties of fly ash on compressive strength of concrete with a high amount of fly ash was experimentally examined from another distinctive aspect. In this research, 50% of ordinary Portland cement weight was blended as the replacement of fly ash in order to measure the compressive strength of this mix design type containing a high value of fly ash and OPC.

Fly ash is widely used as a complementary cementitious material which has been utilized in all kinds of concrete structures over a few decades due to its potential to enhance concrete durability and diminish CO_2 emissions. Therefore, many investigations have been carried out to distinguish the role of fly ash in hydration reactions and pozzolanic mechanisms in cement. The achieved findings from these studies indicate that fly ash would not react with water in the initial hydration stage, but it enables the cement to precipitate the rate of its hydration due to a filler effect in which the cement hydration can be accelerated by providing extra nucleation places for hydration products on filler surface and congruently leads to the enhancement of the water to cement ratio, confirming adequate space for the enhancement of hydration product. In a study by Ghafoori et al. [39], the effect of class F fly ash as the percentage of cement weight on sulphate resistance of type V Portland cement was investigated. The amount of fly ash considered was 15%, 20%, 25%, and 30% by cement weight for this experimental test. The laboratory observations exhibited that replacement of one portion of Portland cement with class F Fly ash led to the improvement of concrete resistance against sulphate attack, however this increment in concrete resistance was not as much as anticipated for class F fly ash.

Regarding the porosity of PCC, this concrete property is typically in the range of 15–25%, which is a larger amount than the concrete with higher density. In fact, the high porosity can lead to structural and environmental defects, especially in the case of concrete strength [40]. Therefore, Wang et al. [40] firstly presented the comprehensive experimental investigation in terms of the effect of material proportion, such as cement–aggregate ratio by mass (C/A) on porosity and determination of optimum value for PCC compressive strength. The second stage was the choice of FA as supplementary cementitious material in order to replace PP at the optimum C/A ratio determined in the previous step. Experimental results showed that C/A and FA percentage as PP replacement have considerable influence on the concrete properties (Figure 3).



(**a**) (**b**)

Figure 3. The relationship between: (**a**) compressive strength after 28 days and cement–aggregate ratio by mass (C/A) ratio; (**b**) concrete porosity and C/A ratio [40].

As for the mix design of geopolymer paste (GPP), the effects of ground granulated blast furnace slag (GGBFS) content along with sodium silicate solution to sodium hydroxide solution (SS/SH) mass ratio and additional water to binder (Aw/Bi) mass ratio on the compressive strength, setting time and workability of GPPs were experimentally investigated in a study by Hadi et al. [41], to conduct GPC tests based on the optimum mix design of GPP previously obtained in the first stage of this study. It was shown that GPC properties were relatively better than those of OPC concrete (Figures 4 and 5).

Having reviewed the improvement of compressive strength and workability of GPCs, other concrete properties affected by this additive material were considered as well. Recently, the development of durable cementitious material is the most important issue, which is related to sulphate attacks and acid attacks, as well as chloride penetration. Therefore, concrete durability improvement is essential in order to reduce concrete permeability by utilizing laboratory methods, in which a superplasticizer is one of the methods which has the potential to improve workability resulting in porosity reduction [42]. Hence, the concurrent effect of pozzolanic and superplasticizer on strength, workability and concrete durability as three significant aspects in the construction field was experimentally studied in the program conducted by Sathyan et al. [42]. It was found that sorptivity value of the concrete mixes blended with SPs was lower than that of control mixes without SP. Durability improvement was seen for concrete specimens containing SP compared to those without SP. More details regarding these prior experimental studies mentioned above are presented in Table 3.

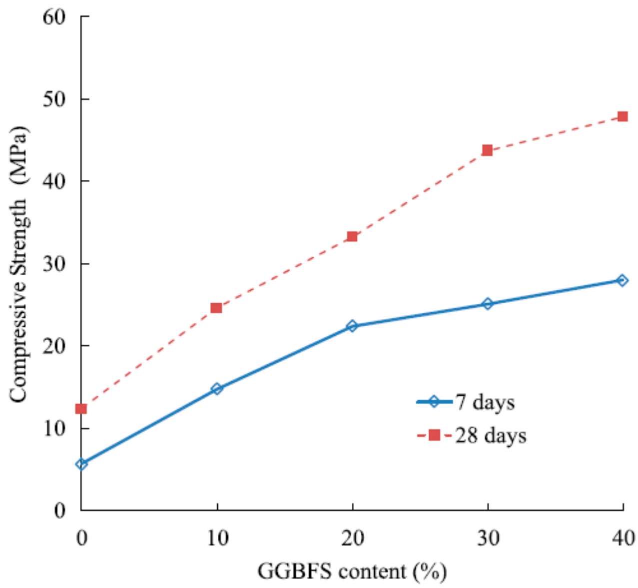


Figure 4. Effect of ground granulated blast furnace slag (GGBFS) content on the compressive strength of geopolymer pastes [41].

