Review

Valorisation of glass waste for development of Geopolymer composites – Mechanical properties and rheological characteristics: A review

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HIGHLIGHTS

- Waste Glass can be utilized as a cementitious material in the manufacturing of GPC.
- Durable GPC which can be incorporated with diverse wastes providing a systematic solution to WG-disposal management.
- Charmingly affordable as manufactured devoid of pricey OPC and following a strategy of "Best out of the wastes".

ARTICLE INFO

ABSTRACT

The present review manuscript examines the most essential phases in the developments of the inorganic class of environmentally benevolent Geopolymer concrete focusing on the valorisation of Waste of Glasses in context of incorporation in the manufacturing of Geopolymer concrete, especially concerning to its properties and applications. Their long-standing applications as structural materials developed through activation of alkali, i.e., Geopolymerization, in the field of sustainable constructions and infrastructures industries, diverse GPC are on the map. Even though, more advanced studies in the context of the said concept will be proved valuable to concerned industries people and of course, to the researchers themselves. Although the available literature in this innovation zone is few and far between, it breaks the surface, for the most of the centre of attention on its, incorporation with other waste materials pointing a finger to its approach to embrace "waste for the best" strategy. Previously, their character is neither well-figured out nor aptly welcomed as in the ordinary Portland Cement based edifice materials enjoying. That is the core reason and objective of this article that review of its handy restricted literature to throw lights on the valorisation of blending of Waste of Glasses for the manufacturing of Geopolymer concrete centring its attributes and uses establishing it as a soon-to-be useful lucrative and sustainable global building material. The suggestions pointed out here in this manuscript will confidently be accommodating for potential research works on the topic. However, a modest challenge viz., curing complications, sometimes practical confronts of application, constrained supply chain, and a prerequisite for an observant directive of mix design for its fabricating, are standing up in its tracks to substitute Ordinary Portland Cement counterparts. Even so, when produced by utilizing vast and within reach precursors, activators and waste glass materials under up to the standard quality control of diverse characteristics, predominantly strength and green footprints of alkali activators, valorisation of Geopolymer concrete incorporated with waste glasses are momentous forthcoming part of the prospect toolbox of sustainable and economically reasonable construction materials. Eventually, the paper categorizes promotion of applications and most importantly the properties aspect for this promising novel type of building material.

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Contents

1. Introduction

Concrete technology has witnessed a revolution since Romans era. Nowadays, a trend towards less energy-intensive, green, innovative, affordable, sustainable user-friendly building materials with low carbon footprint is the subject of attraction to researchers [1–4]. The application of diverse recycled solid waste is drawing the attention of engineers to incorporate them with construction composites. The market for recycled materials like concrete aggregates has been initiated through a project to develop it by Flemish Public Environmental Agency (OVAM) in 2006. It's conclusion suggested that top-level recycled aggregates often finish up in substandard applications owing to the lack of certainty about the technical performances of recycled aggregates viz., consistency of properties, porosity, the presence of Chlorides, Sulphates, etc. and deficiency of regulations to encourage their applications with elevated added value [5].

This review paper endeavours to stimulate the application of recycled aggregates namely, waste glasses (WG) incorporating with GPC. Consequently, it necessitates being verified that the mechanical attributes and the rheological of such type of GPC meet the prerequisites for the preferred application and exposure classes or not. Until now, numerous researches have been carried out on diverse kinds of waste into various types of concrete fabrications chiefly for secondary applications, but also attempting to accomplish with structural performances. The applications of waste in construction composites irrespective of its manufacturing technologies are very eye-catching for the management and reduction of solid waste and the conservation of finite natural non-renewable resources.

Recently the world has been confronted by titanic dilemmas such as global warming, which lead to climate change; degradation of non-renewable, restrained natural resources; removal of various abundant waste generated by various methods in landfills that are responsible for environmental health hazards and pollution [11–14]. The term "sustainable development" throws lights on "the balance between the development of technologies and conservation of the environment simultaneously" is adopted since 1987.

On the one hand, the mushrooming population on the globe necessitates more housings and infrastructures. Intending to erect the essential structures, an exigency of a gargantuan quantity of concrete is cropped up, which in turn, calls for natural restricted deposits for aggregates and OPC as a predominant binder. But, unfortunately, the present process of production of OPC involves high-temperature reactions and devours high energy to produce. It is not only consuming non-renewable restricted natural resources of minerals like Coals to obtain elevated temperature through their burning up necessitated for Calcination of natural rock deposits of Limestone as raw material but also found accountable to global warming, i.e., earth heating, which is the gigantic dilemma the present world is facing in this millennium [15,16].

The nerve-racking boost up in the emission of Green House Gases (GHG) such as water vapor, carbon dioxide, methane, nitrous oxide and ozone, in particular, Carbon Dioxide (CO_2) – a primary GHG, generating from existing OPC production process owing to the decomposition of embodied Calcium Carbonate ($CaCO_3$) [6,17,18]. Not only have that, but it is also costly, consume scarce fossil fuels, electrical power as well as heavy thermal. It is estimated that the production of 1 tonne of OPC not merely gulps down 1.7 t of prime non-renewable restricted resource materials [7–9] but also emits a significantly about 0.85 t quantity of CO_2 into the atmosphere [10,19]. This emission accounts for 5–7% of the overall CO_2 emissions of anthropogenic origin [19,20].

On the other hand, there are copious diverse waste like Waste of Glasses (WG), from various sources laying in landfills creating health hazards and contaminating soils, air, surface and subsurface waters owing to their non-biodegradable chemistry. On top of that, The European Commission, buildings report for 40% of EU final energy exigency, and the Horizon 2020 EU Framework Programme for Research and Innovation have taken it as precedence to deliver affordable, innovative, and viable technological ways for energy competence for building envelopes [21].

As a consequence, all the above challenges have twisted the arm of researchers, scientists, concrete technologists and engineers to investigate for substitute construction composites and binders that should be durable; sustainable; user and eco-friendly, low Carbon footprint [22–24], and low energy consumption, and cost-effective! Nowadays, Geopolymer construction technology has emerged as the potential substitute of the conventional one. Geopolymers are the class of innovative, inorganic polymeric cementitious Alumino-Silicate materials possessing an amorphous three-dimensional structure which comprises of SiO_4 and AlO_4 tetrahedral related by shared Oxygen atoms.[25]. They can be produced through the process of 'Geopolymerization"- an exothermic reaction between aluminosilicate raw materials such as industrial by-products such as Fly ash (FA), Blast Furnace Slag (BFS) or natural primarily Clayey Argillaceous materials like Metakaolin (MK), etc. with concentrated Alkali activators – a mix solution of Alkali Hydroxide and Alkali Silicate (most common are NaOH, Na_2CO_3 and Sodium Silicate Hydrates) [26,27], at as low as room or ambient or maximum up to 100 °C temperatures at atmospheric pressure [25,28,29].What's more, their excellent attributes like – attention-grabbing strength; superb mechanical properties; brilliant resistance to chemicals; the noteworthy high early strength; admirable tractability, exceptional resistance to thermal and fire; antagonistic freeze–thaw conditions, and aggressively anticorrosion nature, altogether have recognized them as promising sustainable green building materials which can be produced appreciably with nine times less carbon footprints [29–31], and six times less energy than contemporary OPC production system [25]. That means, nine fold more production of GPC is possible for the sake of the same amount of emission of CO_2!

Advantageously, they can be produced at a low temperature, helps to prevent degradation of confined natural non-renewable resources of rocks and minerals, as well as they are capable of incorporating the profuse diverse waste in their manufacturing to manage the disposal of the waste systematically. Their structure is analogous to the Zeolites, but there is an absence of regular long-range ordering. All through the course of Geopolymerization, the reactions occurring in alkaline activation that can be considered as a sequence of complex transformation in the preliminary solid which eventually capitulate a dense structure which is baptized as "Geopolymers" by their inventor Joseph Davidovits – a renowned French scientist. The chemistry kinetics of their development takes place in four stages viz., (i) Amorphous Alumino-Silicate solid materials are dissolved, i.e. activated in a alkali-metal silicate solutions (i.e. Alkali-water glass) under highly Alkaline conditions (ii) formation of Oligomers, i.e., Geopolymer precursors – an Alumino-Silicate gel formation phase through the polycondensation between Silicate solution as well as Al and Si complexes sharing the Oxygen atoms in SiA-O-ASi and SiA-O-AAl bonds (iii) partly precursors and the reform of Poly-Silicates form network of Al_2O_3 and SiO_2 in tetrahedral coordination, cross-bonding three-dimensional Alumino-Silicateclosed framework structure linked through shared Oxygen atoms (iv) the solid particles which are not dissolved form a mutual bond through polymerization resulting in hardening and developing the structure of Geopolymer [28,32]. Alkali cations balance the negative charge induced by tetrahedral Aluminates from the activating solution [33,34]. They are a class of synthetic Alumino-silicate materials representing a novel family of building materials, i.e., a new-fangled cement for concrete [26]. "Water glass or Liquid Glass" is the common name for solutions of Na-Silicate or K-Silicate since the solution gets solidification into a glassy solid on evaporation. Geopolymeric materials exhibit the best mechanical behaviour in these water glass-based solutions [35–38]. The Fly ash, as well as Slag derived from coal firing in thermal power stations and steel plants, are mostly used as precursors to developing Geopolymeric construction materials since they are not only pozzolanic being rich in Si and Al but also for their easy and plentiful accessibility. This lends a hand to their disposal management instead of creating piles of them as landfills. This is the core reason for the very economical production of geopolymeric composites based on fly ash and slag and for their effective use as precursor material in current years for geopolymers in civil engineering applications [39].

On the other hand, geopolymerized Slag paste possesses the highest compressive strength of even exceeding 1000 kgf/cm² at normal temperature and pressure [40]. Fly ash, 86 million tons per year, accounted for 81% of the total after ECOBA, Report 2014. Fly ash (FA), as well as Blast Furnace Slag (BFS), are, on the whole, preferably studied and applied materials, owing to their profuse far above the ground global presence [41–46].

Recycled glass is the by-product of crushed, mixed bottles and other glass stuff obtained from streams of municipal and industrial waste [47], which comprises, for the most part, sand particles accompanied by a small percentage of silt-sized particles. Not only have that, But Geopolymeric materials are also capable of incorporating several diverse waste generated from a variety of resources like different waste of Glasses viz., TFT-LCD glass, solar panel glass, glass cullets, Electric and Electronic Equipment glass waste, i.e., E-glasses from recycled E-waste, etc. [48–50,169]. Glass is categorized as material under natural environmental states and can be recycled in a range of techniques sans affecting its chemistry [51]. It is akin to its crystalline materials compositionally except when due to the cooling to which the melt material is exposed, it has an unruly structure that might, a deductive, be companionable with application in yielding alkaline cement. WG gathering and management of its disposal is the subject of significant global concern. Still, the contemporary practice is to dump the majority of the non-recyclable glass into landfills. As glass is a non-biodegradable material, these landfills are unable to make up an environmental solution.