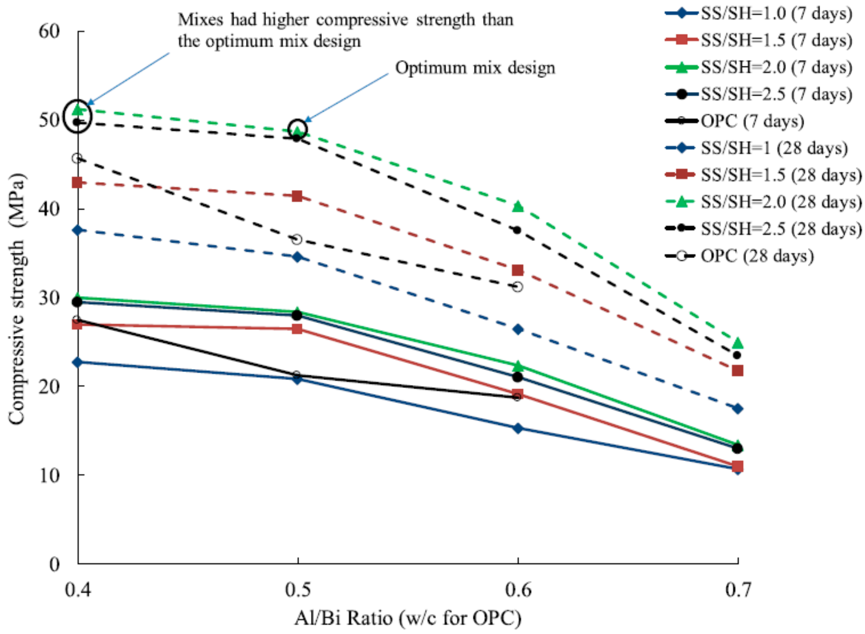


Figure 5. Effect of alkaline solution to binder (Al/Bi) ratio and sodium silicate solution to sodium hydroxide solution (SS/SH) ratio on compressive strength of geopolymer paste compared to conventional concrete (OPC) [41].

Table 3. Effect of combined concrete with diverse Portland cements and fly ash on improvement of concrete mechanical and permeation properties.

Author	Aim	Results
Mehta and Sidique [37]	The effect of low calcium fly ash as partial replacement on compressive strength, water absorption and porosity	An upward trend with the inclusion of fly ash as 20% cement weight was observed at all ages. The increment of fly ash up to 20% resulted in a reduction in permeation properties, such as water absorption. The increase of more than 20% FA marginally reduced the strength and permeation properties.

Table 3. *Cont.*

Author	Aim	Results
Moon et al. [38]	The effect of fly ash on strength of high-volume fly ash mortar	The compressive strength of fly ash mortar (50% FA) was significantly increased, comparable to that of OPC mortar at 7 days. The incremental trend of concrete strength was considerably observed up to 91 days, and after this age the rate of increase was lower compared to 91 days and other early ages.
Ghafoori et. al. [39]	The effect of class F fly ash on compressive strength and sulfate resistance of type V Portland cement	In spite of the effective role of fly ash partially replaced with type V Portland cement on improvement of sulfate resistance, this result was not as much as expected as it hardly went beyond 15% in the best performance. Overall, 15%, 20% and 25% fly ash had the lowest expansion and highest strength of 333 and 416kg/m^3, respectively.
Wang et al. [40]	Mechanical properties and environmental impacts of pervious concrete containing fly ash based on the C/A ratio	C/A has a significant influence on the properties of pervious concrete. C/A ratio in the range of 0.20–0.24 and 20% fly ash were suggested to produce high-strength pervious concrete and porosity.
Hadi et al. [41]	The effect of optimum mix design of GPP on GPC properties	The inclusion of 40% GGBFS in GPP content was found as an optimum mix design. GPC properties based on optimum mix design of GPP were also better compared to OPC properties.
Sathyan et al. [42]	The comparison of SP effect on GPC and OPC	SP has the key role in the reduction of permeability value. Durability improvement was seen for concrete specimens containing SP compared to those without SP.