Moreover, the presence of WG always creates issues for their management since they are copious and extensive. Consequently, there is a strong call for the incorporation of these WG and efforts are quite essential to trim down the quantity of these gigantic waste to save the environment. In accordance with European Union (EU) data, recycling of more than 8 million tonnes of glass containers annually is found on this continent only. It is estimated that out of 18 million tonnes of WG accumulated in 2012 in the European Union, merely 35% of this was recycled [52,168]. Belgium, Norway, Germany and Sweden are the main EU countries recycling glass at a rate of more than 85 percent [53].

Looking at Spain's statistics alone, more or less 897,828 t of glass were recycled in 2014 [53], while approximately 700,000 tons of glass, or say 59 glass containers per capita, were deposit in specific street – side containers and recycled in 2015 [51]. Roughly, 20,000 tons per year of WG residues in the form of powder and granules are generated in the Netherlands which are mostly sent to landfills [54]. About 1.0 million tons of recycled glass are dumped annually in landfills in Australia [55]. Glass accounts for to 95 percent of the entire weight of discarded fluorescent lamps which is considered as E-waste [56]. Its estimated global annual generation is 1.5 billion units [57]. Estimation is made for roughly 740,000 t of WG that are set free in the municipal waste stream only in Iran annually, while merely less than 5% of it underwent recycling [58]. The currently deposited estimates for glass are over 46 million tons per year and by 2025 could reach 77 million tons! [59]0.12 million tons of WG is generated per annum in the U.S.A. alone, with merely 25% of it being recycled [42]. In China, 40 million tons of WG per annum generated, with merely 13% of it being recycled [60]. In 2000, Hong Kong generated some 44,000 plus 20,000 metric tons of domestic sources per year from a commercial sector. Of these, 64,000 tons were recycled or reused annually, only 8,000 tons of WG; the rest was dumped into landfills. [61].

In a life-cycle study in South Africa, 150,000 and 300,000 metric tonnes of WG generate, and only 20,000–60,000 tons, of WG, were recycled annually [62]. Recycling of glass containers in place of dumping them into landfills can result in 27% energy savings (3.3 GJ) and 37% GHG mitigation, i.e. 0.39 metric tons of CO_2 per metric ton of glass [62]. It seems, however, that all WGs are recyclable and be able to be reused in glass factories, but the key quandary is the variation among the quality and colour of the accumulated glass. One challenge in the context of diverse glasses of dissimilar colours and origin is that they result in out of control colour and attributes in the newly formed glass and can not be recycled and this is the core reason to dispose of it off to landfills [63]. On the other hand, the recycle of Urban Waste Glass having 90% of Silica soda lime glass in the glass manufacturing unit is confined owing to crises related to the categorizing its kind and colour.

An amorphous material is having its chemistry-based fundamentally on 65–75% of silica, 6–12% of calcium oxide, 12–15% of sodium oxide, 0.5–5% of aluminium oxide and 0.1–3% of iron oxide is considered as urban glass waste [64–66]. Since WG cullet is a derivative product, the manufacture of precursors for Geopolymer does not necessitate intense energy apart from for the grinding process. This utilization could be a substitute for the recycle channels by now active for glass reviv.al. The foremost channel is the construct of fresh glass products. However, this action is more often than not practicable only if the poles apart colours of the glass have convalesced individually for glass production of the same colour [48].

Nevertheless, the collected WG is usually of mixed type and so inoperative to produce bottles of a specific given colour. Accordingly, an inclination towards secondary applications of recycled WG is developed like glass wool or water filtration media and abrasives while another significant way to dispose of mixed WG is construction composites [48].

Nevertheless, the said applications of WG can direct to two kinds of conduct with vigorous impacts such as alkali-silica reaction (ASR), responsible for causing smash up of concrete and pozzolanic response which that favourable for concrete characteristics [48]. The referred two behaviours essentially are managed, for instance, by grouping both coarse particles as well as fine particles in similar concrete [48].

Apart from the most well-known property of transparency, glass also possesses high resistance to chemical attack through the mechanisms and extent of corrosion may be at variance [67]. It is exceedingly soluble at alkaline pH values [68–70]. For instance, due to the development of silicate ions, the solubility of amorphous silica escalates with a monomer in balance with the solid phase at pH values of 9–10.7. While the amorphous silica dissolves in the solid phase at pH values above 10.7 to produce a soluble silicate. However, elevated temperature also supports glass solubility [71]. The type, chemistry, and particle size of mixture members of WG make its reuse highly complex through conventional technology. So, from 10 to 30% of WG is non-recyclable for the said objectives and substitute consumption corridors must be sought after. Application of such diverse waste for making Geopolymer composites can deliver an optimistic environmental impact and energy saving, carbon mitigation and waste recycling objectives can also be achieved. GPC is an environmentally welcoming substitute for conventional concrete [72–74].

Consequently, the practically feasible and most attractive channel for WG disposal management through its reuse is it's blending with building composites either an aggregate or as a supplementary cementitious material in concrete under any technologies of its manufacturing including GPC technology for the construction and infrastructure industries. Its main component SiO_2 (greater than70% Silica Sand) points a finger to its pozzolanic nature. This bulky content of amorphous Silica escorts to regard WG as a reactive aggregate in concrete manufacturing [75]. However, this high Silica content results in a comparatively poor percentage of Alumina. It is required to adapt the composition of its reactive content through adding up of a definite quantity of materials which are rich in reactive Alumina to ensure the development of Geopolymer.

What's more, its valorisation for developing diverse GPC in terms of the conservation of environmental and non-renewable natural resources, significant energy savings and mitigate GHG emissions along with its systematic disposal management is quite significant. Several investigations on the leeway of employing crushed WG as an aggregate of concrete have been conducted in the past [76–78]. Several researchers have recorded that the degree of Alkali-Silica Reaction (ASR) in GPCs even after employing aggregates is considerably inferior to corresponding OPC concretes [79–82]. Research in the fields of nanotechnology, in particular, has received considerable attention to a demonstration in the last decade of new technology [83–97].

In geopolymer systems with a variety of alkaline concentrations, Williamson and Juenger [82] recently tested ASR and found the spreading out due to ASR to 3 times greater than optimal conditions if extremely reactive aggregates were used and the concentration of alkaline activators was very high than optimal concentration. This significant divergence makes GPCs more fitting for willing to help fines of WG as fine aggregates. The practicability of WG to augment mechanical presentation has been attained with Metakaolin based Geopolymeric materials [98].

On account of its containing high Silica-rich glassy part, WG is one material that found suitable to several authors during their investigations for the feasibility of employing dissimilar kinds of non-hazardous WG taken from dissimilar manufacturing sectors for the construct of inorganic polymers [42,48–50,67,99]. Expectedly, WG has a propensity to dissolve and furnish condensable "Silanol groups (Si—OH)" owing to its chemical unsteadiness in alkaline media, piloting to the development of Silica rich gel which influences the attributes of the concluding product. Geopolymer composites are competent enough to puff up the increase in volume when subjected to a thermal treatment between 600 and 800 °C [100] permitting to develop foamed Geopolymeric materials through the alkali activation of cullet formed WG with or without admixture [79–82]. Since a high amount of amorphous silica content in fines of WG, it can be employed not only as a precursor in GPCs [51,101] but also be applied for producing Geopolymer alkaline activators [67,102,103]. However, these applications require elevated temperatures for curing or dissolving to achieve desired mechanical characteristics. At room temperature, the amount of silica dissolution from WG is trivial [66]. But when glass fine is used as a GPC aggregate, the surface of the glass can react over time with an alkaline solution and bind the geopolymeric paste to good quality on the interface [104]. The dissimilar interface binding behaviour is well known to affect the macroscopic attributes of GPCs [105], and the development of silica-rich geopolymer gel around WG particles is documented in the literature [106]. Since the variations like geopolymer gels in unlike aggregate systems have not been much investigated, it is obscure if at room temperature the voluminous Geopolymer paste will also have any properties such as chalk and cheese with WG versus sand aggregates. The use of identical geopolymer paste, incorporating fine glass and fine sand as aggregates, is used to compare two geopolymer groups. Also made as a control specimen was the Geopolymer paste where aggregates were absent to lend a hand when comparing both systems. In its early stages, the geopolymerization reaction is observed and compared after 56 days of reaction with the attributes of the binding gel.

2. Rheological properties

2.1. Slump and slump flow of WG containing Geopolymers:

Arulrajah et al. [107], Fig. 1 depicts the relation among slump as well as slump flow subsequent to the adding up of Sand of LCD-WG. When L/S (liquid: solid ratio) = 0.5, the slump value of 40% substituted is more than the control mix which having 0% substi-
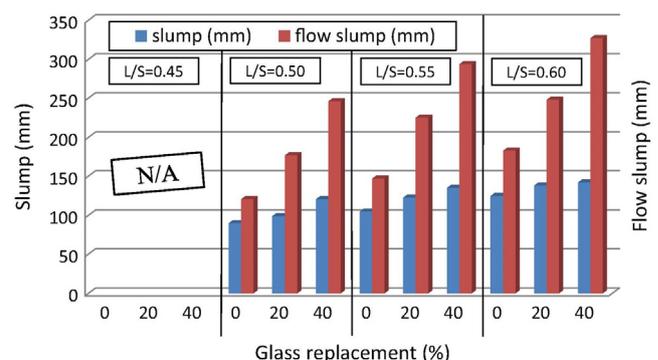

Fig. 1. Effect of glass sand on workability properties of GeopolymerMortar [107].

tution near 34.4%, as well as the value of slump flow is boosted with 103.3%. It means to the slump as well as slump flow enlarged with WG substitution as sand. The WG sand has favourable workability because there is no attend absorptivity, and the slump plus slump flow enhance with advancing L/S ratios. The samples with L/S (liquid: solid ratio) = 0.55 and 0.6 also have the same tendency.

Fig. 2 displays the setting time subsequent to the supplement of Sand LCD-WG. As LCD-WG sand substitution increases, the setting time increases as fluids to solids. When the viscosity is higher with a lack of flexibility L/S = 0.45, it can not test the slump, slump flow and setting time.

Wang et al., [40], Slump value measures the consistency of fresh GPC prior to the setting. The test is carried out to confirm its workability in a fresh state, i.e., the ease with which it flows. That means this indicates whether the product is improperly mixed or not. The slump value of WG containing Geopolymers enhances with the liquid to solid ratio and Alkaline solution as portrayed in Fig. 3.

When the alkaline solution is 1% and the liquid/solid ratio of 0.50, which is 22 mm higher than the resulting slump value when the liquid/solid ratio is 0.60, the slump value is 100 mm. The slump of the liquid to solid ratio is 0.50 with the alkaline solution being 0.5%; then the slump value is 60 mm which, by using the alkaline solution of 1%, is 40 mm greater than the slumped figure.