4.4. Efficiency of Alkaline Solution and Ambient Condition on GPC

In this part, based on the investigations carried out in the previous sections regarding the efficiency of inorganic polymers such as fly ash with considerable amounts of silicon and aluminum on the improvement of concrete properties, especially compressive strength, it is urgent to take a step forward. Other key factors including activator solution ratio and the ambient conditions of concrete are also essential to be considered. Therefore, other experimental attempts carried out by other researchers have been reviewed here to open the new lines of inquiry for this topic. There have been numerous studies to assess the improvement of GPC mechanical properties affected by various ratios of alkaline solution used in this concrete type.

Mishra et al. [43] also explained that alkaline-activated solutions, for instance NaOH, have a main role in the improvement of compressive strength for GPC concrete. This research was centralized on the fly ash with diverse NaOH concentrations as 8M, 12M, 16M and different curing conditions such as 24, 48, 72 h. The laboratory results of this investigation clearly showed that there was an increase in compressive strength with an increase in NaOH concentration. The compressive strength test was performed with the use of three cubes for each set at the ages of 7 and 28 days. Therefore, 7 days compressive strength can be increased with an enhancement in the concentration of NaOH from 8M to 16M for the same curing time. Furthermore, the increase of compressive strength can be observed in the curing time from 24 h to 48 h, however, no significant alteration in compressive strength was observed over the curing time from 48 to 72 h.

In the experimental program by Bhikshma et al. [44], it was proven that GPC typically has high strength, low creep and sufficient resistance to sulphate attacks, as well as acceptable acid resistance. The focus of this investigation was on the evaluation of GPC mechanical properties, such as GPC compressive strength at different ages and concrete workability utilizing slump test. The results of this experimental program supported the hypothesis that the GPC compressive strength was enhanced while increasing the alkaline solution to fly ash ratio up to 0.5 so that the compressive strength of the mix design involved by this value of chemical ratio has the highest compressive strength among all mix designs used for this research. In the case of GPC workability, the slump test indicated that GPC in the fresh state has high viscosity and is workable enough without adding extra water. This result was achieved by the GPC concrete with a high density of 2415 kg/m^3 after blending concrete materials.

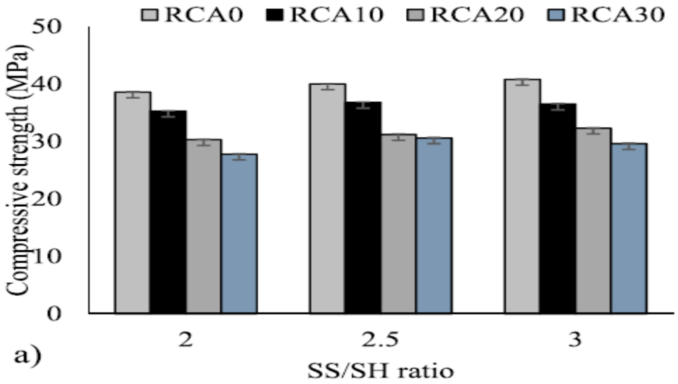
Shehab et al. [45] presented a wide laboratory schedule in order to obtain the achievements on the mechanical properties of GPC replacing 0%, 25%, 50%, 75%, 100% fly ash to OPC in the proposed mix design of this study. Two solutions of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_2) were employed in this program as an activator solution due to cement hydration. The temperature of 60°C for the curing time of 48 h was considered to achieve the optimum strength desired in this test. The significant scope of this study was to check the mechanical properties of GPC as the replacement of conventional concrete using different activator solution ratios and other experimental conditions.

For the reason that some factors such as curing period, alkaline solution composition and diverse binder content may be effective on the properties of natural pozzolan-based alkali-activated concrete (ACC), Ibrahim et al. [46] performed a laboratory program by varying the weight ratio of sodium silicate to sodium hydroxide (SS/SH) from 2.0 to 2.75 and various binder content between 350 kg/m^3 and 450 kg/m^3. In this study, a number of concrete properties such as setting time in alkali-activated pastes, concrete workability and compressive strength were examined. In the case of compressive strength, the specimens for 0.5, 1, 3, 7, 14, and 28 days kept in an oven at 60°C were considered for this investigation. The results showed that alkaline solution activator along with binder content had major effects on the enhancement of concrete strength at the early ages, such as three days and seven days, and this trend was marginally decreased after seven days.

In another experimental program, Aliabdo et al. [47] carried out a laboratory program about the effectiveness of water addition and other chemical desolations incorporated in the concrete content, for instance plasticizer and alkaline solution, on the performance of fly ash-based geopolymer concrete. In this research, concrete properties investigated in terms of fly ash-based GPC were workability, compressive strength, modulus of elasticity, water absorption and porosity. The obtained results from this investigation generally demonstrated that the enhancement of the water amount resulted in the increment of workability, however other GPC properties, especially compressive strength, were slightly reduced by this experimental methodology. These observations proved that the increase of plasticizer up to a certain amount had a significant role in concrete properties due to the improvement of workability in this concrete type. It is necessary to point out that alkaline solution to fly ash ratio and the optimum molarity of sodium hydroxide significantly influenced the concrete properties.

In the case of using other alkaline solution ratios and concrete composite mixes, Ishwarya et al. [48] carried out a microstructural investigation to analyze the effect of Sodium Carbonate-Na_2CO_3 (SC) to Sodium silicate-Na_2SiO_3 (SS) ratio using XRF, XRD and FT-IR techniques. The composite pastes involving FA and slag GPP were considered in this study. The results obtained from this rheological study showed that composite pastes were very stiff, but by adding slag in its yield, stress was approximately twice as high as the concrete mix with only FA.

As for GPC composed of metakaolin (MK) as an aluminosilicate source along with recycled concrete aggregate (RCA) as a partial alternative of natural aggregate, Koushbaghi et al. [49] conducted a microstructural analysis to determine the effects of SS/SH ratio and RCA in diverse dosages on mechanical properties and GPC durability via scanning electron microscopic (SEM). Test results indicated that GPC compressive strength developed with an enhanced SS/SH ratio (Figure 6). Further details of all the abovementioned investigations are presented in Table 4.



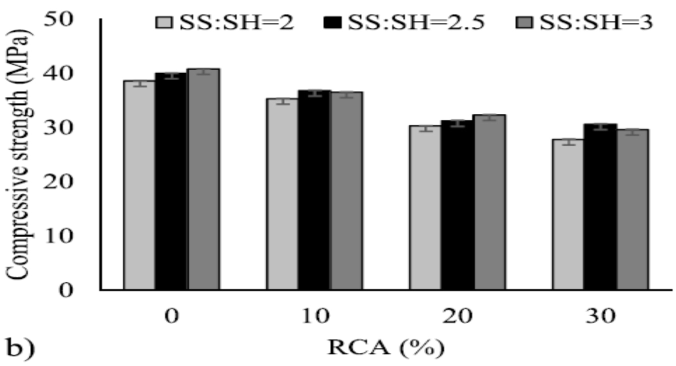


Figure 6. Effect of (**a**) SS/SH ratio; (**b**) recycled concrete aggregate (RCA) replacement on the compressive strength [49].

Table 4. Effect of liquid additives (water-alkaline solution plasticizer) on GPC.

Author	Aim	Results
Mishra et al. [43]	The efficacy of NaOH on the improvement of GPC compressive strength	At 7 and 28 days, the maximum compressive strength was increased while increasing the NaOH molarity from 8M to 16M, as well as the curing time from 24 to 48 h; however, no significant change was seen from 48 to 72 h curing time.
Bhikshma et al. [44]	The efficiency of alkaline solution on compressive strength of GPC	GPC concrete with the compressive strength of 30MPa could occur by adopting an alkaline solution to fly ash ratio of 0.50, which was the highest amount achieved.
Shehab et al. [45]	The effect of alkaline solution on the mechanical properties of GPC and its behavior.	The highest value of mechanical properties such as compressive, tensile, flexural strength at 28 days was at a 50% cement replacement ratio. Compressive strength with material content of 350 kg/m^3 and alkaline solution ratio of 0.55 was the highest value.
Ibrahim et al. [46]	The effect of alkaline solution, binder content and curing time	Workability of fresh concrete was attributed to water/solids ratio in the mixture. The highest value of compressive strength was recorded for the mixture with binder content of 400 kg/m^3, SS/SH ratio of 2.5 and 7-day curing.
Aliabdo et al. [47]	The effect of water addition, plasticizer and alkaline solution constitution	The increment of additional water up to 30 kg/m^3 enhanced the workability of fly ash up to 200%. GPC workability was increased up to 115%. A slight increase in water absorption and porosity and decrease in compressive strength and elasticity modulus were observed while increasing alkaline solution content. The properties of GPC were improved by increasing NaOH molarity up to 16 M. The optimum ratio of NaOH /Na_2SiO_3 was 0.4.