Fig. 4 shows that the WG-Sand substitution slump value augments and that the liquid to solid ratio increases. The slump value was increased by 7.69–17.09 percent with the use of alkaline solution at 0.75% and solid–liquid ratio 0.50, with WG-Sand substitution at 0, 10 and 20%. However the slump is increased by 12.20%–22.76% when fixing the WG – Sand substitution at 10 percent and the liquid at the solid ratio at 0.50, 0.55 and 0.60.
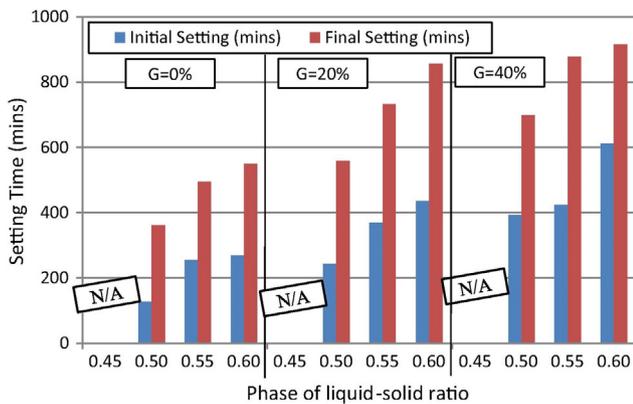

Fig. 4. Slump value of Geopolymer waste glass material and glass content [40].

The illustration of Fig. 5 points towards the increase in the value of slump with WG containing Geopolymers. In addition to the Alkaline solution of 0.5, 0.75 and 1%, the liquid-to-solid ratio 0.60 and the WG-Sand substitution have been augmented by between 4.51 and 6.01–20%. The Geopolymeric material's slump can be improved by improving the liquid to solid ratio, the solution Alkaline and the substitution of the WG-Sand.[40].

In the case of WG-incorporating Geopolymers, the application of the Alkaline solution of 0.5% gave rise to the percentage of the slump flow with an increase of 11.11 to 72.22% when the ratio of L/S enhances; However, while the liquid – to – solid ratio is 0.50 and the solution Alkaline is 0.5, 0.75 and 1 percent, a 1.11–1.46 fold increase is found in the slump flow [40] representing an increase of slump flow with the alkaline solution as illustrated in Fig. 6.

When the use of the solution of alkali metal silicate is reduced, its workability is improved. Because the solution is viscous, too much alkaline silicate can result in an excessive slump flow which significantly reduces the overall workability.

Fig. 2. Glass sand effect on Geopolymer Mortar setting time [107].

Fig. 5. The Slump of Geopolymer waste glass material with L/S = 0.6 [40].
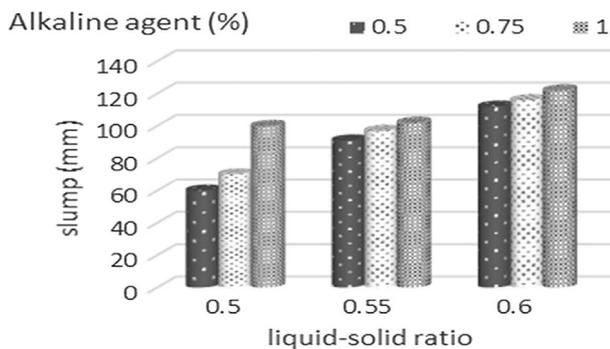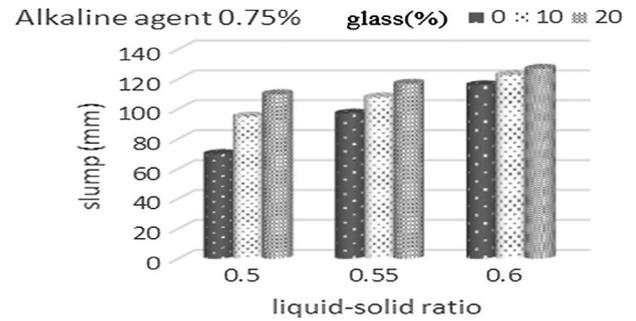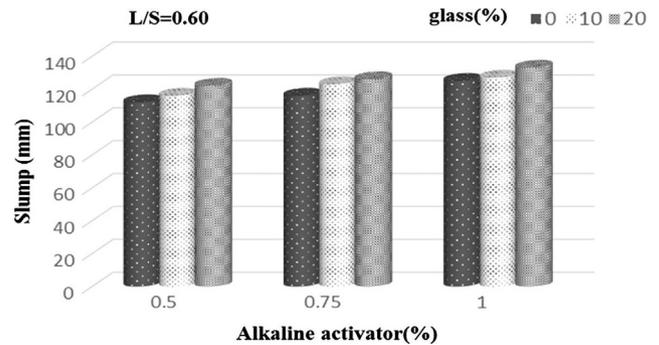

Fig. 3. Effect of waste glass and alkaline solution ratio on slump of Geopolymer waste glass material [40].
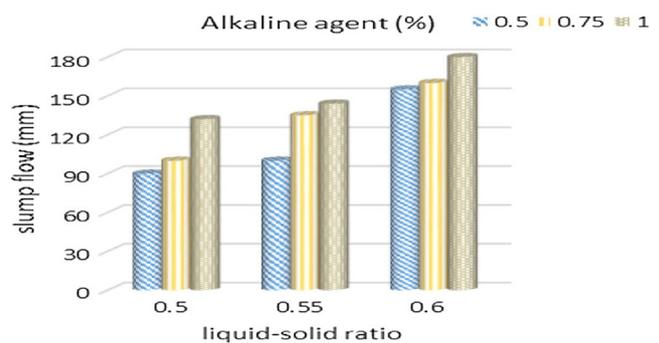

Fig. 6. Slump flow of Geopolymer waste glass material [40].

As the solution of alkaline metal silicate is viscous, too much alkaline silicate can result in an excessive slump flow which significantly reduces the overall workability.

Fig. 7 shows the slump flux value to 1.26 to 1.66 fold when the solid-fluid ratio and the WG-Sand replacement is 0, 10, and 20%. With WG-Sand replacement, slump flow increases. The slump flow value improves with WG-Sand substitution, as this is water repellent when the liquid to solid relation and Alkaline solution is set up.

Lu and Poon [115], A preceding investigation determine that harsh segregation and bleeding observed when recycled WG aggregates substitute fine aggregates in OPC – concrete [71]. The display of dissimilarity in both the Geopolymer cement and OPC is that the former sets fast while the later has slow-setting attributes [72].

3. Strength properties

One widespread material which can be recycled and have the leeway of incorporation with GPC production is WG. It can be regarded as a resource rather than waste since its utilization in the construction and infrastructure industries is progressively getting hold of some grounds. Subsequent to pulverization to very fine particle size it can be employed quite successfully in the construction industry as an ingredient and in paving works by replacing natural Sand. However, the impact of its applications on the strength of the ultimate construction product is of much more significance and should be viewed seriously. Following is an account for the outcomes of the same in previous investigations carried out by diverse researchers on the GPC with the significant incorporation of WG and its influence in valorising them in context of different strength criteria:

3.1. Compressive strength

According to the investigations by Novais et al. [108], on the incorporation of unexplored Fluorescent lamps-WG with Geopolymers. The impact on mechanical properties of the geopolymers of the integration level and the NaOH molarity was assessed. The upshots exhibited that curing methods were found more noteworthy on their attributes than molarity of NaOH. Geopolymers blending with 37.5% WG by weight were productively manufactured, displaying 14 MPa compressive strength subsequent to curing of 28 days, suggestive of the opportunity of their exploitation in the non-structural application. Fig. 8 has represented WG amalgamation and molarity of NaOH. Fig. 8 displays the dissimilarities among the dense and the porous geopolymer specimens.

Incorporated with Geopolymers of unforeseen Fluorescent Lamps-WG. The impact on mechanical properties of the geopolymers of the integration level and the NaOH molarity was assessed.
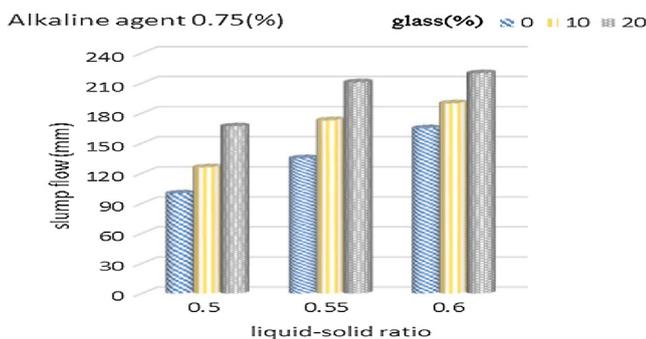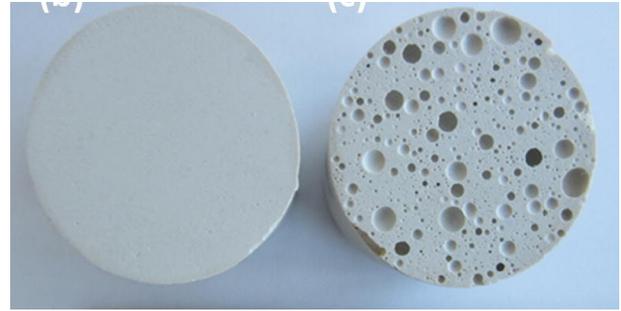

Fig. 8. WG-containing geopolymers [108].

The upshots showed that the cure conditions were more important than the molarity of NaOH.

On the other hand, Fig. 9(a) and (b) depict the apparent density as well as the compressive strength of WG-Geopolymeric materials incorporating activated solutions Sodium Silicate and 12 M NaOH. Fig. 9(a) illustrates that blending of 12.5% WG by weight enhanced the mechanical resistance to 15.5 MPa as compared to pure MK-based Geopolymers **w**hich was found 11.8 MPa on the 28 days; however, WG addition beyond this has caused the reverse influence [108].

Ozer and Soyer-Uzun, [109] revealed that when the content of WG escalates the initial $SiO_2:Al_2O_3$ ratio of the mixes also augments, with expected optimistic impacts on the **s**trength of the activated blends.