Table 4. *Cont.*

Author	Aim	Results
Ishwarya et al. [48]	The effect of SC/SS dosage on the strength of FA/ slag GPP	The increment of slag content and activator dosage caused the increase of compressive strength. The increase of W/b ratio reduced compressive strength. The developed pastes with 30 wt % activator dosage along with 0.21 w/b ratio and FA/slag ratio of 2:1 produced mortar with 72 MPa compressive strength.
Koushkbaghi et al. [49]	The effect of SS/SH on mechanical and durability of GPC containing RCA.	The increase of SS/SH can improve GPC strength. The usage of RCA decreased GPC strength by up to 28%. The enhancement of SS/SH ratio can help to reduce the chloride ions permeability leading to the reduction of GPC absorption. SS/SH ratio of three showed higher density and less porosity compared to the lower ratios.

5. Discussion

A number of important outcomes of the experimental studies reviewed above are presented briefly.

In experimental tests, the 28-day compressive strength is typically examined at the laboratory, however, considering the acquired results from geopolymer compressive strength, it seems that there is a slight increase over the period from 28 to 90 days; hence it is deeply suggested that the compressive strength would be measured for this type of concrete at age of 90 days as well. Despite the slight increment in the compressive strength of GPC observed at 28 days, most of its compressive strength was developed at seven days due to heat curing accelerating the geopolymerization reaction, resulting in the increase of compressive strength.

Direct comparison of GPM and PCM mixes prepared with the same paste amount and two different classes (normal of 37.5 MPa and high of 60 MPa) exhibited that workable GPC mixes could be provided by minimum water value compared to PC mixes. Thus, GPCs have much shorter initial and final setting times than those obtained by PC, which causes GPCs to obtain very rapid enhancement for compressive strength which is 55–66% of their entire strength at 28 days in comparison with PCs which achieved 18–28% over this time period [29].

Fly ash class and superplasticizer type are the key factors in the improvement of workability for GPC. The type of activator, such as simple or multi-compound, has a notable role in the workability and the compressive strength of fly ash. The experimental test with multi-compound activator and the ratio of Na_2SiO_3/NaOH = 2.5 and has higher slump and compressive strength compared to fly ash activated by NaOH. With regard to the better performance of PC for FA class C (low silicate, high calcium), this phenomenon is probably due to the high dispersive capability that appeared in class C, which is strongly related to the presence of positively charged calcium cations leading to the stiffness reduction and fluidity enhancement in concrete mixes [34].

The specific reason that PC was the most effective SP in AAMs, especially where w/b is 0.4, could be due to the presence of several lateral chains on PC molecules causing steric repulsion improving the plasticizing effect of PC [50]. Besides the effect of N-based SP in workability, it can drastically decrease the alkaline activator to slage ratio resulting in notable improvements for compressive strength, provided that FA-based GPC is activated by only NaOH solution [10]. This can be justified due to the fact that N-based SP is the unique type of SP which is chemically compatible with NaOH solution [51].

According to the investigation by Mehta and Siddique [37], it is clear that the values of compressive strength at all ages were gradually increased due to OPC replacement by 20%, and exceeding that, this trend was reduced. Based on this study, the highest value of 66.81 MPa compressive strength was obtained for the specimens with 20% OPC at 365 days due to further reaction occurring between OPC and the use of alkaline solutions in this research. C-A-S-H and C-S-H were achieved as an additional hydrated product which has coexistence with N-A-S-H as additional phases [52–55]. The extra heat increased the effective curing temperature for polymerization and further enhanced the formation of N-A-S-H because of the exothermic nature of the hydration reaction. The additional calcium also accelerated hardening and dissolution by preparing extra nucleation sites. On the other hand, the enhancement of OPC beyond 20% led to an increase in calcium content and consequently, a reduction of silica and alumina values, which was due to high calcium amount and low silica and alumina in OPC. On the contrary, in the chemical combination of fly ash, less calcium and high amount of silica and alumina are available. Thus, this led to the lack of sufficient alumina and silica in order to produce N-A-S-H polymerization in this concrete mix design. Also, higher calcium increased the water demand for hydration, which was released from water-filled pores resulting in extra void spaces. Therefore, it can be concluded that the optimal amount of OPC that would be effective for the high compressive strength of this type of concrete is 20% based on the findings achieved in this research.