Bobirică et al., [110] described a view of the fact that SiA—O—ASi bond is stronger than compared to SiA—O—AAl and

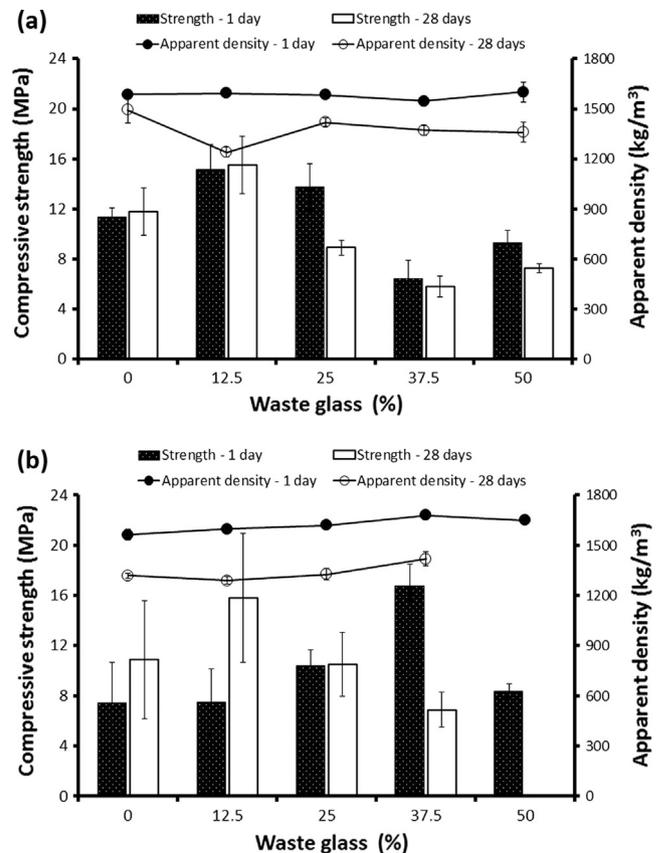**Fig. 7.** Slump flow of Geopolymer waste glass material with L/S = 0.75[40].

Fig. 9. Effect of waste glass on Apparent density as well as the compressive strength of WG-incorporating geopolymers (a) NaOH: 10 M and (b) NaOH: 12 M [108].

AlA—O—AAlbonds. Nevertheless, this kind of correlation is monitored merely while the content of WG equivalents 12.5% by weight. The outcomes can be comprehended as the replacement of MK (precursor) by WG had trimmed down rates of release of Si and Al ions, on account of the slow and inferior dissolution rate of WG as compared to MK, which influences the strength development; and an adding up of more WG has augmented the quantity of non-reacted glass particles.

Analogous upshots were recorded in the context of WG-Geopolymers [49,50], and for MK-Geopolymers having produced employing dissimilar Si: Al ratios [111]. The ratio of Si: Al must be kept among 3.3 and 4.5 intending to forming burly Geopolymeric materials as suggested by Khale and Chaudhary [112].

The polymerized network demonstrates a reduced amount of stability if it is either smaller or more significant than the referred limits,e.g., the incorporations of WG above 25% by weight endorsing the results of Novais et al.,[108].

Also, outcomes display a petite boost concerning compressive strength after curing for the only MK containing as well as for the12.5% by weight of WG incorporating Geopolymers. However, higher WG addition has demonstrated the reverse attitude. The losses in strength can be assigned to phase modifications taking place during aging [113].

The apparent density of Geopolymers declined during aging as shown in Fig. 9. It is on account of water discharge during Geopolymerization and curing [114]. By and large, a progressive strength enhancement of the Geopolymer is monitored besides an augment concerning the concentration of activator [103,114], owing to the greater dissolution of the Alumino-Silicate resources. However, a very high concentration of Alkali could hold-up the reaction of Geopolymerizationas a consequence of restricted ion mobility [108]. Fig. 9(b) reveals that in the case of addition of WG lesser than 25% by weight, inferior compressive strengths subsequent to the first day of curing are attained, while the same strength was obtained as obtained from the10 M compositions. Consequently, an increase made in the NaOH concentration has setback the strength evolution, but have not influenced the eventual strength. What's more, a distinctive attitude was identified in the case of WG composition having 37.5% by weight. A considerably higher strength of 16.8 MPa was recorded subsequent to the first day as compared to the mixture made by employing 10 M NaOH which was 6.4 MPa only. For the said mix, noteworthy losses in strength with aging were found supporting the morphological changes as illustrated in Fig. 10.

Torres-Carrasco and Puertas, [67] have portrayed the values of the first day compressive strength in Fig. 11(a). WG, when activated, has demonstrated compressive strength varying from 17−88 MPa, depending on the activator type as well as conditions of curing. The best presentation was monitored in the samples cured with 6.5% RH (relative humidity) representing the 50–75% higher value than that the samples cured at higher humidity for all activators Fig. 11(b). The samples activated with 10 M, KOH solution whereby no strength variations were found among the two curing conditions was an only exception.

Looking to the compressive strength of WG blended MK-Geopolymers, Hajimohammadi et al. [116], have reported that the compressive strength of GPC depends on the cementitious paste, the aggregate strength, as well as the bonding among the paste and aggregates. The strength of WG blended Metakaolin (MK) based Geopolymers is represented in Fig. 12 [50] which displays an increase with curing period. After curing for 1, 28, and 60 days, the compressive strengths of pure MK – based geopolymers were 47.8, 64.7, and 65.2 MPa in that order. However, WG incorporated MK-based Geopolymers compressive strength found declined when the quantity of WG was boosted, but it enhanced with curing time. When 10% of WG supplemented to MK-Geopolymer, it demonstrated The compressive strengths of 46.9, 61.8 and 62 MPa were shown correspondingly at 1, 28 and
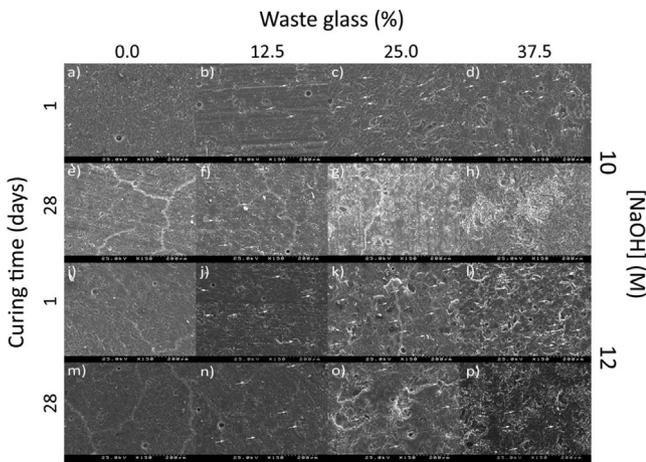

Fig. 10. SEM image of WG-incorporating geopolymer with NaOH, curing time and WG content. (The white patches are un-reacted waste glass particles) [108].
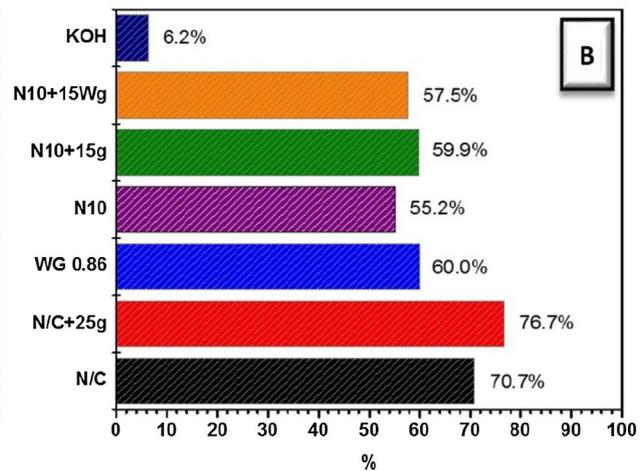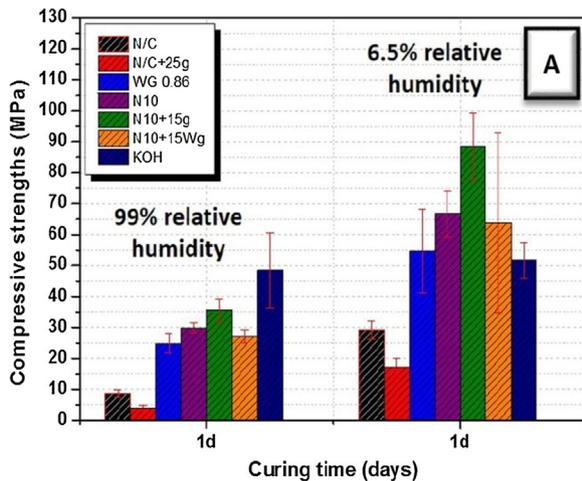

Fig. 11. (a) The Compressive strength of WG incorporating geopolymer with diverse activator (b) fraction diverse between low and high relative humidity curing states [67].
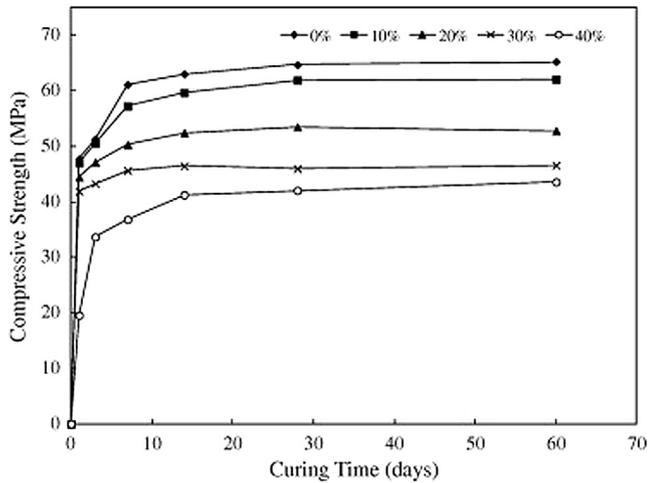
Fig. 12. The Compressive strength of WG-MK geopolymer [50].

60-day curing times. The relationship between the curing period and compressive strength was analogous to pure MK-Geopolymers. The amalgamation of 40% of WG with MK-Geopolymers displayed a compressive strength of 19.5, 42, and 43.5 MPa subsequent to 1, 28, and 60 days of curing, in that order. In that order, the amalgamation of 40% of WG with MK-Geopolymers showed a compressive strength following at 1, 28 and 60 days were 19.5, 42, as well as 43.5 MPa.

Analogous to pure MK-Geopolymers was the relationship between compressive strength and healing time. In that order, the amalgamation of 40% of WG with MK-Geopolymers showed a compressive strength of 19.5, 42, and 43.5 MPa following 1, 28, and 60 days of healing.

Fig. 13 illustrates that the compressive strength decreased with the increased liquid-solid ratio. But with the alkaline solution and glass sand substitution, the compressive strength increased. The compressive strength on day 28 is found for liquid-solid ratio 0.5, 0.55, 0.6 (LS050, LS055, LS060) with 0, 10 and 20% (N05G0, N05G10, N05G20) glass replacement. The compressive strength with 0.5 as 51.52 MPa, 52.63 MPa and 53.22 MPa when Geopolymers are incorporated in the case of WG – Sand and L/S ratio 0.5

(See Fig. 13). The compressive strength value on day 28 is higher than the control group. As the WG – Sand dissolves additional silicon and aluminium, the higher the substitution of WG – Sand, the further the polymerization and the compressive strength of the control group are superior. When Slag is substituted with WG-Sand, the early reaction is delayed by the gel structure. The compressive strength on the 7th day is found inferior to the control group. The higher the content of WG – Sand substitution on the 28th day, however, the further complete the frame structure is, and the compressive strength found is superior to the control group.