Based on the study by Moon et al. [38], it is known that the compressive strength is directly associated with porosity and water absorption. This means that an increase in compressive strength resulted in the reduction of porosity and water absorption up to 20% OPC, whereas there was a slight increase for the rate of water absorption and porosity while increasing the value of OPC by 30% in this attempt. Other obtained observations from the specimens at ages of 90 and 365 days are in accordance with the previous test (28 days). The main significant reason for this phenomenon is the fact that the addition of OPC co-existed with GPC products (N-A-S-H, C-A-S-H) due to the additional hydration products. This resulted in incremental concrete strength and the reduction of water absorption in a concurrent manner. As discussed above, there is a substantial increase in the compressive strength of concrete with the high amount of fly ash after seven days more than that of OPC due to pozzolanic reactions. The difference of approximately 10% can be seen in the mean values of compressive strength of fly ash.

Type V cement plays the main role in terms of the sulfate attack as it contains limited values of C_3A (tricalcium aluminate) and C_4AF participating in the process of chemical sulfate attack, however most companies are struggling to find a more comprehensive solution which resists against sulfate attack better than this type of cement. Some literature in recent years have proved that the use of fly ash, particularly low-calcium or class F, effectively enables an increase in concrete resistance against sulfate attacks [56–63]. However, the improvement of concrete resistance to sulfate attack by the use of class C fly ash containing a high value of calcium is suspected as the materials with rich lime have the ability to produce their own calcium hydration independently. Therefore, the concrete containing fly ash with a high value of calcium is to be exposed against sulfate attack. It also can be realized that class F fly ash is quite effective on the permeability reduction of concrete, however, the optimum percentage of fly ash as the major factor should be considered to obtain more appropriate results [39].

It was noted that a 50% cement replacement ratio has the highest value of mechanical properties such as compressive strength comparable to other concrete mixtures produced by the replacement ratio of 0%, 25%, 75%, and 100% [45]. Furthermore, "Does this cement replacement have similar effects on other concrete mixtures produced from other Portland types (Portland type 2)?" is arguably an important question to be investigated, however other significant factors such as binder materials and activator solution ratio can be considered towards a more profound understanding of the chemical solution role in different concrete mixtures in the near future.

Workability is typically attributed to liquid-to-solid ratio in most concrete mixtures such as natural pozzolan-based alkali-activated concrete. In laboratory schedule by Ibrahim et al. [46], very low slumps were measured for concrete mixtures composed of different binder content and alkaline material, which revealed a number of gaps and shortcoming in this case. Based on the outcomes of this research, it seems that the higher binder content is beneficial for the concrete mixtures containing the low ratio of water-to-solid compared to those with lower values of binder content and sufficient workability, which was achieved from the mixtures including high concrete binder in spite of the low ratio of water to solid.

Generally, the improvement of compressive strength in the concrete mixtures thoroughly consisted of pozzolanic additives (100% natural pozzolan) as the replacement of cement Portland is associated with the following factors:

- Binder content (fly ash quantity)
- Sodium silicate-to-sodium hydroxide (SS/SH) ratio
- Alkaline solution-to-binder ratio

However, the secondary parameters such as concrete age and ambient condition, for instance heating at 60 °C, need to be considered as well. It is urgent to point out that each of the abovementioned factors can be effective for increasing compressive strength in a certain value range and beyond that, affected negatively on concrete strength. For example, the highest compressive strength belongs to the concrete mixture involving 400 kg binder content and SS/SH ratio of 2.5 with the strength more than 36 MPa at 7 days, compared to that with the value of 450 kg binder content. Furthermore, it was observed that the strength related to the concrete specimens with SS/SH ratio of 2.75 was marginally enhanced while increasing binder content from 400 to 450 kg/m^3, suggesting that the higher binder concrete needs a higher ratio of SS/SH. In the case of specimens cured for 28 days, similar results were recorded by the incremental value of 100 kg/m^3 from 350 to 450 kg/m^3 for binder content in spite of a marginal enhancement in the compressive strength while increasing from 400 to 450 kg/m^3. This proved the previous assumption in terms of the appropriate range of materials incorporated in the concrete mixtures [46].