Fig. 14 shows that the compressible strength improves with a substitution WG-Sand when the Alkaline solution is 0.5% while compressive strength is 1%. The structure of the slag can crumble with the 1 percent Alkaline solution and dissolve faster. The 0.5% Alkaline solution damages Slag's structure more easily and not thoroughly as is the case with the 1% solution. The compressive strength of the 1% alkaline solution is higher than 0.5% and 0.75% [40].

In the research works by Toniolo et al., [117], a total ten specimens of each mix have been examined to calculate the compressive strength subsequent to 28 days and the outcomes are illustrated in Fig. 13. Geopolymers based on merely Fly Ash have been produced which demonstrated the best compressive strength, having a value of 75 ± 14 MPa. As a rule, cement exhibiting a compressive strength of up to 70 MPa is considered to be a binder material with high strength [63,117]. The findings represented in Fig. 15 which illustrates the constant propensity in strength development following the adding together of Red mud or recycled WG. The excessive quantity supplement of these materials resulted in the decline of compressive strength. In particular, with a reduction of 40 percent, a mix of recycled WG by weight of 20 percent demonstrated the lowest mechanical strength. Fig. 15 shows the compression strength of geopolymers based on Fly ash that incorporates 10, 20 and 30 percent WG or Red Mud by weight after 28 days of aging. The compressive strength was found in the identical series for almost all percentages by weight except for 10% by weight substitution case, whereby the amalgamation of recycled WG influences the compressive strength significantly as compared to Red mud. Numerous researchers believe that higher addition of Red mud pilots on the whole to low compressive strengths of Geopolymer specimens [64,117].
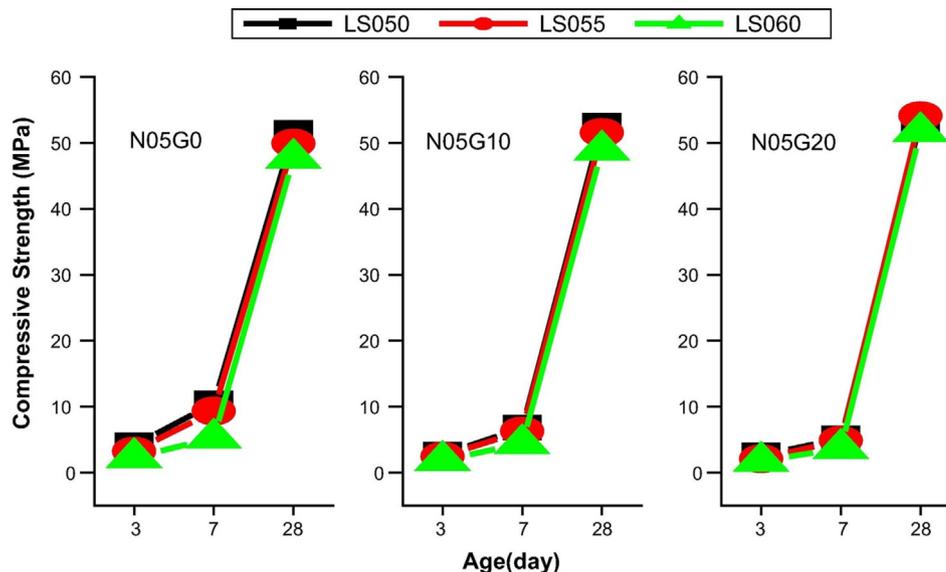

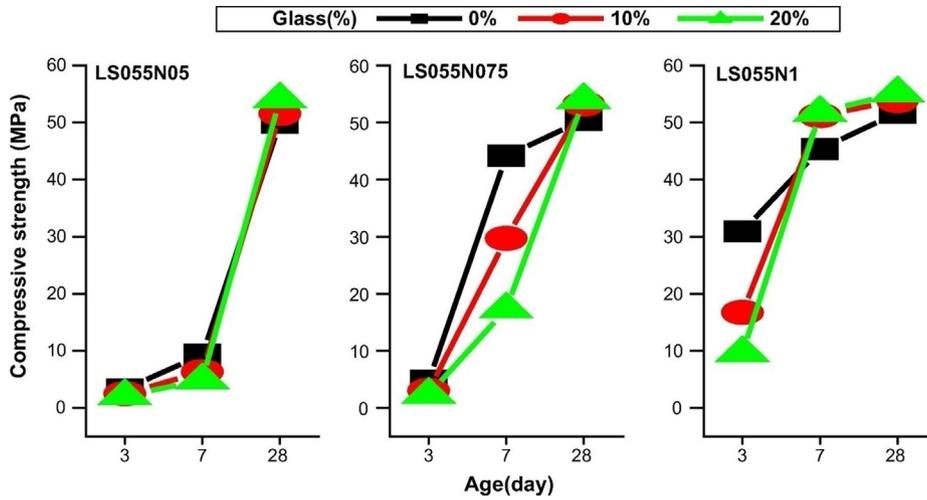Fig. 13. The compressive strength of Geopolymerwaste glass material [40].

Fig. 14. The compressive strength of Geopolymerwaste glass material with diverse content of glass [40].
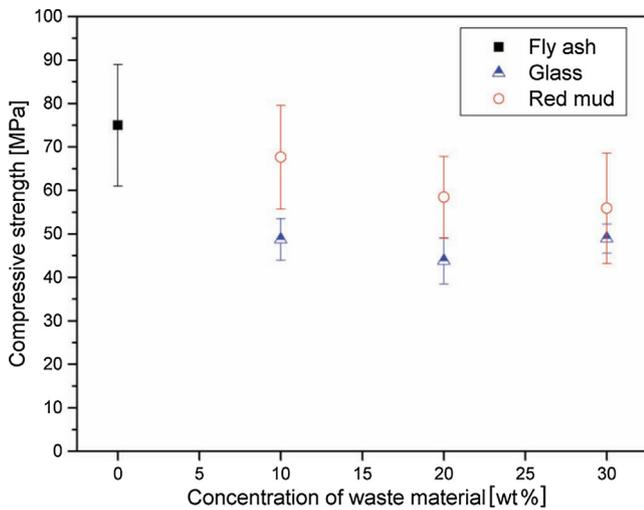

Fig. 15. Compressive strength of geopolymers based on fly ash with glass waste [117].

For instance, Kumar et al., Zhang et al., Mucsi et al., He et al. [118–121] have revealed that an application of ratio of Fly Ash to Red mud (80:20) is capable of attaining a maximum value of compressive strength of roughly 25 MPa. However, an augment of the Red mud quantity over 20% by weight is causing a radical dwindle in the compressive strength of the said material. Fig. 15 provides an idea that there do not found any noteworthy divergence concerning compressive strength on supplementing 20%, 30% Red mud to the control mix. What's more to add, in both the cases, the values of mechanical strength stay in proximity to an acceptable value of 60 MPa. On account of the richness of Silica in the WG as well as Red mud include alumina, it is envisaged that the early molar ratio of $SiO_2:Al_2O_3$ will enhance since the quantity of WG escalates and dwindles when Red mud is supplemented to the Geopolymer. It is well-known that Si—O—Si bonds are stronger than that of Si—O—Al and Al—O—Al bonds and that is why Si-rich Geopolymer could display superior mechanical properties rather than in the case of Al-loaded Geopolymers [110]. Images of SEM have unearthed that the particles of WG were not found entirely incorporated in the interior of the structure as demonstrated in Fig. 16. This could simplify the low mechanical strength of the WG incorporating specimens. Additionally, the supplement of
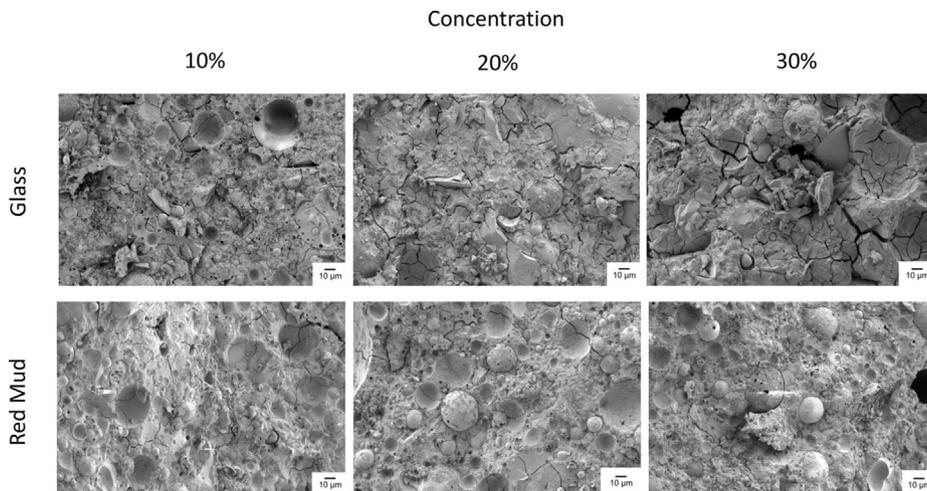

Fig. 16. SEM images of geopolymer with recycled glass or red mud [117].

WG to the system necessitates a high quantity of water, ensuing in the formulation of comparatively bigger cracks and high shrinkage. Also, researchers have already examined the likelihood of blending WG in matrices which were alkaline activated [99]. Incorporation of WG with Fly ash based Geopolymers results in a plunge of their mechanical characteristics beyond optimistic level as reflected from the literature.

For illustration, Bobirica et al. and Novais et al. [108,110] have uncovered a crash of up to 55% in mechanical strength on adding up of 10 and 20% Fluorescent lamps-WG, with the highest strength of 19 MPa. As an amalgamation of Soda lime and WG, a decline of nearly 45% was monitored in the said study even after keeping the compressive strength at an acceptable value of 50 MPa. It can be concluded that the compressive strength of the Geopolymer based on flyash with the addition of Red Mud as well as WG was lower than the Fly Ash-based Geopolymer alone, which was 75 MPa. Still, it is satisfying as per the upshots of the literature.

According to the study of Toniolo et al., [122], Fig. 17 depicts the compressive strength values following 7 and 28 days by shifting molarity of NaOH solution and molar ratio of Silica to Alumina. The dotted line represents the evolution drifts relying upon the molarity of the Na-Hydroxide solution. The molarity of NaOH and molar ratio of $SiO_2:Al_2O_3$ affect the mechanical attributes of geopolymer composites. The compressive strength increases with the augment made in the molarity of NaOH solution as well as the $SiO_2:Al_2O_3$ molar ratio. The said behaviour is authenticated employing NaOH solutions possessing molarity up to 10, while the Geopolymers with dissimilar $SiO_2:Al_2O_3$ ratios demonstrate compressive strength values akin to each other. Specimens examined subsequent to 7 and 28 days displayed no momentous difference with time [123]. When the $SiO_2:Al_2O_3$ molar ratio of the mixes is augmented, an elevated substitution echelon of WG is added to the specimens. WG is partly dissolved in the alkaline medium, forming a Silica loaded gel at the surface of the particles, delaying the absolute dissolution of the primary WG [124]. The amount of Silica of the system is escalated with augmenting the quantity of WG in the production. 5 M NaOH solution engrosses a lower raw materials dissolution ratio. As a result, a bulky sum of particles which have not been reacted probably kept with the ultimate material. While 8 and 10 M NaOH solutions confirmed an increased dissolution of components in the early slurry to more Geopolymer precursor and fewer particles that did not participate in the reaction. After 7 days, the compressive strength of 100 MPa reached declines radically to 36 MPa after 28 days.