As for the effect of alkaline solution-to-binder ratio, the quantity of Si and Na ions in the chemical combination of this concrete type is one of the central factors affecting the value of compressive strength, proving that it is essential to create a balance between total alkaline materials and binder content. This assures that all materials including aluminosilicate (Al-Si) are used in the alkaline activation process remaining very minimum unreacted particles in the mixture [46]. Noticeably, it can be justified that the presence of Si with high consumption in alkaline solution content led to the formation of Si-O-Si, in which this phenomenon probably happened in the experimental program conducted by Ibrahim et al. [46] with alkaline material-to-binder ratio of 0.525.

It is essential to note that the presence of reactive Si in the process of alkali activation has an effective role in the development of compressive strength, particularly for a solution with highly alkaline content. Indeed, Si ions consumed in this chemical activation process led to the formation of Si-O-Si as polymeric chains, which is related to alkaline material-to-binder ratio. Further increases of alkaline material-to-binder ratio beyond the specific value, for instance, 0.500 in the study of Ibrahim et al. [46], can result in the negative effects on concrete strength. However, the role of SS/SH as the other portions of this phenomenon cannot be ignored as it is worth to point out that the increment of SS/SH is effective for increasing compressive strength, provided that sufficient Si ion is available for the chemical process. Otherwise, a decrease in strength can be seen while reducing binder content due to the increase of alkaline material-to-binder ratio resulting in the depletion of Si ions in the system [64].

In producing FA/slag as composite GPP, the use of SC as part activator instead of SH was able to be justified in terms of economic aspects as SC is cheaper in comparison with conventionally used SH. Additionally, slag inclusion in concrete content leads to further cost reduction due to the concurrent use of these two substances (SC and slag) in GPC mixes. Hence, utilizing the optimum dosage and source of alkaline solutions is highly attributed to control the final cost of concrete products. SC has this advantage to avoid high PH development which is very important in terms of safety issues [48].

6. Conclusions

In recent decades, the usage of pozzolanic cementitious materials as sustainable substitute of PPs is a central issue in which researchers are centralizing on the concrete properties, which have key roles in the improvement of concrete performance against environmental factors. Hence, it seems that concrete durability is the most significant concrete property to be considered initially in each investigation. Indeed, major durability issues are related to sulphate attack and acid attack chloride penetration. The reduction of concrete permeability in order to improve the durability of concrete is a significant method, which can be considered by adding SPs to reduce the W/C ratio, leading to the reduction of concrete porosity. On the other hand, this decrement in the amount of concrete permeability also leads to the enhancement of concrete compressive strength, implying its dual efficiency on the development of concrete properties. Other secondary parameters such as FA percentage in concrete mixes, SP type, C/A ratio and SS/SH should be accurately assessed while preparing concrete mixes for experimental testing. The following conclusions can be drawn:

- Temperature is one of the significant factors inducing the reduction in bond strength, when GPC is exposed to temperatures over 300 °C.
- Generally, GPC demonstrates similar or better performance for bond properties in comparison with OPC [27].
- For the percentage of pozzolanic material, the improvement of mechanical properties such as compressive strength and flexural strength in these concrete types can be seen in the range of 30–50% of PC replacement ratio at 28 days [39,45]. On the contrary, the increase of composite reinforced materials such as rubber fiber in concrete content leads to the reduction in flexural strength and elasticity modulus of both GPC and OPC while increasing rubber fiber from 0% to 30% cement by weight, as rubber fiber has this capability to provide a better bridge between propagated cracks [28].
- The ratio of SS/SH ratio and SH concentration are two key factors for the improvement of GPC properties compared to OPC concrete [25,31,46,47]. The optimum SS/SH ratio for less workability is 2.5 compared to the GPC mixes with the ratios of 1.5 and 2 [31].

After assessing all experimental attempts from preliminary literatures discussed in this review paper, the combination of modified Portland cement (PC) types such as OPC and type V containing a lower percentage of calcium (Ca) and higher amounts of Silica (Si) with pozzolanic materials can play the remarkable role in the improvement of concrete properties, especially for compressive strength and other concrete properties. Furthermore, this combinative green concrete mixture can help to significantly reduce the CO_2 emission due to PC production in the atmosphere. However, this does not necessarily mean that the effects of other factors and ambient conditions discussed in this review paper can be ignored, but it is only a comparative assessment subjected to the influencing factors on the development of concrete properties considering eco-friendly criterion.

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