Similar observations are met with Novais et al. [108] who also accounted that Elevated solution alkalinity may disintegrate the aluminosilicate gel subsequent to an extended period. The upshot means that the Geopolymer network can decompose as an influence of Alkali's surplus after 7 days. A drop in mechanical attributes through escalating the alkalinity of the solution is not comprehended even after an attempt to describe it by researchers.

Usha et al. [125] revealed that a surplus of Na+ and OH− ions escalate the dissolution of particles. Nevertheless, the rate of poly-condensation reduced.

On the other side, Kamarudi et al. [126] disclosed that employing low molarity by entailing more water in the system, which facilitates the reaction kinetics of Geopolymerization due to the enhancement of the mobility of ions. From the above facts, they have winded up that activation with as strong as 10 M costly Alkali solution is not essential to activate the precursors. Specimens represent exceptional mechanical characteristics attaining values as high as 45 MPa, following setting time at 7 days and the strength stay invariable correspond to time. The said outcomes lead to a conclusion that 8 Molar solution of Alkali is enough to dissolve more or less entirely the early raw materials, directing to an appropriate ratio among Aluminum and silica present in precursors of the Geopolymeric gel. The specimens talked about enjoying a compressive strength as good as conventional OPC, generally acceptable for constructions [26]. Preceding literature pointed towards the likelihood to integrate up to 30% WG by weight in the Geopolymer system. Nevertheless, compressive strength values obtained are not beyond 20 MPa [110,127].

One more study by Bobiricǎ et al. [110], has illustrated through Fig. 16 that the compressive strength using so fall activated mixes. By and large, the strength has a propensity to dwindle when the quantity of WG added to the mix is increased in excess. Activated mixes with the Na2SiO3 solution (FASS) display excellent compressive strength compared to the remaining mixtures, which is quite evident for WG – free activated mixes. It appears that the supplement of Slag enhances the compressive strength of the activated mixes. There are a few palpable dissimilarities in the context of compressive strength among fly ash activated with sodium hydroxide NaOH (FAN) and fly ash and slag both are activated with sodium hydroxide NaOH (FASN) is depicted in Fig. 18, which turn to more distinct since the quantity of WG incorporated into the mixes is augmented. The strength changes of the activated mixes are closely associated with the early composition of the synthesis mixtures and the other parameters of the geopolymerization process viz., temperature, alkalinity, activator nature, etc. [47]. The early $SiO_2:Al_2O_3$ molar ratio of the synthesis mixes boosts as the amount of WG added to the mixtures increases as expected. This is attributed to Silica's rich content in WG.
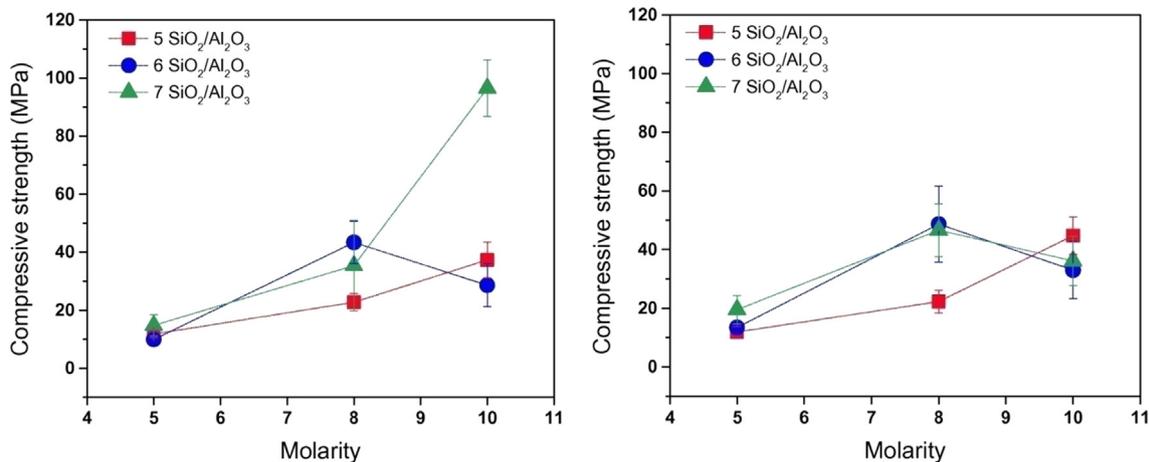

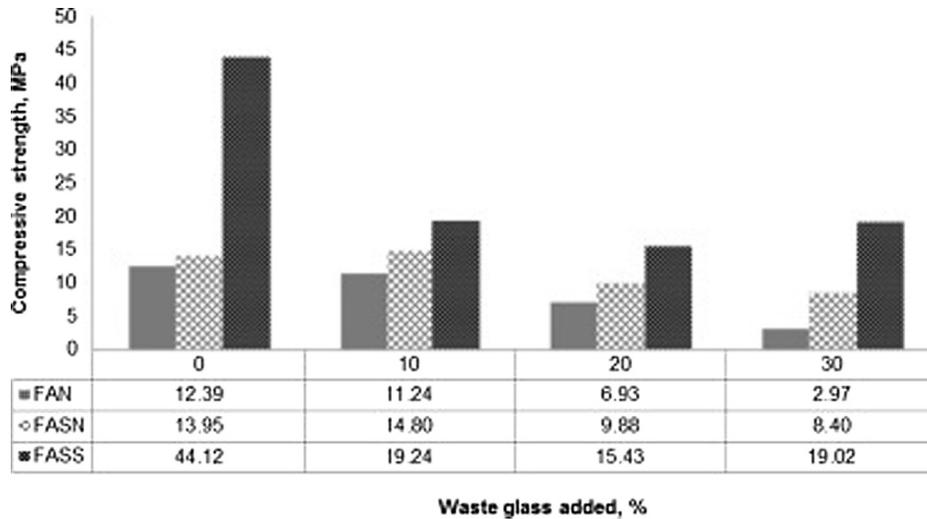**Fig. 17.** Compressive strength of geopolymer [122].

Fig. 18. Compressive strengths of the Geopolymer mixtures [110].

In addition, the molar proportion also tends to be amplified in order fly ash with NaOH (FAN) < Fly Ash and slag with NaOH-enhanced (FASN) < Sodium silicate-enabled mixtures < FASS), because of the relatively low aluminum content and the higher percent of silica present in slag-enhanced mixtures (FASS). Because Si—O—Si is stronger than Si—O—Al and Al—O—Al, the strength of activated mixes is expected to grow as SiO_2:Al_2O_3 ratios increase [52]. The bonds are also expected to increase. This bonding is only monitored when mixing or replacing the activator Slag alters the mixture.

On the contrary, the common tendency demonstrates declining compressive strength by boosting the quantity of WG. Investigations have been carried out on compressive strength of undissolved WG incorporated Metakaolin based Geopolymer mixtures by El-Naggar et al. [129]. They study on reuse of WG in enhancing attributes of Metakaolin based Geopolymers with their mechanical and microstructural investigations. Fig. 19 presents an initial investigation of the impact of particle size of Metakaolin on the strength of Geopolymer mixtures with curing days. By expectation, powder finer than 38 lm of Metakaolin (MK1) provides yields possessing 80.75 MPa compressive strength at 28 days as compared to the rest particle sizes examined. By increasing the particle size of MK to then examining fraction, more than half (50 percent) of this value
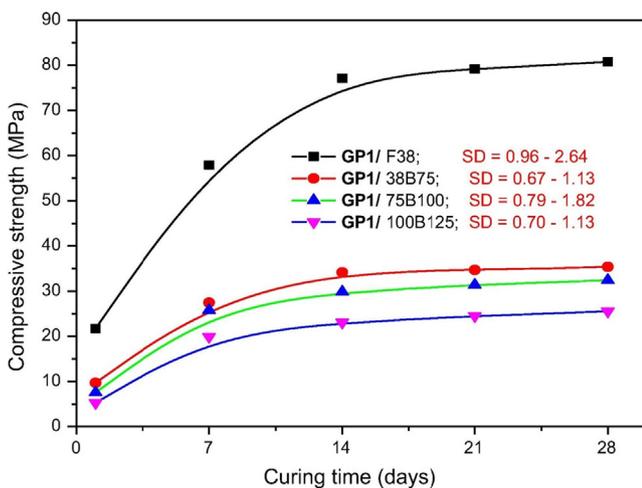
has vanished. Due to a diminish in uncovered surface activation in alkali size by escalating particle sized the decrease in compressive strength [130]. This meant that MK was less than 38 lm in particle size.

Fig. 20 shows MK-based Geopolymers rich of compressive strength with 10 percent WG marked as WG2 that is not dissolved with various solids: liquid ratios, after a long time. The ratio of solid to liquid and curing time both affect the strength of the compression. Solid: liquid ratio of 0.8 contributes the optimum compressive strength which augmented slowly but surely from 8.54 MPa on the first day of curing to 35.09 MPa at 28 days curing. It can be due to the improved Silica-Alumina reaction in the Geopolymer based on the MK [131]. More or less solid: the liquid ratio falls to 0.8, due to the lower MK contents and lower workability.

Fig. 21 demonstrates that both the content percent of WG and its particle size (lm) of undissolved WG have an influence compressive strength of the control specimen at 28 days. The information suggests that loading up to 3% of WG1 or WG2 influences the compressive strength constructively. Replacing MK by 3% WG1 increases compressive strength by 2% for 28 days with 82.36 MPa. The result of the dissolution of WG, which in turn leads to stronger Si—O—Si bonds than Si—O—Al and Al—O—Al [111], can be allocated to the ratio increments of Si: Al. [111].

Fig. 19. MK's effect on MK – based geopolymers compressive strength [129].
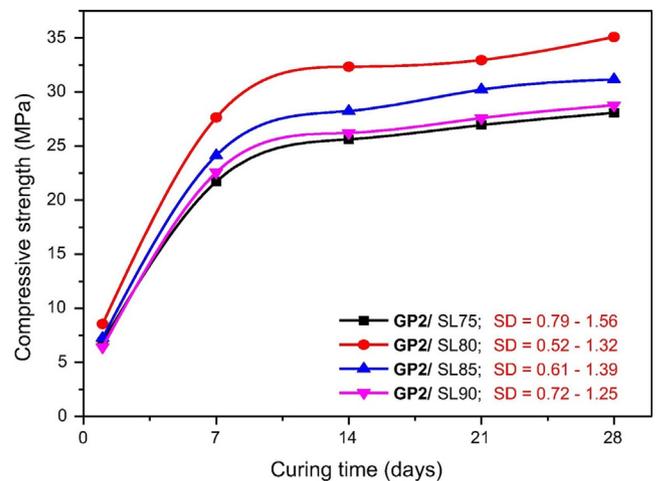

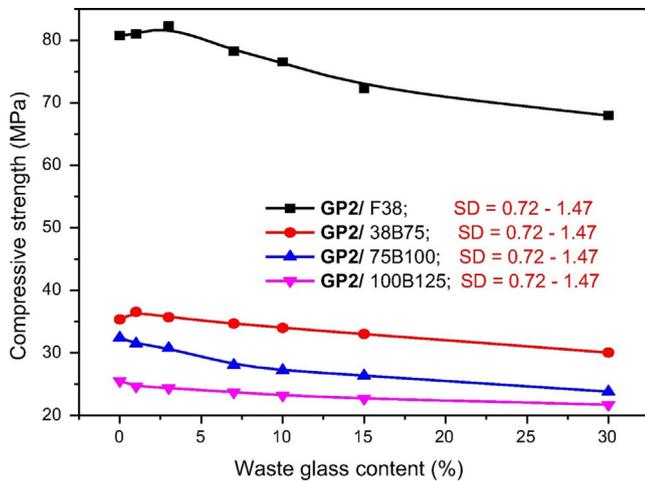Fig. 20. WG/MK – based geopolymers compressive strength [129].

Fig. 21. Effects of WG content with the compressive strength of MK-based geopolymers [129].

Fig. 22 demonstrates that improves compressive strength as an increase in age. In the case of L/S = 0.45, at the28 days the compression force is 42.8% higher than that at 3 days, by 42.8%. During L/S = 0.60, the compression strength of 28 days is greater than 33.3 percent and less than that of L/S = 0.45. In comparison to L/S = 0.60. The compressive strength trims down as the liquid: solid ratio accelerates [107].

Fig. 22 exhibits that the strength in compression boosts with the escalating substitution of sand of WG; nevertheless, the strength slims down as accelerating substitution of sand with WG the quantity of substitution goes beyond 20%. The specimen prepared with of the 20% and 40% substituted, the compressive strength at 28 days of age with 0.45 L/S are 2.5% higher and 22.4% inferior in this order than the control specimen, in which the substitution is 0%. The maximum possible sand of WG substitution is 20%. Also, the same tendency exists for L/S ratio 0.45, 005 and 0.55 samples.

Fig. 23 gives away that WG's sand replacement arithmetic ranges of liquid: solid ratios 0.45 to 0.6 with 0.05 increment, are 0.29–1.60% by 0.86–3.89% and 2,46–5.97%., correspondingly. The rate of loss in weight during Sulphate attack declines as the substitution of Slag by WG sand enhances. Since the sand of WG contributes to an enormous quantity of Silicon as well as Aluminium, the polymerization process is higher comprehensive, and the sample is more homogeneous and denser. Corrosion resistance is found superior. The anti-corrosive impact is improved because of the ratio of liquid to solid augments. As the solution Sulphate enters through the pores of the sample, weight increases, accelerating the development of crystals. The level impacts are optimal if the L/S ratio is 0.50 and the sand substitution of WG is 40%, and the weight loss rate is 5.97%.

3.2. Flexural strength

The examination of flexural strength is one of the widespread majority test carried out on hardened concrete that confirms the load at which elements crack. The study of Toniolo et al. 2017, on flexural attributes, have evaluated through a three-point bending test of beams with a cross-section of 3×4 mm^2 [117]. Fig. 24, displays plotting of typical load-deflection curves for the specimens with only Fly Ash, Fly Ash + WG (having 10 percent by weight) and Fly Ash + Red mud (10 percent by weight). The curves demonstrate a linear behaviour until the fracture is fragile following an abrupt load drop when the strength of the fracture is
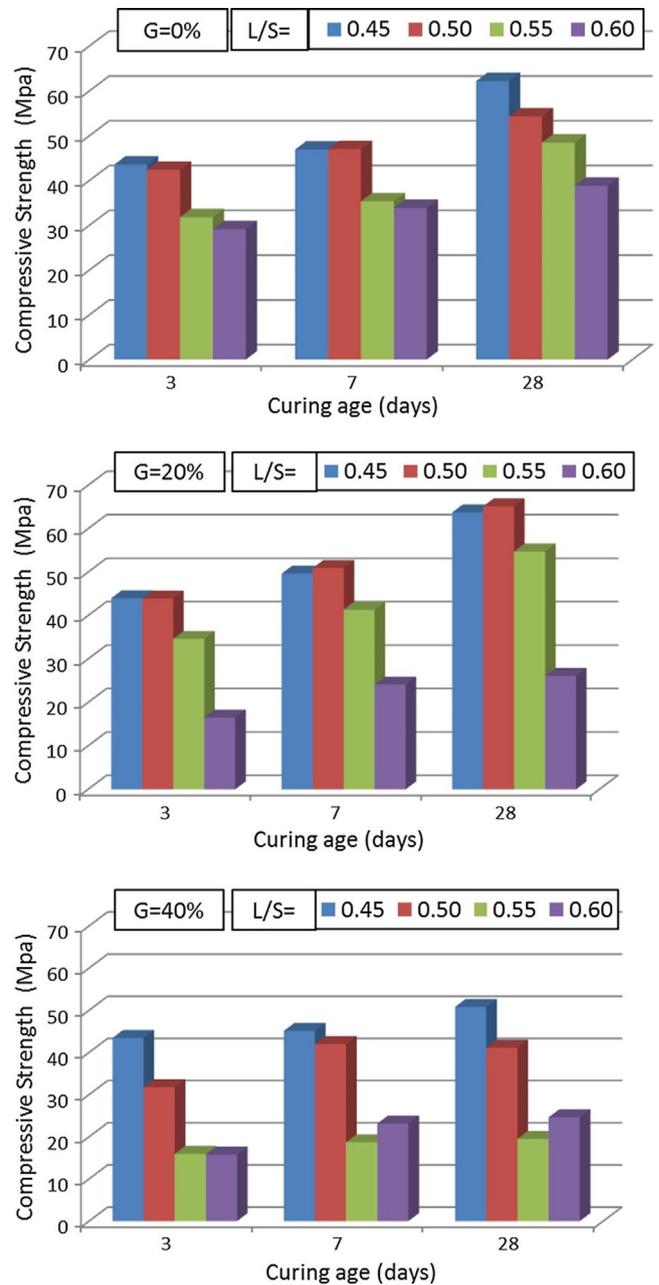

Fig. 22. Compressive strength for Geopolymermortar with diverse waste glass content [107].

attained. Different slopes of the linear part reflect discrepancies in Young's module, even though influenced by the actual cross-section of the specimens.

Fig. 25 displays plotting of average flexural strength of Geopolymer manufactured with only Fly Ash as well as Geopolymers incorporating WG or Red mud. The influence of WG blending in comparison to Red mud amalgamation on the flexural strength is moderately dissimilar. While the inclusion of WG has a pessimistic impact on flexural strength, the adding up of Red mud extends a minor enhancement about flexural strength of only Fly ash based Geopolymers from 11 ± 2 MPa to 15 ± 2 MPa. Additionally, a comparatively higher value of flexural strength is kept almost the same up to a higher amalgamation of Red mud for 30% by weight.

Following the study by Cyr et al., [48], the flexural strength (designated as "f_t") versus the compressive strength plotted, i.e., f_c [48] (See Fig. 26). The outcomes are comparison connecting f_t
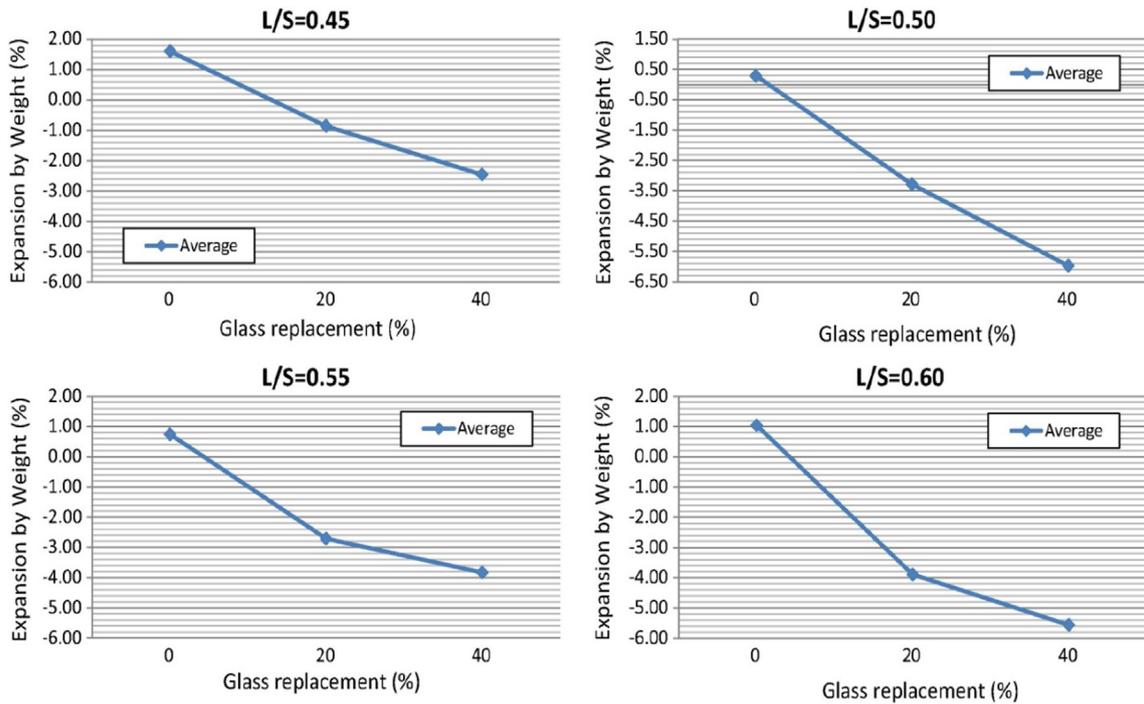
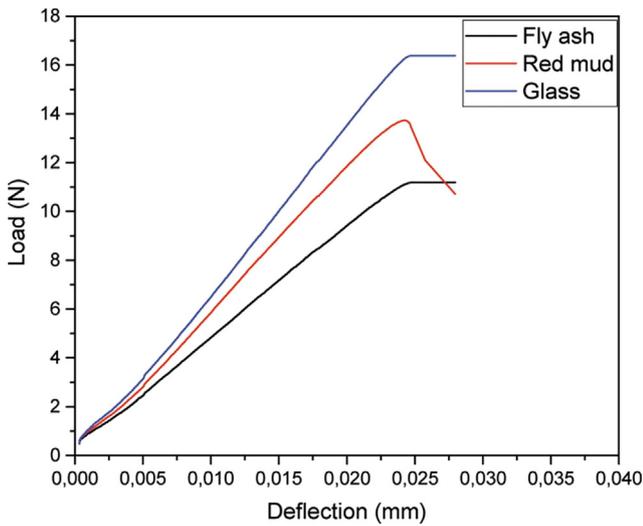**Fig. 23.** Expansion by weight of geopolymer with a waste glass [107].

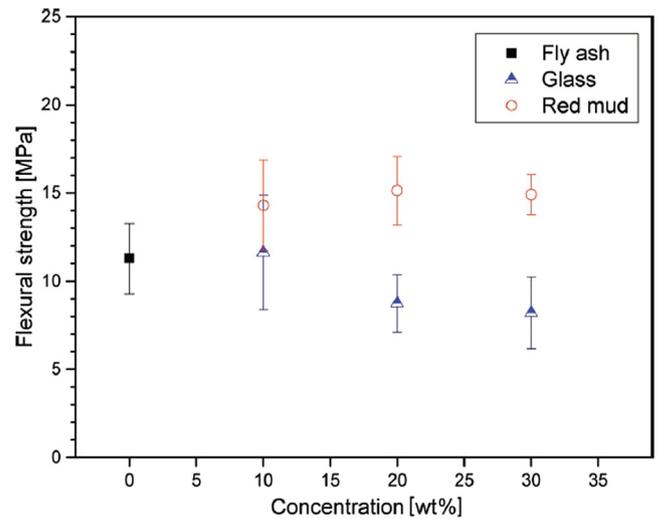**Fig. 24.** Load-deflection curves for the diverse geopolymers [117].

Fig. 25. Flexural strength of geopolymer [117].

and f_c with past literature by Neville, whereby "k" and "α" both are empirical constants. k ranges between 0.2 and 0.3 for OPC-concrete, but it can reach up to 0.45–0.70 for OPC-mortars [55,56]. "α" is generally found varying from 0.5 to 0.75 [52,54]. Fig. 9 provides an idea about Geopolymers incorporating WG-cullet that f_t appears to pursue the similar type of law as in case of OPC-composites. However, the behaviour found quite diverse. Comparatively minute disparities of ft were measured and found to range from 3.5 to 6.1 MPa; while for vast differences of f_c it was varying from 4.6 to 55.7 MPa. Except for low values of fc, and ft of Geopolymer were either equivalent or lesser than that of OPC- mortars which are not matching with the results. Sofi et al. [128], recorded high flexural strength for Fly Ash and Slag based GPCs in comparison with the envisaged values for OPC-concretes. The far above the ground flexural strength attained for

lower compressive strength might be because of the superior quality faithfulness of Geopolymer paste on aggregate particles, and that is why the above-referred materials being known to possess higher bonding attributes [31]. When compressive strength is increased, the low flexural strength performance could be linked to the remarkable vulnerability of the Geopolymer, responsible for the failure at less significant stresses, stress behaviour about acoustic glass. Fig. 26 demonstrates Flexural strength of glass cullet geopolymer.

4. Applications and advantages of waste glass incorporated geopolymer concrete

WG incorporated Geopolymer concrete has attracted the construction and infrastructure industries to a significant extent. Great
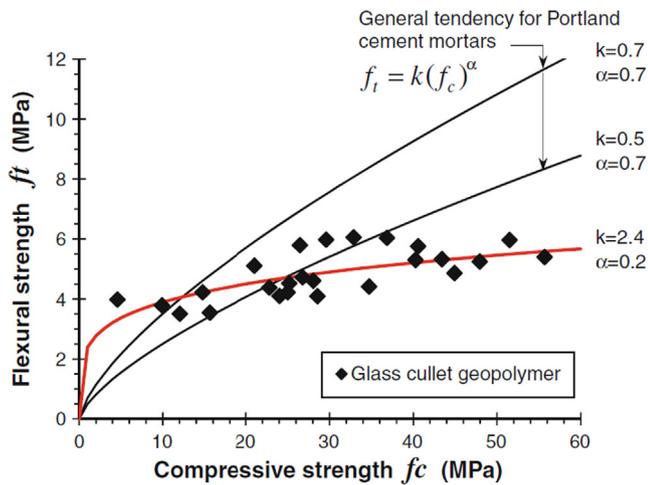
Fig. 26. Flexural strength of glass cullet geopolymer [48].

interest has also been shown towards its applications and has been employed in many areas. In building, chemistry and defence areas, ceramic glass foams which are porous thermal insulation and insonate materials are used [132]. These foams possess excellent attributes like lower density, incombustibility, low thermal conductivity, etc. They not only have better thermal insulation and resistance compared to organic thermal insulation materials against adverse environmental conditions, particularly polymeric foams that could cause severe fire hazards, shortened life, ambient toxicity and inadequate adhesive conditions [133]. At this time, copious technologies are developed to manufacture WG-ceramic foams like a replica, direct foaming techniques and sacrificial template [134], etc. What's more to add, foam concrete containing WG has lots of advantages in construction like reducing the dead load of the buildings, trimming down of the construction time and costs, enhancing the housing affordability, thermal and acoustic performances of buildings [135–139]. Likewise, Geopolymer foam concretes enclosing WG are the more sustainable choice for lightweight elements for construction [140–143]. In the case of Geopolymer concretes, WG has been employed as the agent for alkali activation [103,144], as precursors for making Geopolymer mortars [48] and as the solid constituent of foams which are treated thermally [100]. By taking into consideration Geopolymer as a substitute to OPC, WG-bottles have pozzolanic activity embrace an added value [67]. The employ of Geopolymers to incapacitate radioactive waste is renowned, and WG incorporated concrete can be employed to do this job [145]. Its best use in construction and as building materials as well as radioactive waste immobilization with low energy consumption [146,147] is quite appreciable. Blending of WG in Geopolymer synthesis can mitigate not merely consumption of energy but also emission of CO_2 – a primary greenhouse gas providing relief to global warming dilemma and of course, a systematic solution of its disposal management. Bottles of WG made up of Soda-lime Silicate glass possess quite a lot of potential and practical applications when developed as concrete paving blocks with eco-glass [148], WG incorporated SCC (self-compacting concrete) [149] and mortars [150,151]. Meticulously, the technology of concrete paving block with eco-glass developed and employed commercially recently in Hong Kong [152]. Moreover, subsequent to the advanced grinding of the cullet of WG, the produced powder with the correct size of particle can be utilized as a substitution of OPC [153–156] as it is pozzolanic. Consequently, endeavours have been made to blend WG as a Supplementary Cementitious Material (SCM) in the concrete industry [155–157] because of their content of huge amounts of calcium and silica present in WG. Also, efforts were undertaken to use WG as an ASR (Alkali-Silica Reaction) suppressor, despite the high level of alkali in it [158–160].Of late, more investigations have also fingered out that the finer powder of WG has exhibited a significantly enhanced capability to improve durability property of concrete [161,162]. In the last couple of years, there has also been accelerating research endeavours [40,42,48,110,163–167] directed to recycle WG into alkali-activated cement (AAC) taking benefit of its chemical instability in Alkaline conditions and higher content of Silica rich glassy phase. It is expected that the higher alkali and Silica contents of soda-lime Silicate WG would encourage the alkali activation reaction [48,67] converting it in an eye-catching material for partial substitution of Fly Ash or GGBS in the production of AAC. Additionally, it is also believed to be feasible to apply cullets of Soda-Lime Silicate WG to substitute natural aggregates in the AAC partly. All the above applications and advantages are likely to extend beyond these data in the future as this concept has proved highly valuable.

5. Conclusion and discussion

This article reviews on the valorization of the applications of WG for the development of geopolymer composites and discussed the previous studies on strength, and workability properties along with microstructural behaviour of them. The possibility of employing WG using substituting volumetric percentages of either as aggregate like Sand or precursor-like Fly ash. It is wholly possible to blend these waste in construction and building materials, sans any further makeover beyond crushing to develop innovative Geopolymer building materials. The application of WG is a quite practical in manufacturing geopolymers as a raw material in forms like glass cullet, a waste-glass powder, end-of-life fluorescent lamps, fine sand, soda lime glass etc. and as a precursor for alkaline binders in geopolymer production. No doubt, the size of WG aggregates employed for replacing volumetric percentages of aggregates like Sand puts forth as an imperative impact on the mechanical attributes of the Geopolymer concrete. The uncultivated WG was applied with palpable benefits both from environmental and economical viewpoints. The development of Geopolymer composites in association with WG is fwithin acceptable mechanical strength. Also, this review has piloted to the viability of sustainable reuse of WG to manufacture Geopolymer composites. However, WG's reactive alumina content is low as regards reactions of geopolymerisation, but by adding reactionary alumina with the inclusion of cement from calcium-aluminium aluminium, the geopolymerisation reaction kinetic is improved, which is accompanied by the formation of more molecularly linked sodium-aluminosilicate (N-A-S-H) gel. The microstructure of the materials is further densified, significantly improving the attributes of the material as its compressive resistance. The results achieved so far, about the synthesis of geopolymers, are enthusiastically promising and potential investigations should review sound insulation characteristics to develop a light, energy saving, cost-effective and environment benevolent materials. This review found that recycled glass incorporated Fly ash based geopolymer is a doable substitute technique for developing low carbon footprint composites, which can result in noteworthy savings energy consumption and lesser emission of CO_2 provides relief to global warming too. Careful selection of the source materials to compositionally adding up the glass powder, Geopolymer binders and concrete with a blended with WG powder as the key component can be developed with acceptable mechanical properties. These innovative composites would emerge to offer an attractive, cost-effective material with consistent characteristics. Not merely that, the incorporation of WG in the manufacturing of Geopolymer composites would contribute to resolving

disposal predicaments for solid waste like WG in a user and eco-friendly way. However, advanced investigations are still needed to be conducted in this regard to establish the optimal synthesis mix and functioning parameters which entirely encourage the probable of WG application for the production of diverse Geopolymer composites. For prospect construction projects, escalating endeavours are necessary to promote the use of WG in diverse geopolymer composite applications by leading practitioners from both industry and academia. Demonstration that users are suitable in various business sectors increasingly becomes aware of the technological development of non - OPC binding techniques and several waste are a class of materials which are perfectly positioned to benefit from this awareness. Even though some challenges are standing in front in the pathway of application of waste in geopolymer technology like inaccessibility of particular kind of waste precursors, etc., efforts attempted for commercialisation in parallel with innovative researches will be the merely a step forward to achieve the final target of across-the-board deployment of the Geopolymer composite technology. Ultimately, it can be concluded that WG is a promising admixture for manufacturing Geopolymer construction composites. This new move could be a way of recycling a fraction of the WG that currently lies in deposits and creates environmental risks that represent a significant economic advantage as well as a green solution to the waste disposal challenges. WG has demonstrated its suitability to be used in a workable application to develop Geopolymer composites commercially. To sum up, the use of WG has been established as valuable material to make Geopolymers with excellent and acceptable attributes that value it as an economical and sustainable building material. This is a valuable step in the direction of its valorization.

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